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Membrane Bioreactors: Past, Present and Future?

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Abstract

A brief description of membrane bioreactor (MBR) historical evolution has been presented with emphasis on continual decline of treatment costs and energy requirements. Although MBR can operate at biomass (MLSS) concentrations 5 to 10 times higher than activated sludge these concentrations are limited in practice by increasing biomass suspension viscosity that in turn increases "reversible" membrane fouling and decreases oxygen transfer rates. "Irreversible" fouling is a major operational challenge since it depends on subtle interactions of membranes with various fractions of soluble microbial products resulting from microbial metabolism.

Keywords: membrane bioreactor; MBR; activated sludge; fouling; energy requirements; soluble microbial products;

1. Introduction

Membrane Bioreactors (MBR) are gaining popularity as an effective process for wastewater treatment and water reclamation. A recent review [*Kraume and Drews*, 2010] shows an exponential growth of number of plants and their installed capacity in the past decade with an estimate of market growth rate above 10% per year. At the same time, Kraume and Drews cited a significant decline in annualized costs from about $0.90/m^3 ten years ago to $0.08/m^3 in 2005 primarily due to lower membrane costs but also due to improved energy efficiency to below 0.4 kWh/m^3 [*Cornel and Krause*, 2006]. While many MBR plants have small capacity (and indeed they may be a technology of choice for decentralized treatment) the upper limit of installed MBR capacity expands dramatically. Some examples of large MBR plants include Kaarst, Germany (48,000 m^3/d in 2005) [*Judd and Judd*, 2006], King County, WA, USA (136,000 m^3/d in 2011) [*King County*] and tertiary treatment at Qinghe, Beijing (400,000 m^3/d in 2011) [*water-Technology.net*]. Despite these advances, MBR is still a new technology with limited design and operational experience compared with over a century of activated sludge. This paper will present several important features of MBR and their implications from a personal view of a researcher involved in this topic for a considerable time. It is not a comprehensive review and refers only to select publications.

2. Membrane Bioreactor and Activated Sludge – Process Comparison

MBR originated as a marriage of membrane technology and activated sludge where solids separation was accomplished by filtration rather than by gravity settling. The early versions from 1960s employed a separate membrane filtration unit operated in cross-flow mode and fed from

an aeration tank. This configuration, which is still in use for some applications, allowed for optimization of each process (biological treatment and solids separation) but required a lot of energy, primarily to maintain sufficient cross-flow velocity to control membrane fouling. Since mid-1980s membrane units became submerged directly in the aeration tank resulting is substantial decrease of energy requirements (up to 6 kWh/m^3 for cross-flow versus 1 kWh/m^3 for early versions of immersed membranes) [*Buer and Cumin*, 2010]. These two types of process arrangements are shown in Figs. 1 (a) and (b) together with further evolution of submerged MBR (SMBR) (Figs. 1 (c) and (d)).
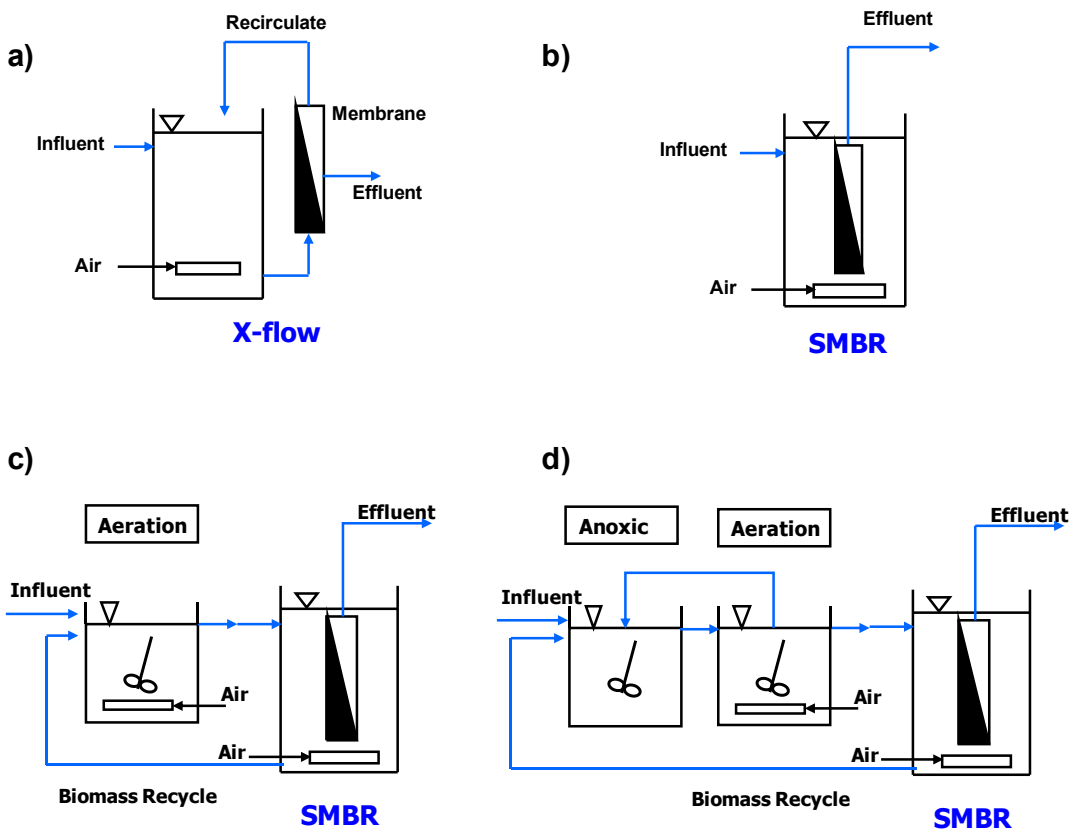

Figure 1 Various MBR configurations

Although MBR partially evolved from activated sludge, they differ significantly from that biological process. Obviously, solids separation is the most visible difference that also impact energy requirements. In conventional gravitational settling, energy loss is due to hydraulic headloss across the settling tank which can be minimized to less than 15 cm which corresponds to pressure drop of 1.5 kPa. In contrast, typical transmembrane pressure (TMP) across the MBR is 40-60 kPa. However, major energy requirement is to provide oxygen for biological processes and to maintain acceptable flux through the membrane and to minimize fouling. In cross-flow units, the energy for fouling control is imparted by high flow velocities while in submerged membranes air is used to scour the membrane. Even in the most advanced SMBR, more than 0.1

kWh/m^3 is needed [*Buer and Cumin*, 2010], orders of magnitude more than for gravitational settling.

Aeration is obviously needed for biological requirements similarly to activated sludge. Oxygen demand in MBR (expressed as kg O_2/kg VS⋅hr) is comparable to that in activated sludge operated at the same conditions. However, oxygen transfer efficiency (hence energy required) is very different. Most of the MBR units operate at biomass (mixed liquor) concentrations (MLSS) in the range of 8 to 12 g/L and occasionally even higher [*van Nieuwenhuijzen et al.*, 2008; *Visvanathan et al.*, 2000; *Yang et al.*, 2006] reaching 20 to 35 g/L since membrane filtration is capable, in principle, to achieve effective solids-liquid separation. The consequence of such high MLSS is that the biomass (sludge) no longer behaves like a Newtonian fluid. Instead, it exhibits much higher viscosity that is also a function of solids, concentration, sludge characteristics, and applied shear stress [*Trussell et al.*, 2007]. Fig. 2 shows a dramatic increase of apparent sludge viscosity as a function of MLSS and MCRT. For comparison, viscosity of pure water is about 1 mPa⋅s, two orders of magnitude lower.
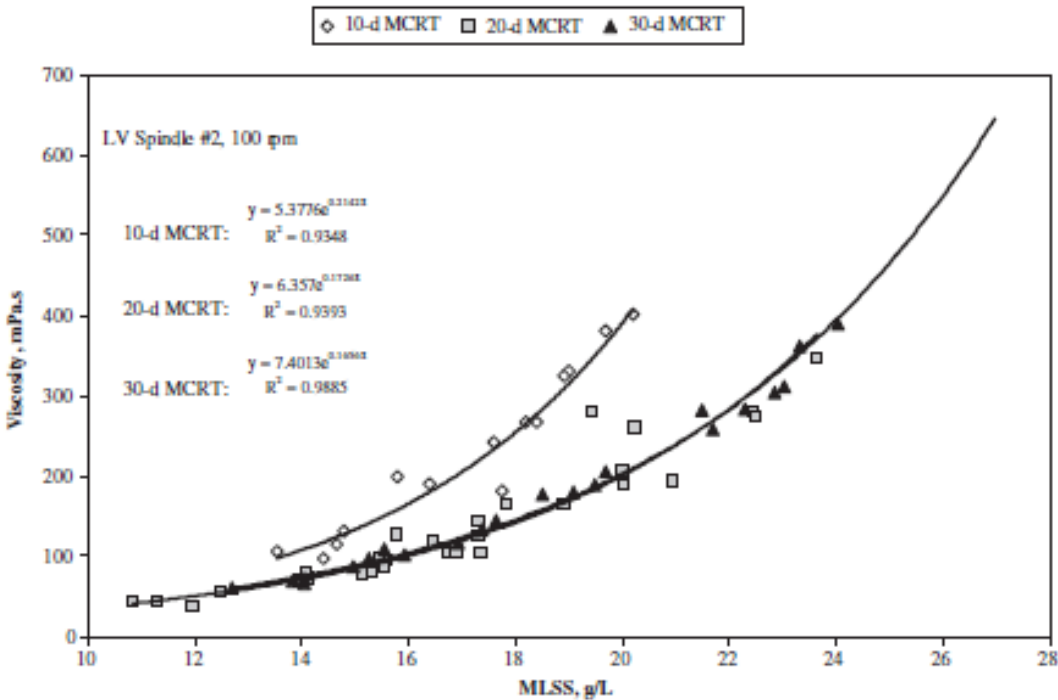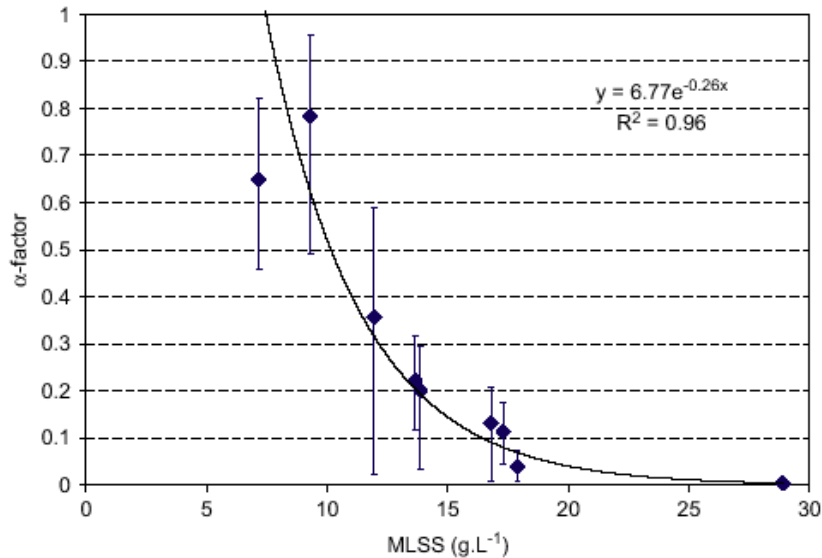

Figure 2 Apparent Viscosity of Biomass Suspension (Mixed Liquor) in SMBR

As a result, mass transfer coefficient of oxygen from air to water decreased significantly requiring much more energy to achieve necessary oxygen transfer rates. This decrease can be expressed as α, a ratio of actual oxygen transfer rate under process conditions to the rate in clean water at the same energy input and oxygen driving force. Fig. 3 [*Germain et al.*, 2007] shows how rapidly α declines with increasing MLSS. For this reason, after initial euphoric attempts to operate SMBR at MLSS concentration exceeding 20 mg/L (to reduce process volume and footprint), current practice is to scale down MLSS to about 10 g/L. Practical oxygen transfer limits due to low α were combined with realization that the type of aeration for oxygen supply is

not suitable for membrane scouring and fouling control. Oxygen transfer efficiency is much improved with fine bubble aeration that increases gas-liquid interfacial surface area and bubble retention time in the tank. In contrast, membrane scouring is best achieved with coarse bubbles imposing high momentum on fluid, solids, and membrane surface. This dichotomy led to separation of single aeration tank (Fig. 1 b) into two or more tanks. One of them is optimized for membrane filtration with coarse aeration (or perhaps other means of fouling control) and the

The plot shows α-factor on the y-axis (0 to 1) versus MLSS (g.L^{-1}) on the x-axis (0 to 30), with fitted curve $y = 6.77e^{-0.26x}$ and $R^2 = 0.96$.

Figure 3 Alpha Factor Decrease for High MLSS

others are devoted to biological process control. For biological nutrient removal (BNR) a sequence of anaerobic, anoxic and aerobic tanks can be used, similar to BNR activated sludge process. As a result, even in a simple aerobic SMBR (like that in Fig. 1 c) there is a need to return biomass (mixed liquor) from the membrane filtration tank to the aeration tank. Since the overall MLSS is already high compared with activated sludge this return flow is also substantially higher compared with typical return activated sludge flows (RAS). In SMBR, the ratio of the recirculation flow to the feed flow is often maintained at 3 to 5 to maintain solids concentration in the filtration tank below a critical value to maintain adequate membrane flux.

3. Membrane Fouling – A Big Challenge

MBR also differ in one important aspect from activated sludge. MBR operation depends critically on the ability of the membrane unit to pass all flow incoming to the plant. If membrane permeability is impaired the plant cannot process all flow with potentially catastrophic results even though effluent quality remains consistently high. This contrasts with typical operation of activated sludge where the plant hydraulic capacity is rarely exceed but effluent quality is much more variable. Hence, membrane fouling (and associated reduction of flux or increase of TMP) is an operational challenge. This issue may become very important at larger plants being commissioned where the margin of safety is smaller due to membrane costs. If membrane fouling occurs at the same time when the plant experiences increased flow (e.g., due to wet weather) serious problems may arise. As an example, Fig. 4 shows drastic reduction of available

specific membrane flux that occurred during a wet weather period in a plant fed by combined sewers. During dry weather the MBR plant was operated sustainably for months at the flux of 22 L/m^{2}h (13 gal/ft^{2}d), after a period of rains this values of flux was impossible to achieve. When such flux was imposed, TMP would increase above its limiting value in several seconds and sustainable operation was possible only at much smaller flux. The exact reason for this dramatic loss of membrane permeability is not completely clear but the episode was associated with massive deflocculation of mixed liquor and large increase in the fraction of colloidal particles, primarily unflocculated microbial cells.
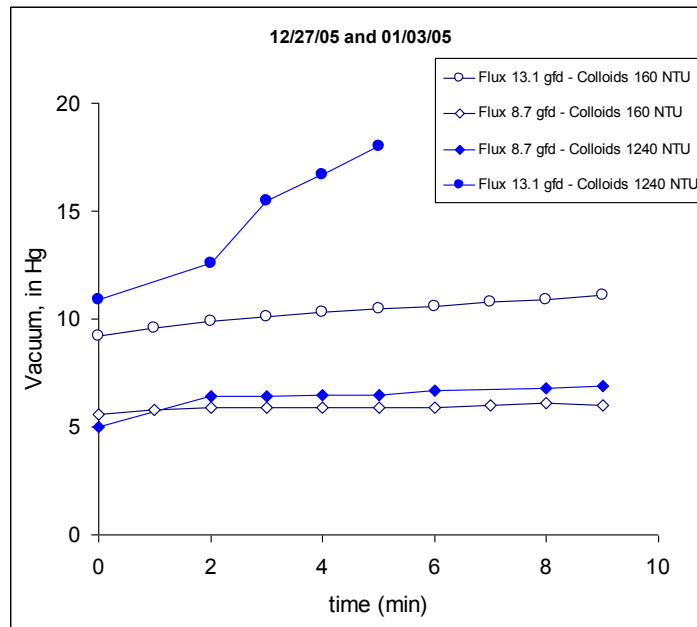

Figure 4 MBR Failure during Wet Weather

This incident shows that membrane fouling remains (and is likely to remain) a big operational challenge. Many studies were devoted to causes and mechanisms of fouling and to its control. It has been recognized that one cause of fouling is solids concentration polarization and cake formation when forward solids flux exceeds backtransfer away from the membrane. This type of fouling is "reversible" in the sense that a reduction of the forward flux (through lowering of the membrane flux or solids concentration) or an increase of backtransfer intensity restores membrane permeability. This type of fouling may be associated with high concentrations of colloidal solids present in mixed liquor.

Fig. 5 [*Trussell et al.*, 2007] shows that when solids concentration in the membrane filtration tank exceeds a threshold, membrane apparent permeability (shown as a ratio of actual membrane flux above threshold solids concentration to the flux below the threshold at the same TMP) decreases rapidly. This decrease is caused by cake formation at the membrane surface due to imbalance between forward solids flux caused by filtration and backward flux (away from the membrane) due to hydrodynamic forces induced by air scouring. The decrease is reversible and can be alleviated by decreasing average filtration flux (membrane relaxation) or enhancing backward flux through increased aeration. This separation of biological and filtration processes for their individual optimization harks back to the concept of cross-flow filtration (compare Fig. 1 a and Fig. 1 c) but in a more refined and efficient way.
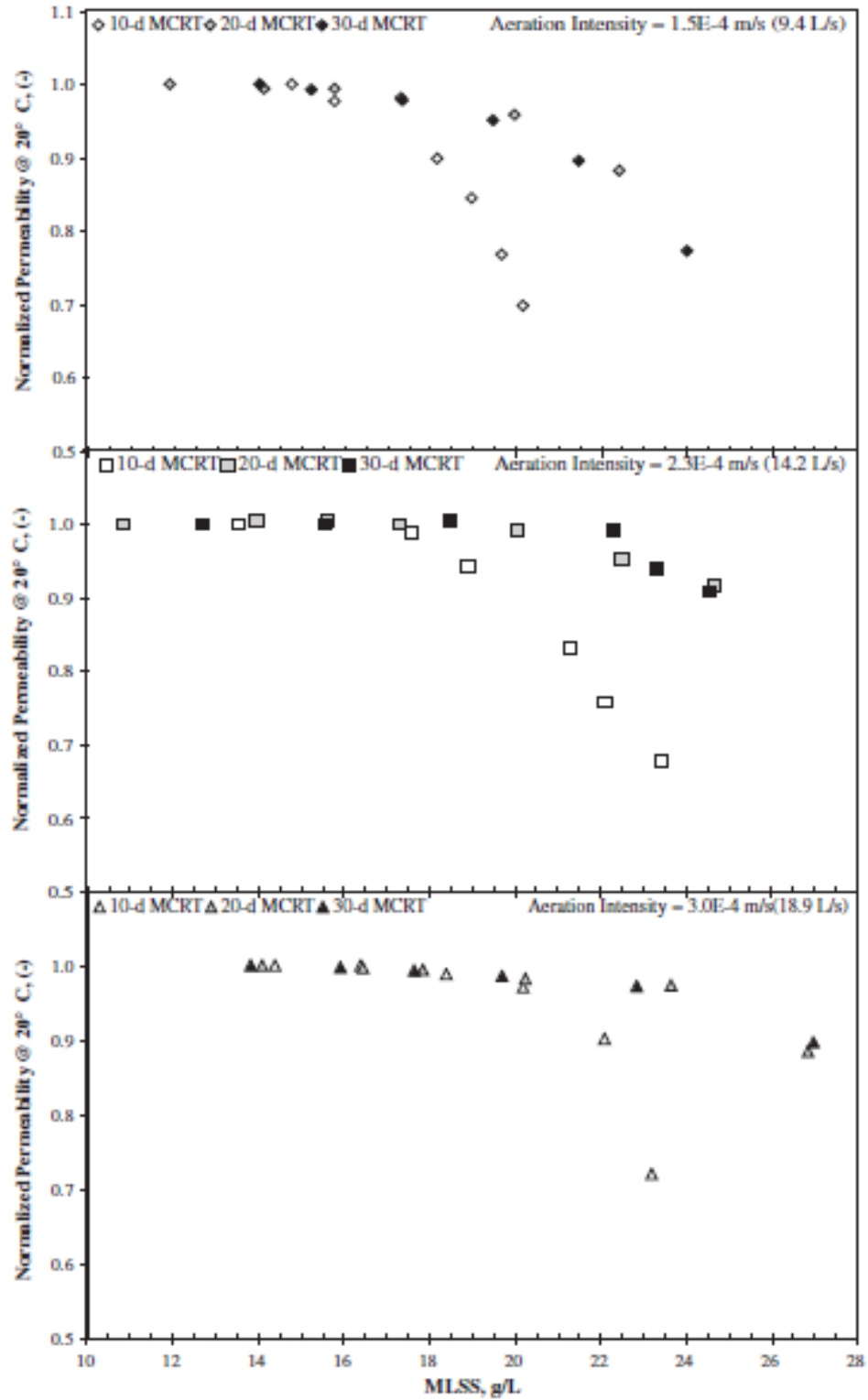
Figure 5 Effects of MLSS on Membrane Permeability at Various Coarse Aeration Intensities

While fouling in above examples was "reversible" (i.e., could be alleviated without chemical cleaning), in many cases "irreversible" fouling is of major concern since it requires application of various cleaning solutions to the MBR unit cleaning [*Cornel and Krause*, 2006; *Lyko et al.*, 2008]. The causes of "irreversible" fouling are still not fully understood despite decades of research [*Drews*, 2010]. Conceptually, such fouling is caused by adsorption of various molecules inside the membrane pores reducing their diameter, pore blocking by particles larger than pore size or by formation of an attached gel layer on the membrane surface. There is substantial evidence that carbohydrates produced as soluble microbial products (SMP) in biological processes or present in the influent play an important role in "irreversible" fouling. However, their exact role and fouling mechanisms are still far from being well understood as many contradictory results were reported in the literature. It is obvious that molecular weight (MW) distribution of SMP (including carbohydrates) should be an important factor. This distribution can vary substantially for different operating conditions and types of influent. As an example, Fig. 6 shows the MW distributions of soluble carbohydrates in MBR influent (municipal primary influent), MBR aeration tank and in the effluent from the MBR (equipped with microfiltration
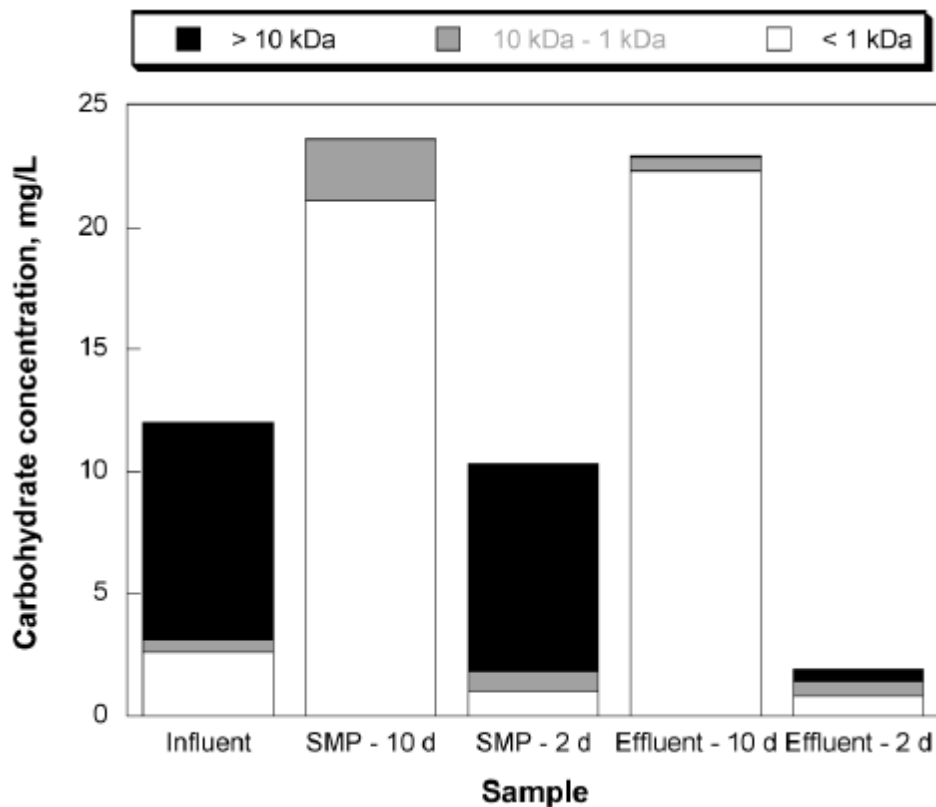
Figure 6 MW Distributions for Influent, Reactor SMP and Effluent Carbohydrates for SRT=2 and 10 d

membranes) [*Trussell et al.*, 2009]. The major feature is the presence of high MW fraction (>10 kDa) SMP in the reactor operated at SRT of 2 d that is almost completely removed by the membrane. In contrast, at SRT of 10 d the SMP consists almost completely of low MW fraction (< 1 kDa) that is not retained by the membrane. In this experiment, the MBR operated at SRT of 2 d exhibited almost ten-fold higher fouling rate (defined as the rate of decrease in time of the specific flux expressed in (L/m^{2}h bar) per day) as shown in Fig. 7.
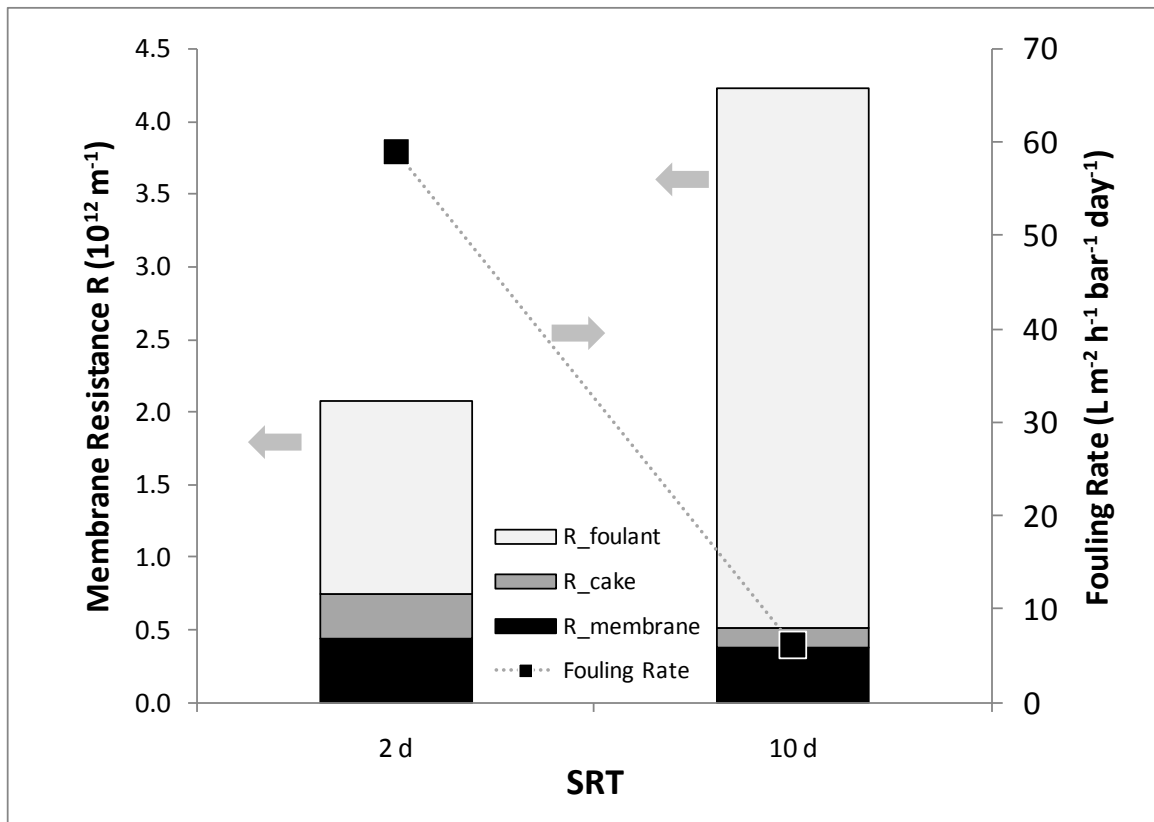
Figure 7 Fouling Rate and Contributions to Total Membrane Resistance at SRT=2 and 10 d

Fig. 7 also shows that the contribution of "irreversible" fouling (indicated by R_foulant) was eventually much greater for SRT of 10 d despite lower fouling *rate* since that MBR was operated without cleaning for 66 days *versus* 5 days at SRT of 2 d.

4. Conclusions

MBR evolved into a highly efficient wastewater treatment process that is competitive with conventional activated sludge, especially where high effluent quality is required. Large progress has been achieved in lowering energy efficiency, primarily through optimization of membrane scouring by aeration in SMBR systems. However, membrane fouling remains a significant operational challenge. "Reversible" fouling is typically caused by high solids concentration that increases the viscosity of the biomass (sludge). High viscosity also affects oxygen transfer rates thus limiting for economic reasons biomass concentrations (MLSS) in practical applications. "Irreversible" fouling requires chemical membrane cleaning to remove foulant molecules and particles that impede filtration through the membrane. Mechanisms of such fouling are still not well understood. Interactions between the membrane and high molecular weight carbohydrates (most likely produced by microorganisms as soluble microbial products) have been implicated in "irreversible" fouling.

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