Fouling of a microfiltration membrane by humic-like substances: a mathematical approach to modelling permeate flux and membrane retention
Eskandar Poorasgari, Ali Farsi and Morten Lykkegaard Christensen

ABSTRACT

Membrane retention of the humic-like substances present in a soluble microbial products (SMP) suspension was studied by using a dead-end filtration system. The SMP suspension was extracted from the sludge of an enhanced biological phosphorus removal-membrane bioreactor. Our results showed that both adsorption and steric retention of the humic-like substances governed their transport through the membrane during the filtration. The adsorption, which followed pseudo-first order kinetics, did not cause substantial decline of permeate flux. The steric retention, on the other hand, formed a gel layer, which in turn led to a major decrease in the flux. The reduction of permeate flux was well predicted by cake filtration theory. Based on the adsorption and the steric retention, a new model was developed for predicting the overall membrane retention of the humic-like substances. The general trend of the modelled overall retention was in partial agreement with the experimental results.

Key words | adsorption, filtration theories, gel, steric retention

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Membrane surface area [m²]</td>
</tr>
<tr>
<td>C_f</td>
<td>Feed concentration [mg L⁻¹]</td>
</tr>
<tr>
<td>C_p</td>
<td>Permeate concentration [mg L⁻¹]</td>
</tr>
<tr>
<td>C^o</td>
<td>Concentration that gets inside the pore channel [mg L⁻¹]</td>
</tr>
<tr>
<td>J</td>
<td>Permeate flux [L m⁻² h⁻¹]</td>
</tr>
<tr>
<td>K</td>
<td>Adsorption kinetics rate constant [s⁻¹]</td>
</tr>
<tr>
<td>n</td>
<td>Adsorbed mass at any time [μg]</td>
</tr>
<tr>
<td>n_eq</td>
<td>Equilibrium adsorbed mass [μg]</td>
</tr>
<tr>
<td>Q</td>
<td>Permeate flow [m³ s⁻¹]</td>
</tr>
<tr>
<td>R</td>
<td>Overall retention [-]</td>
</tr>
<tr>
<td>R_{init}</td>
<td>Initial filtration resistance against SMP suspension [m⁻¹]</td>
</tr>
<tr>
<td>R_g</td>
<td>Gel resistance [m⁻¹]</td>
</tr>
<tr>
<td>R^o</td>
<td>Steric retention [-]</td>
</tr>
<tr>
<td>V_p</td>
<td>Permeate volume [m³]</td>
</tr>
<tr>
<td>V_{Po}</td>
<td>Pore volume [m³]</td>
</tr>
<tr>
<td>t</td>
<td>Filtration time [s⁻¹]</td>
</tr>
<tr>
<td>Z</td>
<td>Membrane thickness [m]</td>
</tr>
<tr>
<td>α</td>
<td>Specific resistance [m kg⁻¹]</td>
</tr>
<tr>
<td>ε</td>
<td>Membrane surface porosity [-]</td>
</tr>
<tr>
<td>ω</td>
<td>Area specific amount of gel [kg m⁻²]</td>
</tr>
<tr>
<td>μ</td>
<td>Dynamic viscosity [Pa s]</td>
</tr>
<tr>
<td>ΔP</td>
<td>Applied pressure [kPa]</td>
</tr>
</tbody>
</table>

INTRODUCTION

Membrane bioreactors (MBRs) are widely used for wastewater treatment because, as compared with conventional activated sludge systems, they produce effluent of higher quality, have a smaller footprint and produce less sludge (Judd 2006). Notwithstanding, membrane fouling has curtailed widespread application of the MBRs (Le-Clech et al. 2006). MBR fouling is the decrease of permeate flux due to the deposition of the components of the MBR sludge on and/or within membrane pores. In order to better control the MBR systems, membrane fouling models which can accurately predict permeate flux are valuable tools (Khan et al. 2009).
In a general view, the MBR sludge components are located in two phases: solid and liquid. It has been shown that the liquid phase of the sludge plays a crucial role in fouling (Ji et al. 2008). The liquid phase contains such biopolymers as protein, carbohydrate and humic-like substances, which are generally known as soluble microbial products (SMP). Sometimes MBR systems are combined with anaerobic hydrolysis and denitrification units to remove phosphorus and nitrogenous compounds from wastewater (Zhang et al. 2009). Such systems are called enhanced biological phosphorus removal (EBPR)-MBR, in which SMP of the MBR sludge was shown to be primarily composed of humic-like substances (Poorasgari et al. 2014a).

It is well accepted that humic-like substances adsorb to polymeric membranes (Jucker & Clark 1994), causing irreversible flux decline (Jermann et al. 2007). However, the results on the contribution of adsorption to MBR fouling are still contradictory (Le-Clech et al. 2006). Apart from adsorption, some studies have shown presence of humic-like substances in a covering formed on the MBR membranes (Geng & Hall 2006). Through an experimental study (Poorasgari et al. 2014a), the covering was revealed to be a gel layer. Thus, adsorption and gel formation are expected to be important in retention of the humic-like substances in the EBPR-MBR systems.

There have been a few modelling attempts considering gel formation and adsorption. Having combined adsorption kinetic and Hagen–Poiseuille equations, Bolton et al. (2006) worked up a model to predict permeate flux as a function of pore narrowing during filtration of a fouling solution. Shen et al. (2011) depicted that molecular properties of SMP components should be considered as important parameters. Xiao et al. (2013) proposed a mathematical formula to quantify fouling by gel formation, which occurred during filtration of SMP suspension.

The executed investigations, nevertheless, are not able to address the exclusive effects of gelling and adsorption on permeate production, where both of them take place, e.g. in MBR systems. Furthermore, research is needed to fully understand whether the occurrences of the aforementioned mechanisms are simultaneous or asynchronous; particularly where the retention of the humic-like substances is the main culprit of membrane fouling. Discerning the dilemma is a stepping stone to predicting retention of the humic-like substances, which may be useful for modelling the permeate flux of full-scale EBPR-MBR plants. In the current study, the separate roles of adsorption and gel formation in fouling have been figured out. Furthermore, based on adsorption and gel formation, a novel retention model has been put forward.

THEORY

A mathematical model has been developed for retention of the humic-like substances. In this model, adsorption and steric retention have been considered to be the responsible mechanisms. The following assumptions were considered:

(a) Steric retention occurs at the membrane surface, and it is constant during filtration.
(b) Steric retained substances form a gel layer, which remains adhered to the membrane surface.
(c) A mono-layer adsorption takes place on the inner wall of the pore channels.
(d) Inner pore volume behaves as a continuous stirred tank reactor; therefore, the liquid phase concentration inside the pore channel, equal to permeate concentration, is the same throughout the pore space.
(e) The equilibrium adsorbed mass is independent of the changes that occur in the liquid phase concentration inside the pore channel during filtration.

Assumptions (a)–(c) are based on a previous investigation (Poorasgari et al. 2014a) showing that a gel layer was formed on, and some of the molecules adsorbed to, the membrane surface during filtration of SMP suspension. Further, it was also demonstrated that rejection does not increase during formation and growth of the gel layer. Additionally, a certain level of tortuosity exists in porous membranes, which can bring about an intense agitation when the flow-through is high and pore volume is low; thus, assumption (d) is satisfied.

The overall and steric retentions are calculated by Equations (1) and (2), respectively:

\[ R = 1 - \frac{C_p}{C_f} \]  
\[ R^* = 1 - \frac{C^*}{C_f} \]  

where \( R \) is the overall retention, \( R^* \) is the steric retention, \( C_f \), \( C^* \) and \( C_p \) are feed concentration, the concentration of the solution that just arrived into the pore channels, and the permeate concentration, respectively. Adsorption kinetics was considered to be pseudo-first order, and Equation (3) (Poorasgari et al. 2014b) was used to simulate the adsorption process:

\[ n = n_{eq}(1 - e^{-Kt}) \]
where \( K \) is the adsorption rate constant, \( n_{eq} \) is the equilibrium adsorbed mass, \( n \) is the adsorbed mass at any given time and \( t \) is the filtration time.

**Mass balance**

A simple mass balance has been set up for the concentration of humic-like substances in the membrane pores, as defined in Equation (4):

\[
\frac{\partial (V_p \cdot C_p)}{\partial t} = Q \cdot C^* - Q \cdot C_p - \frac{dn}{dt} \tag{4}
\]

where \( V_p \) is the inner pore volume and \( Q \) is the permeate flow. Time derivative of \( n \) from Equation (3) is inserted into Equation (4) and the left-hand side of Equation (4) is expanded to obtain Equation (5) after some rearrangements:

\[
\frac{\partial C_p}{\partial t} = \frac{Q}{V_p} \cdot (C^* - C_p) - \frac{K}{V_p} \cdot \left( n_{eq} \cdot e^{-Kt} \right) - \left( C_p \cdot \frac{\partial V_p}{\partial t} \right) \tag{5}
\]

The ratio \( \partial V_p/\partial t \cdot V_p \) is the change of the pore volume over the pore volume and filtration time. The humic-like substances adsorbed to the inner walls of the pore channels could not have hydrodynamic diameter greater than 8.98 nm (Poorasgari et al. 2014A), meaning at least 22 times smaller than the nominal pore diameter of the membrane, 200 nm (Alfalaval A/S Copenhagen, Denmark). Having considered the assumption of monolayer adsorption, the maximum change of pore volume over filtration time has been calculated as 0.096 at the time of adsorption equilibrium. When this value is divided by \( \partial t \) of only 10 s, the final term on the right-hand side of Equation (5) equals 0.0096\( C_p \) at its maximum. It is emphasized that most of the humic-like substances of the SMP suspension have hydrodynamic diameters smaller than the predicted value. Not all the adsorbed molecules would have the largest possible diameter, and the adsorption equilibrium is expected to be reached at a much longer time than 10 s; accordingly, the actual \( \partial V_p/\partial t \cdot V_p \) would be considerably smaller than 0.0096\( C_p \) even at its topmost. As the aforementioned fraction is negligible compared with the other two terms on the right-hand side, Equation (5) can be simplified to Equation (6):

\[
\frac{dC_p}{dt} = \frac{Q}{V_p} \cdot (C^* - C_p) - \frac{K}{V_p} \cdot (n_{eq} \cdot e^{-Kt}) \tag{6}
\]

The permeate flow can be calculated by multiplying the permeate flux (\( J \)) by the membrane surface area (\( A \)), i.e. \( Q = J \cdot A \). The pore volume can be calculated from the porosity (\( \varepsilon \)) and the thickness of the membrane (\( Z \)), i.e. \( V_p = \varepsilon \cdot A \cdot Z \). By inserting them into Equation (6), Equation (7) is obtained:

\[
\frac{dC_p}{dt} = \frac{J}{\varepsilon \cdot Z} \cdot (C^* - C_p) - \frac{K}{A \cdot \varepsilon \cdot Z} \left( n_{eq} \cdot e^{-Kt} \right) \tag{7}
\]

**Permeate flux**

The permeate flux is modelled by a modified version of the Darcy’s law:

\[
J = \frac{\Delta P}{\mu \cdot (R_{init} + R_g)} \tag{8}
\]

where \( \mu \) is the dynamic viscosity, \( \Delta P \) the transmembrane pressure, and \( R_g \) and \( R_{init} \) are the gel resistance and the resistance observed at the beginning of filtration of the SMP suspension, respectively. According to cake filtration theory, the particles (i.e. humic-like substances) deposit on the surface of the membrane during filtration and form a permeable fouling layer, which is the gel layer in the current study. The resistance of a gel layer increases linearly with the amount of deposited materials (Willis & Tosun 1980; Shirato et al. 1991). Equation (9) describes the gel resistance as a linear function of area specific mass of deposited materials (\( \omega \)):

\[
R_g = \alpha \cdot \omega \tag{9}
\]

where \( \alpha \) is the specific resistance of the gel layer. \( \omega \) is calculated by Equation (10):

\[
\omega = \frac{R \cdot C_f \cdot V_p}{A} \tag{10}
\]

where \( V_p \) is the permeate volume. By substitution of Equations (8)–(10) and bearing in mind \( J = dV_p/(A \cdot dt) \), the Darcy equation can be rewritten as Equation (11):

\[
\frac{dV_p}{Adt} = \frac{\Delta P}{\mu \cdot (R_{init} + \alpha \cdot R^* \cdot C_f \cdot V_p)} \tag{11}
\]

When Equation (11) is integrated, \( V_p \) is obtained as a second order function of \( t \), which can be simplified to Equation (12):

\[
V_p = A \cdot \left( -R_{init} + \frac{R^2_{init} + 2 \alpha \cdot R^* \cdot C_f \cdot \Delta P \cdot t}{\mu} \right) \div \alpha \cdot R^* \cdot C_f \tag{12}
\]
Either substitution of Equation (12) into Equation (8) by considering Equations (9) and (10) or time derivative of permeate volume (i.e. $dV_p/(A·dt)$) gives Equation (13); therefore, the permeate flux can be calculated as a function of time by an analytical model:

$$J = \frac{\Delta P}{\mu} \cdot \sqrt{R_{init}^2 + \frac{2\alpha \cdot R \cdot C_f \cdot \Delta P \cdot t}{\mu}} \quad \text{(13)}$$

Concentration in permeate

Substitution of Equation (13) into Equation (7) gives:

$$\frac{dC_p}{dt} = \frac{\Delta P}{\mu \cdot e \cdot Z} \cdot \sqrt{R_{init}^2 + \frac{2\alpha \cdot R \cdot C_f \cdot \Delta P \cdot t}{\mu}} \cdot (C_f - C_p)$$

$$- \frac{K}{A \cdot e \cdot Z} \cdot (n_{eq} \cdot e^{-k \cdot t}) \quad \text{(14)}$$

A numerical method was applied as follows: filtration time was considered as a set of $N$ non-overlapping steps in which the permeate concentration was simulated numerically using the fourth and fifth order Runge-Kutta method in MATLAB® (R2012b) environment. The numerical simulation accuracy was set at a reasonable value (i.e. $<10^{-5}$). Having $C_p$ calculated, the overall retention is computed by Equation (1).

**MATERIALS AND METHODS**

**Extraction and characterization of SMP suspension**

MBR sludge was sampled from the MBR unit of a pilot EBPR-MBR plant fed with municipal wastewater. SMP suspension was obtained by means of centrifugation of the MBR sludge and microfiltration. Similar procedures have been used to extract the SMP suspension, reportedly (Rosenberger et al. 2005). Concentration of carbohydrate was measured by Anthrone method, and concentration of protein and humic-like substances was measured by modified Lowry method (Frolund et al. 1995). Concentration of the humic-like substances was 25 ± 1 mg L$^{-1}$, and no protein was detected. Concentration of carbohydrate was 2 mg/L in both feed and permeate. Moreover, rheometric analysis showed that the SMP suspension was a Newtonian fluid with the same viscosity as water, $10^{-3}$ Nm$^{-2}$s$^{-1}$, at room temperature (CVO 120, Bohlin Instruments, UK).

**Membrane properties and preparation**

An anisotropic flat sheet microfiltration (MF) membrane was used. The active surface of the membrane was mainly made of polyvinylidene difluoride. The membrane thickness was 250 μm and its average porosity was 40%. The membrane sheets were immersed and shaken in ethanol and subsequently in Milli-Q water for 3–4 h to remove the protective glycerol coating. After that, 47-mm-diameter discs were cut from the prepared membrane sheets. The membrane preparation was done based on the information and the instructions received from the membrane manufacturer.

**Filtration experiments**

The prepared membrane discs were used for filtration experiments. Filtration experiments were done using an unstirred dead-end filtration setup shown in the supplementary material (Supplementary Material Figure S1, available with the online version of this paper). The applied pressure was supplied from a compressed air source. Permeate flow was measured by a gravimetric method, and permeate flux was calculated by dividing the measured permeate flow by the surface area of the membrane discs. Constant permeability of the membrane discs (3,200 L·m$^{-2}$·bar·h$^{-1}$) was checked by filtration of Milli-Q water at 25 kPa at room temperature. Then, the SMP suspension was filtered through the membrane discs at the same temperature and applied pressure as those for the constant permeability check. Moreover, the gel layer was visualised (Supplementary Material Figure S2, available online) by a scanning electron microscope (model Zeiss EVO 60, Carl Zeiss, Oberkochen, Germany). The clean and fouled membrane samples were dried and then coated with gold before imaging.

For permeate concentration measurement, the permeate was collected in separate fresh and clean vials at nine volume steps (Supplementary Material Table S1, available online). The collected volume of permeate in each vial was increased during filtration of the SMP suspension. The mentioned collection method was carried out because an earlier study (Poorasgari et al. 2014b) had shown that the change of the permeate concentration was sharp at the beginning of the filtration but decreased over the cumulative permeate volume, i.e. filtration time. Filtration of the SMP suspension was done four times, and the concentration of the humic-like substances was measured in the permeate. Using the measured feed concentration (25 mg L$^{-1}$) and Equation (1), experimental $R$ was calculated.

In order to better analyse retention of the humic-like substances, size-exclusion chromatography (SEC) was done on
both feed and permeate collected during filtration of the SMP suspension. The size exclusion column was Agilent SEC, 3 μm, 300 Å, 7.8 × 300 mm. Based on the recommendation of the column manufacturer, phosphate buffer solution of pH 8.5 was used as eluent and the elution time was 20 min. Detection was performed using a UV detector (DIONEX, Sunnyvale, CA, USA) measuring at 254 nm.

RESULTS AND DISCUSSION

Adsorption and steric retention

Permeate concentration of the humic-like substances, \(C_p\), was measured to study adsorption kinetics and steric retention. The permeate concentration was 14.8 mg L\(^{-1}\) at the beginning of filtration, which is 60% of the feed concentration (Figure 1(a)). The permeate concentration increased over filtration time and levelled off at almost 1,000 s. In other words, retention decreased over time of filtration and plateaued after approximately 17 min. The adsorption sites of the membrane were free at the beginning of filtration. The initial retention was due to both adsorption and steric retention (i.e. the two processes began at the same time). As filtration continued, the adsorption sites became saturated and retention happened only due to steric retention.

The steric retention has been shown to be 19 per cent. Permeate concentration altered over permeate volume with the same pattern as it did over filtration time (Figure 1(a)). The area representing retention due to adsorption has been named the non-steady state region (NSSR) and the area representing steric retention has been named the steady state region (SSR). The mass of the adsorbed humic-like substances was calculated by numerical integration of the NSSR. The experimental adsorbed mass was plotted versus the filtration time. The coefficient of determination \((r^2)\), \(n_{eq}\) and \(K\) have been calculated as 0.9821, 0.1662 mg and 0.06144 s\(^{-1}\), respectively. It is evident that Equation (3) fitted the experimental data well (Figure 1(b)), which supports the assumption of monolayer adsorption. The explanation is that there were enough molecules to form and adsorb onto several superimposed layers. That is, SMP suspension with the same initial concentration was passing through the membrane during the entire filtration time. Hence, if multi-layer formation was to take place, the adsorbed layer would grow over time and, due to the extremely low pore diameter, equilibrium might never be reached. Moreover, as foreseen, adsorption equilibrium was reached after a much longer time than the exemplified 10 s span. Hence, the maximum \(\partial V_p/\partial t\cdot V_p\) was extremely small and the simplification of Equation (5) to Equation (6) was quite realistic.

SEC analysis (Supplementary Material Figure S3, available with the online version of this paper) showed that there was a certain fraction removed from the beginning of the filtration; that is, the peak that appeared at 6 min retention time. The component(s) of that peak are the largest among the others detected on the chromatogram. Their permanent retention by the membrane is another indication of steric retention. Thus, the largest component(s) participate in gel formation strongly.

Calculation of specific resistance

\( \omega \) was calculated by integrating the area of the SSR (Figure 1(a)). According to Equation (9), \( R_g \) is linearly correlated with \( \omega \) and

![Figure 1](https://iwaponline.com/wst/article-pdf/73/12/3033/363306/wst073123033.pdf)
the slope of the linear correlation is $\alpha$. The values of $\omega$ were plotted versus their corresponding calculated gel resistance $R_g$ (Figure 2), where a good linearity is observed and $r^2$ is 0.9935. In this study, the specific resistance of the gel layer was calculated to be $8.5 \times 10^{14} \text{ m kg}^{-1}$. The linearity between $\omega$ and $R_g$ indicates that the gel layer was responsible for the decline of permeate flux, and the flux decline can be described by cake filtration theory, in line with the study of Shirato et al. (1991). The specific resistance determined in the current study is lower than that determined by Jiang et al. (2010). The discrepancy may be explained by the differences in the SMP composition.

The experimental filtration data were fitted to pore blocking and cake filtration models (Hermia 1982). The pore blocking models include complete, standard and intermediate. Based on the complete pore blocking, every particle in the suspension is able to block a pore and the deposited particles do not sit on top of each other. The standard pore blockage considers that the particles are able to penetrate inside the pore, get trapped inside the pore channel and reduce the voidage. The intermediate pore blocking model assumes every particle has a probability of partial blockage of the pore mouth and the deposited particles can build up on each other. The model fittings (Supplementary Material Figure S4, available online) showed the best fit for cake filtration model except for the first 30 mL of permeate. This may have happened due to the interference by adsorption and concentration polarization: phenomena which were not included in the conventional cake filtration model. The lack of an acceptable fit for the standard pore blocking model is important because it shows that the reduction in the internal pore space by the adsorption of the humic-like substances was not significant. This is another indication of the negligible change of pore volume, further supporting the low probability of multi-layer adsorption.

**Simulation of permeate flux and retention**

By using $R_{init}$, $R^*$ and $\alpha$ obtained from the experimental results, Equation (13) was used to predict permeate flux over filtration time. As can be seen in Figure 3(a), there is a good agreement between the experimental and the analytically modelled permeate flux, in line with the good fit between the experimental data and the linearized cake filtration equation. The model simulation to some extent overestimates the flux until 500 s and after 1,500 s. The initial over-prediction could be due to what has been already explained for the conventional model fitting. The overestimation after 1,500 s may be due to compression of the fouling layer. The mentioned mechanisms have not been
included in the model; otherwise, a few more governing equations would have had to be considered and many more simplifications, including omission of some more terms, would have been necessitated.

Equation (14) was used to simulate the concentration of the humic-like substances in the permeate flow. The model constants $C^\circ$, $n_{eq}$ and $K$ were obtained from the experimental results of the current investigation. Such a self-dependent approach was taken due to the fact that the mentioned model parameters are highly associated with the intrinsic features of the membrane employed in the study. Thus, none of the parameters was adjusted to show the model agreement as factually as possible. The computed $C_p$ was used to calculate the modelled overall retention, which, together with the experimental overall retention, has been shown in Figure 3(b).

The general trend of the modelled overall retention is determined by the permeate flow. At the beginning of the filtration, the permeate flux is very high, which results in quick transport of the humic-like substances through the pore channels. In other words, the retention time of the humic-like substances inside the pore channels is quite low at the beginning of the filtration. At such a low retention time, although the adsorption sites are free, not many of the humic-like substances will have enough contact time to be adsorbed. The permeate flux decreases quickly after the start of the filtration, leading to longer retention time while most of the adsorption sites are still unoccupied. As a result, the adsorption rate and the modelled overall retention rise during the first minute, which creates a small peak. The adsorption sites then become occupied rapidly, resulting in a significant decline of the modelled overall retention from 60 to 1,000 s, when all the adsorption sites get saturated and the overall retention occurs only due to the steric retention and remains constant.

The experimental and modelled overall retentions are in agreement after the first minute of filtration. The lack of agreement between the experimental and the modelled retention in the first 60 s of filtration may be due to the low number of permeate samples and relatively large sample volumes. The permeate concentration in the first few seconds of filtration would be extremely low, and this could bring about a much sharper kinetic curve (i.e. larger $K$); thereby, a much better fit would be obtained for the first minute. The big samples presumably hid the real adsorptive removal efficiency. It is explained by assuming the permeate flow as separate volumes; when mixed as one sample, solution of higher concentration permeating through the membrane at a later time can mask low concentration of the initial tiny volumes. The speculation, nonetheless, does not shed light on the maximum point estimated by the model at 60 s, which might have happened at an earlier time during the filtration. Hence, some further investigation is required to elucidate the underlying complexities.

CONCLUSIONS

SMP suspension was extracted from the sludge of an EPBR-MBR plant, which predominantly consisted of humic-like substances. Retention of the humic-like substances was investigated by the filtration of the SMP suspension through an MF membrane. Both steric retention and adsorption occurred during the filtration. The gel layer formation caused by the steric retention was the main fouling mechanism. The effect of gel formation on permeate flux was well explained by cake filtration theory, and adsorption trend was in a good agreement with the pseudo-first order adsorption kinetics. By considering the adsorption and the steric retention, a new model has been proposed for the overall retention of the humic-like substances during the filtration time. The modelled and experimental overall retention were in partial agreement. The procedures and results of the current study are useful for management of gel layer fouling in EBPR-MBR systems.

ACKNOWLEDGEMENTS

This study was part of the EcoDesign MBR project funded by the Danish Council for Strategic Research. The authors would like to acknowledge Katja König for SEM imaging and her contribution to preparation of the manuscript.

REFERENCES


First received 17 December 2015; accepted in revised form 30 March 2016. Available online 6 April 2016


