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Sludge fractionation as a method to study and predict fouling in MBR systems

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ABSTRACT

Membrane bioreactors (MBRs) are continuously being improved, but membrane fouling still causes severe problems, so effective measures to reduce fouling are imperative to minimize operational cost. Potential foulants can be found in MBR sludge flocs, but it is not known which fraction(s) that mainly influence fouling and how sludge flocs affect fouling. A standard procedure was developed to separate sludge into floc/colloid, colloid/solute, and solute fractions. The fouling properties of MBR sludge and sludge fractions were evaluated in a lab-scale MBR equipped with aerated flat-sheet membranes. The fastest flux decline took place in the solute fraction due to formation of irreversible fouling; this fraction contained foulants smaller than the membrane pore diameter (0.2 µm), causing pore blocking and/or adsorption. Flux declined more slowly in the colloid/solute fraction, where fouling was more reversible. The external fouling layer on the membrane was shown to protect it from pore blocking/adsorption. Flux decline was slowest in unfractionated MBR activated sludge. Thus, presence of sludge flocs reduced the concentration of foulant and also directly reduced the formation of an external fouling layer by shear. This may be due to surface erosion or more turbulence close to the membrane surface by sludge flocs which thereby partly removed the external fouling layer. To reduce membrane fouling, concentrations of solutes (e.g., macromolecular extracellular substances) and colloids (e.g., single cells) should be kept low and concentration of sludge flocs high.

1. Introduction

Membrane bioreactors (MBRs) offer advantages such as higher effluent quality and more compact plant design compared with conventional activated sludge (CAS) plants. Nevertheless, organic and inorganic compounds foul the membranes, thereby reducing their capacity, increasing energy consumption, increasing the need for chemical cleaning, and shortening membrane lifetime. Various methods have been used to study membrane fouling, such as: (1) filtration of sludge from different wastewater treatment plants, after which sludge characteristics are correlated with membrane performance [1,2]; (2) direct analyses of materials deposited on the membrane either after or in real time during filtration [3]; and (3) fractionation of activated sludge and analyzing the fouling potential of the different fractions [4]. All these methods yield valuable information on the fouling risk and the properties of the compounds that cause problems. For example, it has been hypothesized that extracellular exopolymeric substances (EPS) are important foulants and that their concentrations should be limited to prevent severe membrane fouling [5–11]. Other studies indicate that mixed liquid suspended solid (MLSS) levels [12], floc size [13], number of filamentous bacteria [14], and cation concentration [5,15] are important for the performance of MBRs. In the case of MLSS, there is some inconsistency in the literature as to whether or not higher MLSS levels increase fouling, possibly because different fractions contribute unequally, or because of the complexity of various interacting parameters [12,14,16]. Overall, it is difficult to identify the foulants, as activated sludge is a complex mixture of multiple substances, including sludge flocs, single cells, filaments, EPS, and salts, all interacting within the MBR reactor and at the membrane surface.

Sludge flocs have a positive effect on membrane performance as formation of flocs indirectly improves the process because foulants such as colloidal particles and EPS are bound within or on the flocs [17,18]. However, our observations indicate that the flocs also directly affect membrane fouling, which may explain some of the contradictory results

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in the literature. Data indicates that large particles can improve the permeate flux, for example, via erosion by activated carbon, which has been suggested as a method for fouling reduction [19]. Whether sludge flocs reduce membrane fouling or whether the flocs are disrupted near the membrane surface has not been studied. In order to investigate the influence of sludge flocs on membrane fouling, sludge fractionation may be a valuable method as membrane performance can be tested with and without flocs, but with the same concentration of colloids and solutes.

Fractionation of activated sludge can be used to study the interaction between different sludge components during membrane operation [4]. Sludge components can be fractionated based on their hydrodynamic size, which is relevant because the fouling mechanism during cross-flow filtration largely depends on the particle sizes of the foulants. Particles smaller than the membrane pores pass through the membrane or adsorb to the membrane surface or within the pores [20]. Colloidal particles often end up on the membrane surface, resulting in the formation of an external fouling layer [21]. Large particles (above approx. 10 µm) are often removed from the membrane due to lift forces or particle erosion [22].

Several fractionation studies have been reported in literature. However, the methodology for separating and then filtering the sludge fractions is not standardized but varies from study to study, complicating the comparison of experimental data. Activated sludge is usually separated into different fractions, the individual resistance characteristics of which are measured or calculated, and used to evaluate the fouling risk of different compounds [4,13,23–26]. Often three fractions are considered: suspended solids, colloids, and solutes. In most studies, activated sludge is centrifuged to obtain a supernatant containing colloids and solutes [24,25,27–31], but sedimentation has also been used [4,26]. To isolate the solute, the supernatant is filtered [4,24,27,31] or flocculated and sedimented/centrifuged [25,26,30].

The fouling properties have been evaluated by filtering the different sludge fractions and calculating the resistance from the measured flux and pressure:

$$R = \frac{\Delta P}{J_V \mu} \tag{1}$$

where ΔP is the pressure difference across the membrane/filter medium, J_V is the volumetric flux, and μ is the viscosity of the filtrate/permeate.

The resistance is often divided into a membrane resistance (R_m) and a fouling resistance (R_f), where the membrane resistance is obtained from Eq. (1) by filtering pure water.

$$R = R_m + R_f \tag{2}$$

The fouling resistance comprises various types of fouling, such as pore blocking, adsorption, and gel-layer formation. If an external fouling layer is formed, the resistance usually increases linearly with the amount of material on the membrane [20] and a specific cake resistance can be defined:

$$\alpha = \frac{R_f}{\omega} \tag{3}$$

where ω is the dry mass of the fouling layer per unit of filter medium area.

By filtering activated sludge, supernatant, and solute suspensions, the individual resistances of suspended solids, colloids, and solutes have been determined by assuming that the individual resistances are additive [4], but the use of the resistance-in-series method has been criticized because resistances are usually not additive, as demonstrated in several studies [32–35]. However, sludge fractionation is still a valuable method for studying membrane fouling. The filtration of different sludge fractions can be used to study how different groups of sludge components foul the membrane, and the fractions can be mixed to study how different sludge components interact. This gives valuable information that is difficult to obtain by other methods, making the results more relevant to full-scale studies.

The fouling properties of sludge fractions can be evaluated by means of filtration using either dead-end filtration [27,31] or cross-flow filtration [4,29,30]. Regarding the choice of filtration method, it is important to use a system and settings comparable to those of the relevant full-scale MBR [4]. Previous studies have demonstrated that it is impossible to use data obtained from dead-end experiments in directly analyzing fouling phenomena in cross-flow filtration [36]. In cross-flow filtration, the particle size distribution in the fouling layer on the membrane is usually lower than in the bulk suspension, unlike in dead-end filtration [37]. Furthermore, particle deposition depends on the shear rate at the membrane surface, and the specific cake resistance can be up to three times higher in cross-flow than dead-end filtration [38].

The aims of this study were to: (1) develop a standard method for sludge fractionation, (2) study the fouling mechanisms during filtration of different sludge fractions, and (3) by doing this, investigate how the presence of sludge flocs affects membrane fouling. Activated sludge was fractionated into three fractions: (1) a floc and colloid fraction, (2) a colloid and solute fraction, and (3) a solute fraction. Untreated activated sludge and the three sludge fractions were filtered using both a dead-end system operating at low pressure and a mini aerated lab-scale MBR system. The mini MBR system was equipped with aerated flat-sheet membranes that mimic a commercial full-scale MBR system from Alfa Laval (Søborg, Denmark). The full-scale MBR system operates at low and constant pressure to prevent compression of the fouling layer and to prevent high initial fouling. Dead-end filtrations were used to build up fouling layers of known thickness, to enable fouling layer compression to be studied. The data were compared with data from the aerated membrane system to examine the difference between dead-end and aerated membrane filtrations.

2. Theory

Fouling is defined as an accumulation of materials on or inside the membrane structure that reduces the capacity of the membranes [6]. Membrane fouling can either be due to passive transport of material from the feed suspension to the membrane or due to microbial growth on the surface of the membrane. This work focuses on fouling due to passive transport of molecules or particles to the membrane. Due to the liquid flux through the membrane, convective transport is the most important transport mechanism conveying material to the membrane surface and can be calculated as the product of concentration and flux. Membrane operations are usually operated in cross-flow mode to ensure that part of the material is removed from the membrane surface. Some particles are easily removed from the membrane surface by means of back diffusion, lift forces, and erosion, whereas other particles are difficult to remove even at high cross-flow rates [22].

Due to the convective transport of materials to the membrane surface, the particle concentration increases from the bulk to the surface of the membrane. Thus, diffusion away from the membrane surface dominated by Brownian diffusion (D_B) for small molecules and by shear-induced diffusion (D_S) for large particles. The diffusion coefficients can be calculated from Eqs. (4) and (5):

$$D_B = \frac{k_B T}{3\pi\mu d_p} \tag{4}$$

where k_B is the Boltzmann constant, T is temperature, μ is viscosity, and d_p is the hydrodynamic diameter of the particles; and

$$D_S = 0.5\left(\phi \frac{d_p}{2}\right)^2 \frac{\tau}{\mu} \tag{5}$$

where ϕ is the solid volume fraction and τ is the shear stress.

Back diffusion is highest for small molecules (if they do not penetrate the membrane) while shear-induced diffusion is highest for large