Influences of electroosmosis and electrophoresis on permeate flux and membrane fouling in submerged membrane bioreactors (SMBRs)
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ABSTRACT
The objective of this study was to investigate the influences of electroosmosis (EO) and electrophoresis (EP) on the permeate flux in submerged membrane bioreactors. When a polymeric membrane is placed in between an anode and a cathode, both EO and EP occur simultaneously, causing enhancement in flux. Results showed that after 150 min of filtration, the permeate fluxes were 60, 115, 175 and 260 L/m²/h at 0, 30, 40 and 50 V, respectively. It was shown that the EO was linearly changing with increasing voltage, reaching up to 54 L/m²/h at 50 V. EP was found to be a significant process in removing soluble microbial products from the membrane surface, resulting in an increase in permeate flux as the filtration progressed. About 20-fold of smaller protein and carbohydrate concentrations were found in the cake layer when the electrical field (EF) was applied. However, the EF application promoted pore fouling, because of the calcium and magnesium scaling.

Key words | electrofiltration, electroosmosis, electrophoresis, membrane bioreactor

INTRODUCTION
Membrane bioreactors (MBRs) have been commonly used in wastewater treatment. MBRs eliminate the requirement for a sedimentation tank, provide excellent water solid separation and have a small footprint. However, membrane fouling is a major concern in their operation and it limits their widespread use. It has been reported that extracellular polymeric substances (EPSs) and soluble microbial products (SMPs) are the major compounds causing membrane fouling (Rosenberger & Kraume 2003; Massé et al. 2006). SMPs and EPSs are large molecules and are released by bacteria. Other researchers identified colloidal particles as the major foulants in addition to those biopolymers (Bouhabila et al. 2001; Hwang & Lin 2002; Dizge et al. 2012). In order to control the concentration of foulants within the reactor, applications of diatomaceous earth, powdered activated carbon, iron and aluminum salts, inorganic polymeric substances and organic poly-electrolytes to the biological reactor have been studied in recent years (Le Roux et al. 2005; Koseoglou et al. 2008; Sagbo et al. 2008; Koseoglou-Imer et al. 2011). In recent years, the application of electrocoagulation has also been investigated to enhance the filterability of biological suspensions (Sasson & Adin 2010; Bani-Melhem & Elektorowicz 2011; Bani-Melhem & Smith 2012).

The fouling reduction studies summarized above have primarily focused on SMP content reduction and/or on floc size enhancement. It is also possible to control fouling to conduct the filtration under an electrical field (EF). Various processes, including electrophoresis (EP), electroosmosis (EO) and hydrolysis reactions, occur when an EF was applied to a membrane which is placed in between an anode and a cathode. EO occurs toward the cathode if the membrane pores are negatively charged (Yano et al. 2013). The cations with the water of hydration move toward the cathode causing a net water flow from the anode to the cathode. This process occurs in the diffuse layer and contributes as an additional flux from the feed side to the permeate side. The other important process is the EP in which charged colloids move toward the respective electrodes. Usually colloids (bacterial flocs and SMPs) are negatively charged; therefore, they are pushed away from membrane surface toward the anode. The magnitudes of
the EP depend on the electrophoretic mobility, which can be represented by the Helmholtz–Smoluchowski equation.

\[ u_e = \frac{\varepsilon_o D_i \zeta}{\mu} \quad (1) \]

where, \( D_i \) dielectric constant (-), \( \varepsilon_o \) vacuum permittivity \((8.854 \times 10^{-12} \text{ CV}^{-1} \text{ m}^{-1})\), \( \zeta \) zeta potential of particles (V) and \( \mu \) is the dynamic viscosity (Pa.s). Another process that occurs in electrofiltration is the oxidation and reduction reactions on the electrodes. Hydrogen ion is formed on the anode and hydroxyl ion is formed on the cathode because of the electrolysis. As a result, pH in the cathode chamber increases.

Earlier studies related to the filtration under EF have mostly focused on separation of proteins and colloids in a cross flow filtration system. In a study, a 10-fold increase in flux was reported in the filtration of a soluble polymer when 167 kV/m EF was applied (Akay & Wakeman 1997). The purification of proteins in a crossflow microfiltration unit was investigated in another study. It was reported that both cake and pore resistances decreased as DC was applied (Park 2006). Electrofiltration studies with more complex solutions (wastewater, biological suspensions, etc.) have also been investigated and reported in the literature. It was shown that the membrane fouling decreased and the permeate flux increased when 6 V/cm pulse EF was applied to an activated sludge suspension (Akamatsu et al. 2010). In a recent study, high voltage (4 to 20 kV/cm) in pulses (100 and 300) at 20 to 70 \( \mu \)s was applied in a stirred batch cell. It was reported that the cake layer could be removed from the membrane surface more effectively; however, cell damage occurred at high voltages (Lee & Chang 2014). In recent years, researchers investigated reduction of fouling using conducting membranes as anode and cathode. It was shown that organic, inorganic and bacterial fouling could be reduced by applying a small amount of electrical potential (Duan et al. 2014, 2016; Dudchenko et al. 2014; Zhang & Vecitis 2014; Ronen et al. 2015).

In most of the submerged membrane filtration studies under an EF, an inert anode electrode was replaced with an iron or aluminum electrode to allow simultaneous electrocoagulation and filtration. Bani-Melhem & Elektorowicz (2010) studied the submerged membrane configuration with iron cathode and anode in wastewater treatment. It was reported that fouling reduced by 16.5% due to the increase in size of flocks in the cake layer, causing increase in permeability. The other studies in the literature mostly focused on the effectiveness of electrocoagulation and filtration in specific contaminant removals rather than flux enhancement (Wei et al. 2009; Bani-Melhem & Elektorowicz 2011; Hasan et al. 2014).

The submerged filtration studies focused mostly on the influence of electrocoagulation on filtration and on contaminant removals. The influence of EO and EP on submerged membrane filtration have not been identified independently in the literature yet. Therefore, in this study, the influence of EF on filtration of activated sludge has been investigated. The effects of both EO and EP on membrane filtration were demonstrated separately in a single experimental setup. The magnitude of electroosmotic flow, the influence of EP on cake layer and the effect of hydrolysis reactions on pore fouling were identified independently. The fouling mechanism in the presence of EF was shown experimentally without circumstantial evidence in a complex media such as activated sludge suspension.

**MATERIAL AND METHODS**

**Experimental methods**

The experiments were conducted using a custom made filtration module. The schematic representation of the filtration module is represented in Figure 1(a). The module consisted of a perforated stainless steel cathode, an
ultrafiltration (UF) membrane and a platinum plated titanium anode. The cathode was fixed to a Teflon block (end plate). On top of the cathode, a 0.05 μm pore sized PES membrane (Microdyn Nadir, Germany) was placed. The same membrane type was used in all experiments. Each membrane module had a surface area of 25 cm². A Teflon frame was used to seal the cathode and the membrane to the end plate. The anode was placed 1 cm away from the membrane surface. The distance between membrane surface and the anode was adjusted with screws and rods placed on the end plate.

Three different membrane modules were submerged into a continuously operated aerobic biological reactor with a volume of 25 L. Diffusers were installed into the bottom of the reactor so that air could scour the membrane surface and provide the necessary mixing. Two of the membrane modules had membranes in both sides of the modules and were operated independently. The outlets of four membranes (two membrane modules) were connected to a vacuum chamber in which 200 mbar of constant vacuum was maintained using a vacuum regulator connected to a vacuum system existing in the laboratory. DC was applied to two membranes at prescribed voltages. Thus, two membranes were operated under EF and the other two membranes were operated without the EF with all four at the same transmembrane pressure (TMP). The fifth module with one membrane was used to measure the degree of EO in the absence of TMP. Therefore, the outlet of one membrane module was connected outside of the vacuum chamber at the same water level as the biological reactor (TMP = 0). The same EF (the same voltage) as the other membranes connected to the vacuum chamber was applied to the last module. Permeates of five membranes were collected in beakers which were placed on balances separately to determine the permeate flux of each membrane. The schematic representation of the experimental setup is presented in Figure 1(b).

The biological reactor was fed by synthetic wastewater. The wastewater contained 1,000 mg/L glucose, 50 mg/L peptone, 100 mg/L urea, 50 mg/L KH₂PO₄, 5 mg/L K₂HPO₄, 50 mg/L (NH₄)₂SO₄, 50 mg/L MgSO₄·7H₂O, 250 mg/L NaHCO₃, 10 mg/L CaCl₂·2H₂O, 50 mg/L NaCl, 10 mg/L KCl and low concentrations of other trace elements. The hydraulic residence time of the reactor was about 12 h with sludge age of 20 d.

**Analytical methods**

Measurements of chemical oxygen demand (COD), mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS) were performed as defined in *Standard Methods* (APHA 1998). Influent COD measurements were performed after filtering the samples through 0.45 μm membranes. The EPS and SMP analysis were made through a physical–chemical extraction method (Li et al. 2008). A 5 mL activated sludge sample was taken from the reactor. First, the suspension was centrifuged at 4,000 × g, for 10 min, at 4 °C. Then, the supernatant was decanted into another sterile tube and re-centrifuged (13,200 × g, 20 min, 4 °C) to ensure complete removal of the suspended solids. The resultant supernatant contained soluble polysaccharide and soluble protein. The supernatant was analyzed for SMP content. The sediment in the tube was re-suspended with distilled water to obtain another 5 mL of suspension for EPS analysis. Then, 6 μL formaldehyde (37%) was added into the suspension and was left at 4 °C for 1 h, and the addition of 500 μL NaOH (1N) for another 3 h at 4 °C followed. The suspension was centrifuged at 13,200 × g for 20 min and at 4 °C. The supernatant, containing bound polysaccharide and bound protein, was analyzed for EPS content. For the samples obtained from the cake layers, SMP was not analyzed separately. Instead, EPS analysis was conducted to account for the sum of SMP and bound EPS. The measurement of protein content was carried out according to the Lowry method (Lowry et al. 1951). Carbohydrate content was determined according to the Dubois method (Dubois et al. 1956). The zeta potential of mixed liquor was measured by a zeta potential analyzer (Zetasizer, Malvern, UK). Streaming potential measurement of the membrane was performed with an electrokinetic analyzer (SurPASS, Anton Paar GmbH, Austria) at pH 6.5 and 9.2.

**RESULTS AND DISCUSSION**

**Reactor operating conditions**

The biological reactor was operated for 2 months prior to the filtration experiments. MLSS, MLVSS, influent and effluent COD values, SMP and EPS concentrations were measured in the reactor during the operation. MLSS of the reactor ranged from 5,200 to 5,800 mg/L during the experiments. Initial COD concentration was about 1,000 mg/L with removal efficiencies greater than 90%. Both protein and carbohydrate content of SMP were in between 10 and 20 mg/L. EPSc content was about 20 to 30 mg/g MLSS; whereas, EPSp, remained between 30 and 40 mg/g MLSS.
Zeta potential of the biological suspension was measured as $-14.8 \pm 1.3 \text{ mV}$.

**Continuous electrical field applications**

The experiments were conducted at 30, 40 and 50 V in order to observe the influence of EF on permeate flux and membrane fouling. At each voltage, two membrane modules were operated without the EF, and the other two were operated with EF. The variations of the average flux (from two membranes) with time are presented in Figure 2. The flux rapidly declined from 300 L/m$^2$/h to 60 L/m$^2$/h within 140 min in the absence of EF. However, the degree of decline in the flux for the membranes with EF was much smaller. Two to four times greater fluxes were obtained depending on the voltage value when DC was applied. After 140 min of continuous EF application, the fluxes were 115, 175 and 260 L/m$^2$/h at 30, 40 and 50 V, respectively. This increase may be attributed to the existence of EO and/or EP in the presence of EF. Independently measured electroosmotic fluxes obtained in the membrane module operated under EF with zero TMP at two voltage values are presented in Figure 3. The electroosmotic flux ranged from 2 to 10 L/m$^2$/h with an average value of 8 L/m$^2$/h at 30 V; whereas, it varied from 15 to 38 with an average of 25 L/m$^2$/h at 40 V. These values did not correspond to the increase in permeate flux values observed in Figure 2. For example, approximately 55 L/m$^2$/h of flux increase was obtained at 30 V. However, independently measured average electroosmotic flux at the same voltage was only 8 L/m$^2$/h. Similar results were also observed at 40 V. While the flux increase was about 110 L/m$^2$/h, the electroosmotic flux was only 25 L/m$^2$/h. Therefore, it was apparent that other processes such as EP were also contributing to the flux enhancement in the presence of EF. It was also possible that the magnitude of electroosmotic flux in the presence and the absence of TMP were not the same as discussed in the section ‘Variable voltage applications’. The effect of EP on the flux is discussed below as well as in the ‘Variable voltage applications’ section.

It has been reported that the flux enhancement due to EP continued up to a critical EF value at which net particle migration toward the membrane surface was zero (Huotari et al. 1999). The increase in flux was greater than the magnitude of electroosmotic flux and continued with increasing voltage. These results suggested that the critical EF for EP was not reached in this study. Once the filtration of activated sludge suspension was completed, the membrane modules were removed from the biological reactor, and immersed into a reactor filled with tap water. One-hour filtration experiments were performed without EF at the same TMP as the filtration of biological suspension. The average permeate flux values were determined using the last 10 min of data. After filtration of tap water, the membrane modules were taken out of the

![Figure 2](https://iwaponline.com/wst/article-pdf/74/3/766/460457/wst074030766.pdf)
reactor and their surfaces were physically cleaned by water and a sponge. After that, the modules were immersed into another reactor filled with fresh tap water and filtration was performed at the same TMP without EF. The permeate fluxes obtained in those experiments as well as the ones obtained in the biological reactor as discussed above are presented in Table 1. In the membranes without EF (0 V), the permeate flux either remained the same or increased when tap water was filtered before surface cleaning. Increase in water flux was due to the elimination of concentration polarization. Typically, concentration polarization does not occur significantly in micro and ultrafiltration membranes. However, when fouling occurs on the surface and inside the pores, SMPs accumulate on the membrane surface forming a gel layer (Dizge et al. 2014). For the membranes with EF, increased or at worst the same flux values are expected since the influence of the concentration polarization was eliminated (i.e. filtering tap water). However, significant flux decline was observed as opposed to the membranes operated without EF when biological suspension was filtered. For example, fluxes declined from 113 to 96 L/m²/h at 30 V, 168 to 152 L/m²/h at 40 V and 251 to 158 L/m²/h at 50 V applications. This was a clear indication of the contribution of electroosmotic flow on the permeate flux. Since the filtration of tap water was performed in the absence of EF, the EO did not occur in those experiments (for $J_{av,bw}$ and $J_{av,aw}$). Therefore, the decline in flux was attributed to the absence of EO. The degree of EO for membranes with TMP was different than the membrane without TMP. This is discussed in more detail in the section ‘Variable voltage applications’.

Another important aspect of this experiment was that the $J_{av,bw}$ values were greater for the membranes operated

![Figure 3](https://iwaponline.com/wst/article-pdf/74/3/766/460457/wst074030766.pdf)

**Figure 3** | Variation of electroosmotic flux in the absence of TMP.

**Table 1** | Permeate flux values of biological suspension and tap water (before and after surface cleaning)

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Activated sludge $J_{av,sl}$ (L/m²h)</th>
<th>Before surface cleaning, filtration with tap water* $J_{av,bw}$ (L/m²h)</th>
<th>After surface cleaning, filtration with tap water* $J_{av,aw}$ (L/m²h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>54.2</td>
<td>91.0</td>
<td>350.9</td>
</tr>
<tr>
<td>0</td>
<td>56.2</td>
<td>86.4</td>
<td>313.5</td>
</tr>
<tr>
<td>30</td>
<td>112.7</td>
<td>95.8</td>
<td>270.5</td>
</tr>
<tr>
<td>30</td>
<td>116.0</td>
<td>110.1</td>
<td>286.6</td>
</tr>
<tr>
<td>0</td>
<td>66.3</td>
<td>65.6</td>
<td>301.2</td>
</tr>
<tr>
<td>0</td>
<td>66.2</td>
<td>75.7</td>
<td>328.7</td>
</tr>
<tr>
<td>40</td>
<td>168.4</td>
<td>152.0</td>
<td>273.8</td>
</tr>
<tr>
<td>40</td>
<td>181.8</td>
<td>142.4</td>
<td>294.3</td>
</tr>
<tr>
<td>0</td>
<td>70.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0</td>
<td>72.7</td>
<td>72.0</td>
<td>241.8</td>
</tr>
<tr>
<td>50</td>
<td>251.0</td>
<td>157.8</td>
<td>166.1</td>
</tr>
<tr>
<td>50</td>
<td>265.4</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*The experiments were conducted without EF.
under EF. The influence was more apparent when the voltage increased. This was attributed to a lower fouling in the cake layer in the presence of EF. An additional experiment was conducted in order to investigate the properties of the cake layer in more detail. Two membrane modules with and without EF (at 40 V) were immersed in the activated sludge reactor and 4 h of filtration experiment were performed. The cake layer formed on the membrane surface (biofilm) was scrapped and the protein and carbohydrate contents were determined. The results are presented in Figure 4. Both protein and carbohydrate contents of the cake layer were much lower when the EF was applied. Protein content of the biofilm was about 42 mg/g in membrane without EF; whereas, it was about 2 mg/g for the membrane operated under EF. Similarly, carbohydrate content was 1.5 and 18 mg/g for the membranes with and without EF, respectively. Furthermore, the visual observation showed that the cake layer was very different for membranes with and without EF. Thicker more sludge-like cake was formed on the membrane with EF; whereas, a thinner, compact slimy cake layer formed on the surface of the membrane in the absence of EF. It was apparent that the structure of the cake layer was substantially different when EF was applied.

After tap water filtration ($J_{av, bw}$ in Table 1), the cake layer was cleaned with a sponge and clean water fluxes were determined ($J_{av, aw}$ in Table 1) in order to identify the magnitude of pore fouling. Lower permeate fluxes were obtained in the membranes operated under EF. This was a clear indication of higher degree of pore fouling in the presence of EF. The cathode was just behind the membrane (in contact) and the pH value was about 10 to 12 in the cathode chamber depending on the voltage values due to the electro-hydrolysis of water. The elevated pH likely caused the formation of inorganic scaling. In order to test this hypothesis, a different experiment was performed. After an electrofiltration experiment, the membrane surfaces were cleaned physically and the modules were immersed in a small reactor filled with clean water at pH of 3. Calcium, magnesium and iron analysis were performed in the collected permeate. The results are presented in Figure 5. Both calcium and magnesium content in membrane with EF was almost twice as much as those in the membrane module without EF. In particular elevated calcium concentrations up to 120 mg/membrane module were obtained, indicating the presence of significant CaCO$_3$ scaling on the membrane.

**Variable voltage applications**

In the previous section, the EO and the EP were shown to be important factors in permeate flux enhancement. However, the magnitude of EO could not be identified explicitly. Therefore, a new experiment with a sequential voltage increase was designed without any cleaning in

![Figure 4](https://iwaponline.com/wst/article-pdf/74/3/766/460457/wst074030766.pdf)
between voltage switches in order to clarify the degree of EO during the filtration and to identify the effect of EP on surface clean up. Two membrane modules were operated without EF and the other two were operated with sequential voltage increments. In between voltage increases, 150 min of voltage interruptions were applied. The experiment was started at 0 V and continued for about 150 min. The voltage was first increased to 10 V and then to 20 V for 150 min each. A voltage interruption (0 V) was followed for about the same time period. After that, 30 V, 0 V, 40 V, 0 V, 50 V and finally 0 V were applied for 150 min each. The results are presented in Figure 6.

A sudden flux increase was observed when the EF was applied. On the contrary, when voltage was interrupted, a sudden flux decrease followed. This was a clear indication of the effect of EO. When 20 V was applied, 9.0 L/m²/h of flux enhancement was observed within seconds. Once the voltage application stopped, 2.7 L/m²/h of flux decrease was observed. The increase and decrease in fluxes were 23.5 L/m²/h and 16.7 L/m²/h at 30 V, respectively. When voltage increased to 40 V, 37.1 L/m²/h of flux increase occurred. When the voltage stopped, 38.7 L/m²/h reduction in flux was noted. Finally, the jumps and drops in flux values were 54.1 and 54.0 L/m²/h at 50 V, respectively. This behavior with electrical applications was due to the electroosmotic flow. The magnitudes of jumps and drops were similar at each voltage value. This was certainly true at high voltage conditions (i.e. 40 and 50 V). It was apparent that the electroosmotic fluxes ranged from 17 to 24 L/m²/h at 30 V, from 37 to 39 L/m²/h at 40 V and it was about 54 L/m²/h at 50 V. The magnitude of electroosmotic flux showed a linear increase with increasing voltage. The average values of electroosmotic flows were determined by averaging the magnitudes of jumps and drops, and their variation with increasing voltage is presented in Figure 7. Only the drop value of the flux data (2.7 L/m²/h) was used for the 20 V experiment since the jump occurred from 10 V to 20 V, which did not correspond to the same voltage difference as the drop. A linear relationship was observed between EF strength and electroosmotic flow rate at the range from 20 to 50 V. The effect of EO on permeate flux was relatively insignificant below 20 V. The effect of Ohmic heating (including Joule’s heating effect) may have some effect on the electroosmotic flow rate. The temperature of the reactor was controlled and up to 2 to 3 °C of increase was allowed. The increase in temperature cause reduction in viscosity of water and increase in diffusivity of ions. Degree of flux change due to the change of viscosity will be the same for the flux caused by pressure difference since all membrane modules (with and without EF) were submerged into the

![Figure 5](https://iwaponline.com/wst/article-pdf/74/3/766/460457/wst074030766.pdf)
same reactor. However, the change in viscosity of water and diffusivity of ions would affect the degree of electroosmotic flow. The change of diffusivity with time can be represented as follows (Tang et al. 2004):

\[ D_i(T) = D_{i0} + 0.025D_{i0}(T - 298) \]  

(2)

Figure 6 | Variation of flux values under sequential voltage increase.

Figure 7 | Variation of electroosmotic flux with voltage.
where, $D_f(T)$ is the temperature dependent diffusion coefficient, $D_{lo}$ is the diffusion coefficient at room temperature, and $T$ is the temperature (K). Hence, 12.5% of increase would be expected in diffusivity. The viscosities of water at 20°C and 25°C were 1.0050 and 0.8937 cP, respectively (Geanopoulos, 1993). Therefore, based on Equation (1) the temperature may affect the electroosmotic flow due to the viscosity change and diffusivity at most of 20 to 25%. However, since the magnitudes of drops and sudden jumps were almost the same after 150 min of operation at high voltages at which more heating was expected, it was concluded that the effect of Ohmic heating on EO was relatively insignificant in these experiments.

In this experiment, the electroosmotic flow occurred simultaneously with the flux due to TMP. The electroosmotic fluxes showed significant differences than those obtained in membrane modules without TMP. While electroosmotic flow was in between 2 and 10 L/m²/h (with no TMP) at 30 V, it was about 18 to 24 L/m²/h with TMP.

The observed electroosmotic flow rates were lower in the absence of TMP. This may be attributed to the change of zeta potential of the membrane due to the accumulation of the foulant on the membrane surface. In the presence of TMP, more foulants (SMP and colloids) accumulated in the pores and on the membrane surface, as seen in Figure 4. Since most colloids and SMPs are negatively charged, it was likely that the zeta potential of the fouled membrane/liquid interface decreased, causing greater electroosmotic flow. The zeta (or streaming) potential of the fouled membrane was not measured in this study. However, the streaming potentials of the clean membrane were $-6.7 \pm 2.4$ mV and $-8.6 \pm 4.2$ mV at pH 6.5 and 9.2, respectively. On the other hand, the zeta potential of bacterial suspension was smaller ($-14.8$ mV). Therefore, the occurrence of the smaller zeta potential on the fouled membrane surface and the fluid interface was likely possible. Enhanced electroosmotic flow likely occurred at any voltage values due to membrane fouling caused by TMP. However, this effect was more noticeable at lower voltage (i.e. 30 V) value. As discussed below, the electrophoretic forces were more dominant at larger voltage gradient, removing negatively charged particles from the surface. Therefore, the accumulation of the foulants on the membrane was not as significant at high voltages as it was at low voltages. It was concluded that the cake layer on the membrane surface promoted the electroosmotic flow rates. Formation of cake induced electroosmotic flow was also reported in other studies (Wei et al., 2011).

EP is another factor contributing to the flux enhancement in addition to the EO. Typically, a decrease in flux is expected with time due to membrane fouling. However, EP may decrease the degree of fouling by removing the accumulated colloids and polymeric substances from the membrane surface. As a result, an increase in flux with time may be observed. Therefore, the differences between the initial and the final flux values at each voltage application were determined. 1.9 L/m²/h of flux reduction was observed between the initial and final voltage application of 20 V. The flux reduced from 58.2 to 56.3 L/m²/h. However, the flux started increasing at higher voltage applications. The flux slightly increased at 30 V by about 2.0 L/m²/h. On the other hand, when 40 and 50 V of EFs were applied, the fluxes increased substantially with time. The initial flux was 60.2 L/m²/h and increased by 16.7 L/m²/h, reaching 76.9 L/m²/h at the end of 40 V. Even larger increase in flux with 19.2 L/m²/h was observed at 50 V. This was a clear indication of membrane clean up by electrophoretic forces at larger voltage applications. Above a certain voltage, electrophoretic forces were able to remove foulants from the membrane surface, resulting in faster clean up rates than the fouling rates. This result has an important implication in practical applications of electrofiltration. Continuous EF application may not be economically feasible. Furthermore, at elevated voltage values cell disruption occurs and this reduces the biological activity (Wei et al., 2011). In addition, chlorine gas formation on the anode may have a potentially adverse effect on the biological system in long operations. Therefore, intermittent electrical applications may be more appropriate for surface clean up in real life applications. The results showed that intermittent EF may potentially be used in submerged membrane bioreactors for surface clean up.

CONCLUSIONS

- The EF application enhanced the permeate flux substantially, which was attributed to the EO and EP. After 150 min of filtration, the permeate flux values were 60, 115, 175 and 260 L/m²/h at 0, 30, 40 and 50 V applications, respectively. The flux ratio between the membranes with and without EF application was 1.7 at 20 V and 4.6 at 50 V.
- The EO was linearly changing with increasing voltage above 20 V. The magnitude of EO reached up to 54 L/m²/h at 50 V.
• Presence of TMP promoted the magnitude of the EO, especially at lower voltage values due to greater accumulation of negatively charged foulants on the membrane surface and pores (i.e. below 30 V).
• The EP significantly removed SMPs from the membrane surface. About 20-fold of smaller protein and carbohydrate concentrations were observed in the cake layer when EF was applied. As a result, the cake resistance decreased substantially.
• However, the EF application promoted pore fouling, because of the calcium and magnesium scaling. Since pH increases in the cathode compartment, calcium and magnesium formed insoluble precipitates. More than twice as much calcium was accumulated in the membranes when EF was applied.
• The EP above a certain voltage value cleaned up the membrane surface and enhanced the flux as the filtration continued. As the voltage increased, the surface cleaning due to EP was more apparent.

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REFERENCES

Geankoplis, C. J. 1995 Transport Processes and Unit Operations. P T R Prentice Hall, USA.


