

Introducing membrane specie permeability coefficient and economic assessment of polycomposite membrane bioreactor integrated with electric field



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ABSTRACT

A novel estimation of membrane specie permeability coefficient (K_{si}) in a polycomposite electro-membrane bioreactor (eMBR) was carried out in this study. The susceptibility of the eMBR to membrane fouling was assessed via the estimation of the temporal variations of K_{si} and specific cake resistance (α). These membrane fouling parameters and unit cost of treated water produced from the eMBR are being reported for the first time. The increasing order of K_{si} for individual measured contaminants was $\text{PO}_4^{3-}\text{-P} < \text{COD} < \text{NH}_4^+\text{-N} < \text{heavy metals}$. The mean values of K_{si} obtained for COD, $\text{NH}_4^+\text{-N}$, $\text{PO}_4^{3-}\text{-P}$, Ni, Fe and Cr were 20, 33, 1.0, 58, 70, and 102 mg/d.m^2 , respectively. The peak value of α obtained was $33.7 \times 10^9 \text{ m/kg}$. This means that heavy metals were more permeable through the membrane than COD and nutrients and the specific cake filtration was much lower than the typical range. These results were also confirmed by a reduction in the rate of membrane fouling, as established by the peaks and troughs of the transmembrane pressure. With an operational life time of 15 years, the unit cost of treated water obtained was $\$0.86/\text{m}^3$. This assessment presents the studied method as more cost-competitive than many wastewater treatment approaches.

1. Introduction

Membrane bioreactors (MBRs) combine activated sludge process with membrane filtration for wastewater treatment [1–3]. However, MBRs are faced with high cost requirements resulting from membrane fouling, aeration, excess sludge management, and removal of phosphorus and heavy metals. Firstly, membrane fouling is a problem in MBRs because it contributes to the cost of periodic membrane cleaning and replacement [4,5]. A critical factor contributing to membrane fouling in MBRs is the formation of soluble microbial products (SMP) or soluble extracellular polymeric substances (EPS) which are secretions from the metabolism and lysis of microbial aggregates [6,7]. Apart from contributing to water flux reduction and increase in operating costs of MBRs, SMP/EPS are also difficult and expensive to measure [8].

Secondly, MBRs require some levels of coarse aeration around the membrane area to scour the membrane and prevent membrane fouling. Coarse aeration is responsible for high energy costs and constitutes a significant portion of the total MBR operating cost [9–11]. Some studies had reported that aeration cost is the highest of all cost components in MBRs [12–14], with membrane aeration contributing up to 35–50% of total operating cost [15].

Thirdly, because of the retention of volatile suspended solids in

MBRs and subsequent increase in sludge production in accordance with the selected sludge age, considerable amounts of waste sludge are produced in MBR plants [16,17]. The production of huge amounts of waste sludge in MBRs leads to high costs of sludge handling and treatment [18]. In contrast to huge aeration costs, Yoon et al. [19] observed that, at reasonable hydraulic and sludge retention times, sludge treatment cost contributes more to the total cost of sludge treatment when compared with aeration cost and should be given more attention during cost analysis. Although less volumes of waste sludge are produced in MBRs when compared with the activated sludge process [20], significant levels of excess sludge are still produced. Also, sludge characteristics influence the efficacy of the sludge treatment process and the economics of waste sludge disposal or reuse [21,22].

Fourthly, biological processes in MBRs are not adequate for phosphorus removal [23]; hence there is a need for enhanced biological phosphorus removal mechanisms via phosphorus accumulating organisms [24]. However, phosphorus is mostly removed by adsorption or coagulation leading to precipitation during pre- or post-treatment and not by the membrane filtration or biological activity of microorganisms in MBRs [25,26]. Therefore, increase in pre- or post-treatment costs normally arise from the removal of phosphorus in MBRs so that good-quality treated effluents that would meet regulatory requirements can

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be obtained. In addition, the removal of heavy metals from wastewater by MBRs is limited by the inhibitory action of soluble heavy metal ions on volatile suspended solids. Also, these ions are too small in size to be retained in the mixed liquor by the membrane, in most cases [27]. Therefore, additional treatment units are required to be added to MBRs to ensure adequate removal of heavy metal ions. These additional units would require pumping power and capital costs.

To mitigate the aforementioned drawbacks, the integration of electrokinetics treatment with MBR has proved to be an effective solution. The coupled technologies in eMBR have been demonstrated to enhance SMP removal and reduce membrane fouling [28], enhance sludge physicochemical properties [22], and improve phosphorus and heavy metal removal [29]. In spite of its benefits, however, the electrical energy consumed through the use of direct current (DC) for electrokinetics in the integrated system calls for concern. The total cost of an eMBR system for wastewater treatment has not been investigated before this study and it might be wrong to state that the electrically-enhanced system is more (or less) expensive than the conventional MBR, when all economic factors are considered because this system further reduces the environmental footprint of wastewater treatment and improves effluent quality [30].

In this work, membrane fouling parameters such as the newly defined “membrane specie permeability coefficient” and specific cake resistance were used to evaluate the propensity of eMBR to undergo membrane fouling. Empirical models were employed to calculate the magnitudes of these parameters. In addition, the temporal profiles of these parameters were obtained in order to investigate the changes in these parameters with time. These trends were then compared with the fouling cycles measured via the transmembrane pressure (TMP) in order to establish a relationship between the treatment system and the rate of membrane fouling. The unit cost of treated water produced from the eMBR was also investigated and compared with the costs reported by studies on conventional MBRs.

2. Materials and methods

2.1. Experimental setup and materials

The eMBR was fabricated with polycarbonate walls for the production of treated wastewater. Fresh activated sludge was collected from a municipal wastewater treatment plant at Masdar City, Abu Dhabi and fed to the reactor. Unscreened variable-feed raw municipal wastewater was then added directly to the activated sludge in the reactor, using a food-to-microorganisms ratio of 0.6 mg COD of wastewater per mg COD of activated sludge per day. The anode was made up of aluminum sheet and the cathode was made up of stainless steel. The experimental setup of the treatment system is illustrated in Fig. 1.

These electrodes were placed in the reactor and connected to a DC power supply. A commercial flat sheet microfiltration polycomposite membrane with mean pore size of 0.4 μm was inserted at the centre of the reactor and submerged in the mixed liquor. The flat sheet polycomposite membrane was donated by Kubota Corp. and it was composed of acrylonitrile butadiene styrene, polypropylene, polyethylene terephthalate and chlorinated polyethylene mixed in the ratio 1:2:2:2, respectively. A continuously stirred system was ensured by aerating the reactor content and pumping the wastewater and treated effluent into and out of the mixed liquor. The total volume of the reactor was 31.5 L. The volume of the electrical zone between the electrodes was 8.0 L. The effective reactor volume was about 71% of the total reactor volume while the volume of the electrical zone was about 26% of the total reactor volume. The effective height of the anode was 34 cm and the effective membrane area was 11 dm^2 . A hydraulic retention time of 13.5 h and sludge retention time of 10 days were maintained. The eMBR was allowed to run continuously for 60 days. Pumping was ensured by using Cole-Parmer's MasterFlex peristaltic pumps (with an in-built digital flow meter) while mixing was aided by the passage of air

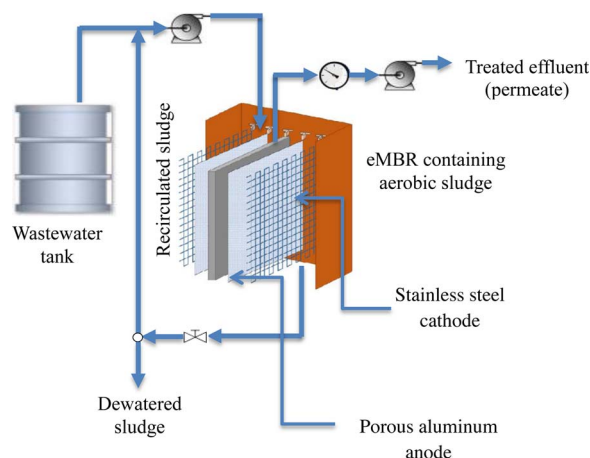


Fig. 1. The schematic of the experimental setup of the treatment system. The eMBR is connected to direct current (DC) electric power.

through fine bubble diffusers attached to the base of the reactor.

An initial water flux of 15.2 $\text{L}/\text{m}^2\cdot\text{h}$ across the membrane and effluent flow rate of 40 L/d was set at the start of the experiment. Biodegradation of the wastewater was ensured by the microbial species in the mixed liquor while the filtration of fresh water from the mixed liquor was ensured by the membrane. Electrocoagulation of the colloids and non-biodegradable species in the wastewater was ensured by the vertical electrodes inserted inside the reactor. A current density of 15 A/m^2 was maintained in the system. Intermittency of current was ensured in order to control the discharge of electrocoagulants (Al^{3+}) into the mixed liquor by connecting the power supply to a timer maintained at 5 min: 15 min ON: OFF mode.

The diffusers were connected to Cole Parmer's EW-03217-30 150 mm correlated air flow meter from where the air flow rate was adjusted. Fine air bubbles of flow rate 2.3 L/min were passed to the bulk mixed liquor to maintain the dissolved oxygen (DO) above 2 mg/L for biological activity but the air flow rate near the membrane surface was kept at 4.6 L/min for coarse bubble scouring. The quantity of each capital item used for the fabrication of the reactor is provided in Table 1. The capital items in the reactor are shown in the detailed description of the eMBR presented in Fig. 2.

DO was measured using HQ40d Multi meter. Some wastewater and treated effluent components were measured using HACH LANGE DR3900 spectrophotometer with radio-frequency identification (RFID) technology. This technology employed electromagnetic fields to automatically recognize, track and convert barcodes attached to the spectrophotometer cuvettes into readable estimates. The measured components were chemical oxygen demand (COD), ammonia as ammonium-nitrogen ($\text{NH}_4^+ - \text{N}$), orthophosphate or soluble phosphate

Table 1
Capital items used in the eMBR.

Component	Quantity
Tank assay	1 unit
15 A – 3 core power wire	1 m
Membrane	1 unit
½" conduit tree	1 m
3/8" inlet pipe	1 m
Electrode – porous aluminum sheet	2 pairs
Electrode – stainless steel	2 pairs
Inlet SS tubing ½"	1 m
½" outlet pipe	1 m
Air blower	1 unit
3/8" Aqua pipe	1 m
Diffuser	3 units
Electrical socket	2 units
Housing	1 unit

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