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Modelling bioprocesses and membrane fouling in membrane bioreactor (MBR): A review towards finding an integrated model framework

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HIGHLIGHTS

- ▶ State-of-the art in mathematical modelling studies of MBRs were summarized.
- ▶ Integrated mathematical model for MBRs and membrane fouling is yet to be developed.
- ▶ Interaction between MBR processes and membrane limit the application of ASMs to MBR.
- ▶ Empirical expressions of model parameters for calibration are essential.
- ▶ Switching functions between model variables could exclude less important parameters.

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ABSTRACT

The bioprocesses taking place in activated sludge wastewater treatment system itself are characterized by great complexity and yet incomplete understanding of some of the phenomena involved. The MBR technology inherent deficiencies for its simulation due to additional intrinsic complexities resulting from the interaction between concurrently occurring and dynamic biological processes with membrane filtration and the straightforward adoption of the activated sludge models' (ASM) frameworks or their modified variations. In this backdrop, this paper compiles a brief overview of the previous developments to the current state-of-the-art mathematical modelling approaches of the MBR system. With extended discussions on particular topics such as applications of modified ASMs to MBR modelling, ASM extensions incorporating soluble microbial products (SMP)/extracellular polymeric substances (EPS) concepts, this paper also provides a guide for different end-users of mathematical models of MBR systems.

1. Introduction

Wastewater treatment has been a challenge throughout the past few decades due to varying influent characteristics and stringent effluent regulations. Standalone biological wastewater treatment systems have been able to handle most of these difficulties, but at the expense of huge economical cost to achieve the desired effluent water quality particularly at medium to large wastewater treatment facilities. In this backdrop, Membrane bioreactors (MBRs) are being increasingly implemented to treat and reuse wastewater due to their many advantages over conventional activated sludge (CAS) processes. Besides membrane fouling and the high cost of membranes as identified main obstacles for wider application of MBRs, recent studies have reported several crucial specificities of the treatment system. Although several innovative lab-scale MBRs could show convincing achievements to reduce few of the problems, those innovations are yet to be reflected into implemented treatment facilities of MBRs. There exists, therefore, a pressing demand to develop appropriate integrated models which can translate experimental results of various lab-scale MBRs and also can validate those against true observations at implemented MBR systems. This obviously will require intelligent modelling of the biokinetics, membrane fouling and hydrodynamics of the MBR system resulting desired outcomes against treatability and fouling control targets.

The efforts for modelling of wastewater treatment systems, so far, have always targeted either the treatment quality targets or various aspects of system management. In an attempt to develop mathematical models for the MBR system focusing on the biological processes only, the activated sludge models (ASMs) (Henze et al., 1987, 1995, 1999; Gujer et al., 1999) formerly developed for CAS processes, have been applied with or without modifications to simulate biomass kinetics of the MBR systems. However, buildup of SMPs and/or extracellular polymeric substances (EPSs) can cause reduction in membrane permeability (Rosenberger et al., 2006; Ahn et al., 2006). For this reason, formation and degradation kinetics of SMPs (Lu et al., 2001; Wintgens et al., 2003; Jiang et al., 2008) and EPSs (Ahn et al., 2006) have been introduced in

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the ASMs derived hybrid models assuming their useful role for understanding and controlling fouling phenomena. Different approaches have also been developed for modelling the physical and biological aspects of membrane fouling, i.e., fractal permeation model (Meng et al., 2005), empirical hydrodynamic model (Liu et al., 2003) and sectional resistance model (Li and Wang, 2006). On the other hand, to improve the knowledge about the correlation between the biological processes and various membrane fouling phenomena, integrated (hybrid) MBR models have been proposed which combines biomass kinetic models with membrane fouling models. However, most of these integrated MBR mathematical models (Lu et al., 2001; Lee et al., 2002; di Bella et al., 2008; Zarragoitia et al., 2008; Janus and Ulanicki, 2010; Mannina et al., 2011) have focused only on few targeted aspects of steady-state biological processes linked to membrane fouling models leaving many unresolved issues in models' calibration. Several reviews of modelling studies on MBR have highlighted some issues in this regard, i.e., mini-review of MBR modelling studies (Ng and Kim, 2007), ASM based modelling of MBR (Fenu et al., 2010), bioprocess modelling of MBR system and fouling predictions (Patsios and Karabelas, 2010). This review aims to synthesize previous studies and current state-of-the-art in MBR modelling studies with special regard to some specificities of the treatment system. Fundamentals of correlation between MBR bioprocess and fouling phenomena are discussed first in order to guide the reader to understand missing links in unmodified and modified ASM based modelling of MBR systems. Particular emphasis is placed on the discussion about the MBR bioprocesses and SMP/EPS modelling which have influences on membrane fouling. Significant efforts have been paid to identify key variables of mathematical MBR models which may establish an integrated framework for coupling MBR bioprocesses with fouling.

2. General overview of MBR process kinetics and stoichiometry

2.1. Crucial specificities of MBR biological processes

Though the CAS and MBR systems are similar from a biochemical engineering viewpoint, recent studies have reported several crucial specificities of the MBR system, i.e., medium to very high sludge retention times (SRT), high mixed liquor suspended solids (MLSS) concentration, accumulation of SMPs rejected by membrane filtration, and high aeration rates for scouring and good nitrification performance (Ng and Kim, 2007; Fenu et al., 2010). High MLSS concentrations in MBR system causes its operation at high viscosities effecting the energy requirement for pumping, air scour of the membranes and oxygen supply of the micro-organisms. The difference between MBR and CAS systems in terms of sludge characteristics and performance is especially pronounced at high SRTs when deterioration of sludge settleability and effluent quality of the CAS is observed at relatively higher SRTs. Above all, the major process problem associated with MBRs is the membrane fouling which often contributes to huge system operating cost. The rejected constituents in the retentate tend to accumulate at the membrane surface, and as a consequence a reduction in the permeate flux at a constant transmembrane pressure (TMP) or conversely an increase in the TMP at a constant flux is observed. A balance between flux, TMP, energy demand and cleaning frequency is, therefore, very crucial in case of MBR process design. There are further operational issues such as greater foaming propensity, a less readily dewaterable sludge product and generally greater sensitivity to shock loads of MBR compared to CAS.

2.2. Process kinetics of membrane fouling in MBR

Membrane fouling in an MBR can be classified into different categories at different stages of operation of an MBR. Reversible fouling refers to fouling that can be removed by physical means such as backflushing, while irreversible fouling refers to fouling which can only be removed by chemical cleaning (Judd, 2006). The fouling that occurs over long periods cannot be removed by any cleaning and termed as irrecoverable fouling.

Since deposits are brought to the membrane mainly by convective transport, the rate of fouling dominantly depends on the velocity orthogonal to the surface – the permeate flux (Drews, 2010). Traditionally, three factors thought to affect fouling are membrane, sludge characteristics and operation (Chang et al., 2002; Le-Clech et al., 2006). Aeration ports and module dimensions have been added to the original three factors and make up the group of relevant design parameters for the MBR system (Judd, 2006). In fact, the rate of fouling depends on various other interrelated parameters making the correlation between flux and fouling rate a dynamic variable. As there still remains a lack of fundamental understanding of the kinetics involved, the term fouling is often used to lump all phenomena that lead to a loss in permeability. Numerous researches have been conducted to identify factors that reduce fouling and thus to increase permeate flux i.e., Ngo et al. (2008) have identified that increasing the attached growth biomass by introducing polyester-urethane sponges in the bioreactor MLSS increases sustainable flux with consequences to reduced membrane fouling.

Membrane fouling in a typical MBR system occurs due to the following general mechanisms (Meng et al., 2009): (i) adsorption of solutes or colloids within/on membranes; (ii) deposition of sludge flocs onto the membrane surface; (iii) formation of a cake layer on the membrane surface; (iv) detachment of foulants attributed mainly to shear forces; and (v) the spatial and temporal changes of the foulant during the long-term operation. While there are more or less established theories to explain fouling mechanisms by adsorption-deposition, cake layer formation and detachment of foulants from the cake layers during short-term operation of an MBR system, researchers are still faced with the difficulties of linking the spatial and temporal changes of foulants during its long term operation.

Since the long-term operation of an MBR is typically conducted at a flux lower than the critical flux, the rate of particle convection towards the membrane surface is usually balanced by the rate of back transport and hence the particulate fouling is not a dominant problem to deal with. Experimental evidences suggest that the critical thing to deal here is the change of bacterial community and biopolymer components in the cake layer with time. The rate of membrane fouling aggravates with time principally due to the high rate of cell lysis of the biopolymer components of the cake layer. This gradually results in more of the membrane pore closure due to the higher rate of trace foulants' adsorption as compared to the rate of desorption and back-transport of such trace foulants. These ultimately increase the specific cake resistance, cake compressibility and irreversibility during the long-term operation of an MBR system.

2.3. Fractions of MLSS responsible for membrane fouling

Unlike the simple mathematical expressions proposed (Ishiguro et al., 1994; Fan et al., 2006; Liang et al., 2006; Busch et al., 2007; Guglielmi et al., 2007) to describe the relationship between the concentration of dissolved organic matter (DOM) and membrane flux decline or TMP change, the MLSS or the mixed liquor volatile suspended solids (MLVSS) concentration has a rather complex relation to MBR fouling. Kornboonraksa and Lee (2009) found that MLSS and sludge floc size are the dominant factors that control the membrane filterability in an MBR treating wastewater. Different research groups have reported various empirical mathematical expressions describing membrane flux or fouling rate which included MLSS/MLVSS concentration, although contradictory findings about the effect of these parameters on membrane filtration have also been