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Review

Membrane fouling in membrane bioreactors—Characterisation, contradictions, cause and cures

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ABSTRACT

Despite more than a decade of worldwide research on membrane fouling in membrane bioreactors (MBRs), many questions still remain unanswered. In the light of the complexity of the system, it is not surprising that researchers jumped to conclusions on observing any correlations at all, many of which now have to be re-examined as more and more contradictory results are being published. This work therefore aims at stepping back and at critically re-evaluating fouling characterisation methods and results. MBR technology and fouling in particular have been reviewed extensively in 2006 by Judd [1] and Le-Clech et al. [2]. Since then, a large number of both fundamental studies on the interacting biological, chemical and physical phenomena as well as full-scale data have been published. With a focus on recent discoveries and emerging innovative fouling mitigation strategies that might lead to more economical and robust MBR operation, this work is therefore also meant as an update and supplement to these previous reviews.

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Abbreviations: AMR, automated model recognition; AHL, N-acyl homoserine lactone; ATU, allylthiourea; BFM, Berlin Filtration Method; BOD, biological oxygen demand; BPC, biopolymer clusters; BSA, bovine serum albumin; CAS, conventional activated sludge process; CFD, computational fluid dynamics; COD, chemical oxygen demand; DFCm, Delft Filtration Characterisation method; DLS, dynamic light scattering; DOM, dissolved organic matter; DOTM, direct observation through the membrane; EEM, excitation–emission matrix; EPS, extracellular polymeric substances; ESEM, environmental scanning electron microscopy; FS, flatsheet; HF, hollow fibre; MBR, membrane bioreactor; MFI, modified fouling index; MLSS, mixed liquor suspended solids; MPM, multi-photon microscopy; MWCO, molecular weight cut-off; P, protein; PAC, powdered activated carbon; pe, population equivalent; PIV, Particle Image Velocimetry; PS, polysaccharide; PSD, particle size distribution; RO, reverse osmosis; SEC, size exclusion chromatography; SEM, scanning electron microscopy; SIA, sequential injection analysis; SMP, soluble microbial products; SVI, sludge volume index; TEP, transparent exopolymer particles; TOC, total organic carbon; VFM, VITO Fouling Measurement; VOF, volume of fluid method.

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1. Introduction

1.1. Membrane bioreactors (MBR)

Due to their unique advantages like high quality effluent, membrane bioreactors (MBR) – combinations of common bioreactors and membrane filtration units for biomass retention – have become state-of-the-art in wastewater treatment and are becoming increasingly popular. The market value of MBR technology was approx. US$ 217 million in 2005. With an average growth rate of 10.9% per annum it has been growing significantly faster than other advanced wastewater treatment processes and than other membrane technologies [1,3]. The market is currently assumed to double every seven years [3]. More than 50 new industrial MBR >20 m^3/d and more than 20 municipal plants >500 pe were installed per year between 2002 and 2005. Based on installed membrane surface, the municipal sector held 75% of the market volume between 2003 and 2005 [4].

A lot of experience in MBR operation has been gained. However, due to the complexity of the interacting biological and membrane filtration phenomena, plant design remains rather empirical and paces ahead of indepth understanding. In comparison to the conventional activated sludge process (CAS), this results in higher operational costs mainly for membrane aeration (e.g., Refs. [1,5–7]), and in an additional environmental burden through the use of aggressive chemicals for membrane cleaning, etc. [8,9].

The bioreactor and membrane stages cannot be regarded as separate unit operations since they interact with regards to both biological reactions and membrane filtration – in the case of MBR, "1 + 1 does not equal 2" [10,11]. If the result, so to say, turns out to be greater or less than 2 very much depends on the state of the biomass and in particular on microbiology–membrane interactions.

Despite their often cited advantages like decreased footprint and reduced excess sludge production, arbitrarily high mixed liquor suspended solids (MLSS) concentrations are not typically employed due to rising and non-Newtonian viscosities at increased MLSS concentration [12]. Operating with a high viscosity affects the energy required for pumping, air scour of the membranes and oxygen supply of the microorganisms. For these economic reasons, full-scale MBR treating municipal wastewater today are operated in an MLSS range of approx. 8–18 g/L [1,8,13,14]. These are rather empirical values, the optimum depending on the individual installations, such as pumps, piping, aeration devices and also on other biomass characteristics besides MLSS concentration.

Models and parameters describing either biological reactions or membrane filtration have been used extensively (e.g., Refs. [15–18]). However, since the biological and membrane filtration stages affect each other, a revision of such models as they apply to MBR is required [10,19]. Although several practical experiences and data are available for MBR processes, no systematic investigations taking into account all interactions have been carried out so far.

1.2. Fouling in MBR

The main drawback of MBR technology in comparison to CAS still is its high cost. While membrane module costs have decreased dramatically over the last years (to <US$ 50/m^2 [1]) leading to a decrease in capital costs, membrane fouling abatement leads to elevated energy demands and has become the main contribution to overall MBR operating costs. Fouling affects these in a number of ways as listed below.

- Decreased plant productivity/permeate yield due to
  - filtration breaks and backflush: To remove the deposit layer, backflushing from the permeate side (hollow fibre modules) or relaxation (flatsheet modules) are commonly applied for approx. 15–60 s every 3–12 min of filtration [1,14,20], and
  - frequent cleanings (maintenance cleanings approx. every 2–7 d, main cleanings once or twice a year [1,14]). This also leads to environmental hazards through the formation of chemical cleaning by-products such as adsorbable organic halogens (AOX) (e.g., Ref. [8]).
- Damaging, inefficient or late chemical cleaning which might reduce the modules' lifespan and result in higher replacement costs.
- High energy requirement for aeration: With up to 70% of the total energy costs [1,6,14], membrane aeration is the biggest contribution to operating costs. From 10 years of experience of operating a full-scale MBR, it was found that only in 10% of the operational time, i.e. during peak loads, the supplied energy is optimally used [21]. This shows the large optimisation potential.

Fouling in its strict form is the coverage of the membrane surface (external and internal) by deposits which adsorb or simply accumulate during operation. However, the term is often used to lump all phenomena that lead to a loss in permeability. Such a loss results in larger required membrane surfaces, higher applied pressures or crossflow velocities/shear rates which both result in higher energy expenditure, or frequent chemical cleanings of the fouled membranes. Permeability loss, though, can also be caused by clogging or sludging of the module. This results from the local breakdown of crossflow conditions and the subsequent dewatering of the biomass which leaves a rather solid deposit in the voids of the modules.

Since deposits are brought to the membrane mainly by convective transport it is clear that the rate of fouling depends on the velocity orthogonal to the surface – the permeate flux. This results in a typical trade-off or optimisation problem: At higher flux, capex decreases while opex increases. If the correlation between flux and fouling rate was known, an optimisation could be performed. Unfortunately, the rate of fouling depends on numerous other and inter-related parameters. To date, there still is a lack of fundamental understanding, so this relationship is a blur.

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