


## Position paper – progress towards standards in integrated (aerobic) MBR modelling



C. Brepols , J. Comas , J. Harmand, M. Heran , Á. Robles , I. Rodriguez-Roda , M. V. Ruano , I. Smets  and G. Mannina 

### ABSTRACT

Membrane bioreactor (MBR) models are useful tools for both design and management. The system complexity is high due to the involved number of processes which can be clustered in biological and physical ones. Literature studies are present and need to be harmonized in order to gain insights from the different studies and allow system optimization by applying a control. This position paper aims at defining the current state of the art of the main integrated MBR models reported in the literature. On the basis of a modelling review, a standardized terminology is proposed to facilitate the further development and comparison of integrated membrane fouling models for aerobic MBRs.

**Key words** | integrated model, MBR modelling, terminology

**C. Brepols**  (corresponding author)  
Erttverband,  
Am Erttverband 6, D 50126,  
Bergheim, Germany  
E-mail: [christoph.brepols@erttverband.de](mailto:christoph.brepols@erttverband.de)


**J. Comas**   
**I. Rodriguez-Roda**   
Catalan Institute for Water Research (ICRA) and  
Universitat de Girona (LEQUIA-UdG),  
Girona, Spain

**J. Harmand**  
LBE, INRA, Univ. Montpellier,  
Narbonne, France

**M. Heran**   
Université Montpellier,  
Montpellier, France

**Á. Robles**   
**M. V. Ruano**   
Universitat de València,  
Valencia, Spain

**I. Smets**   
KU Leuven,  
Leuven, Belgium

**G. Mannina**   
Engineering Department,  
University of Palermo,  
Palermo, Italy  
and  
College of Environmental Science and Engineering,  
Tongji University, China

### INTRODUCTION

Worldwide membrane bioreactors (MBRs) are employed for aerobic wastewater treatment in a strongly increasing number of installations and larger plant capacities (Brepols *et al.* 2017; Xiao *et al.* 2019; Mannina *et al.* 2020a). The performance of MBR processes is driven by complex interactions between biological processes, fluid (rheological) properties and membrane filtration. The nature of the membrane feed (wastewater–biomass–matrix), membrane and module characteristics and the hydrodynamic environment influence fouling behaviour by reactor set-up and load as well as numerous operating modes (Zhang *et al.* 2006). Various computational models have thus been used to describe and master unit processes of MBR operations under dynamic conditions (Fenu *et al.* 2010; Naessens *et al.* 2012a, 2012b).

Despite the efforts performed in MBR-based technology modelling, this topic has not yet fully matured and needs further work. Specifically, the research community has not yet reached a general consensus about some critical issues related to the biological and physico-chemical processes and their kinetics (e.g. kinetics of soluble microbial product (SMP) formation and degradation process, precipitation processes, biodegradability in terms of high sludge retention time or aerobic/anaerobic conditions), fouling propensities of components and, consequently, to translate them into mathematical expressions (e.g. SMP modelling, influent fractionation, etc.). Furthermore, up to now, a complete, clear and generally accepted nomenclature/terminology surrounding the MBR modelling field is still lacking. This

complicates comparisons among different models and impedes insights from previous applications.

With this position paper, the IWA Task Group (TG) on Membrane Bioreactor Modelling and Control aims at establishing a next step towards standardized MBR modelling. This paper will mainly focus on the so-called integrated MBR models which jointly take into account biological and physical (membrane filtration) processes. Modelling of the latter is often accomplished by resistance-in-series (RIS) models for membrane fouling.

Building upon previous and recent literature reviews (Chang *et al.* 2009; Naessens *et al.* 2012a, 2012b; Di Bella & Di Trapani 2019; Hamed *et al.* 2019) a brief summary and update is given to identify current trends in MBR modelling with special regard to integrated MBR models and the temporal and spatial scale of modelling applications in research and engineering.

In the modelling of biological wastewater treatment processes, issues with ambiguous terminologies and nomenclature have been addressed previously (Corominas *et al.* 2010; Rieger *et al.* 2013). Which of these issues persist in the used MBR models is examined. Based upon the approach of Rieger *et al.* (2013) a way to provide a common and unambiguous terminology for variables, parameters and processes is proposed.

## UPDATED LITERATURE REVIEW

### Physico-chemical or mechanical unit operations

Various computational models have been used to describe and master (physico-chemical or mechanical) unit processes of MBR operations under dynamic conditions. Simple mechanistic approaches have been used to model energy consumption of MBRs based on heuristic rules and models of pumping and aeration energy (Verrecht *et al.* 2008). Although they can provide information on various design options, these models generally do not predict filtration performance based on membrane fouling.

### Biodegradation

Activated sludge models (ASM) are well established and widely used (Langergraber *et al.* 2004; Rieger *et al.* 2013) and have been applied to simulate biomass kinetics in MBR systems (Fenu *et al.* 2010). Additional sub-processes or complementary models of different or additional biological pathways can be implemented to describe e.g. greenhouse-gas

(GHG) emissions (Mannina *et al.* 2018c; Massara *et al.* 2018; Wisniewski *et al.* 2018) and energy consumption (Grau *et al.* 2007). ASMs have also been modified to include the presence and fate of soluble microbial products (SMPs) which allegedly play an important role in membrane fouling, in so-called hybrid ASM models (Zuthi *et al.* 2012). Hybrid ASM models could also be used to model the fate of extracellular polymeric substances (EPS) or diluted organic matter.

### Filtration

Different MBR models have focused on the physical aspects of the fouling process by various methods with the aim of describing several processes involved in membrane fouling. Among them, mathematical models are the most widely developed, which include empirical hydrodynamic models, conventional mass transfer and tangential filtration models, fractal permeation models, sectional resistance models and RIS models (Ng & Kim 2007; Chang *et al.* 2009; Naessens *et al.* 2012a).

Regarding the number of publications, RIS models seem to be highly popular. Based on an application of Darcy's law, non-stationary mathematical equations are used to describe the total hydraulic resistance. The filtering system (physical membrane plus internal and external fouling) is characterized by different resistance contributions, which can be correlated to local parameters (cross-flow velocity, mixed liquor suspended solids (MLSS) concentration, etc.), the resistances to filtration and the viscosity of a Newtonian fluid. Usually, fouling analysis is based on a quantification of the total resistance as the sum of different resistances-in-series, each related to a specific fouling mechanism: the so-called resistance decomposition (Di Bella & Di Trapani 2019).

When applied to MBR with activated sludge, the RIS concept should be used with caution (Chang *et al.* 2009), because the complex living suspension is not easily represented by simple addition of resistances and the additivity of components often cannot be found. Furthermore, various complementing or competing concepts on fouling phenomena in MBR have to be acknowledged (e.g.: superficial cake deposition, deep-bed fouling, complete or partial pore-clogging). The analytical detection and identification of foulants is challenging. Fouling classifications and fouling mechanisms reported in the literature highlight the diverse nature of membrane fouling: reversible, irreversible, irremovable fouling and cake layer deposition, intermediate blocking, concentration polarization, pore blocking, pore narrowing, etc. Predicting long-term filtration performance is further complicated by the applied

membrane cleaning strategies, and by the wide range of physical scales of the examined MBR systems (Drews 2010; Wang *et al.* 2014; Di Bella *et al.* 2018).

Computational fluid dynamics (CFD) modelling in the wastewater treatment (WWT) field is continuing to grow and is used to solve increasingly complex problems. CFD models have been used to describe various aspects of the MBR filtration process (Naessens *et al.* 2012b) at different scales, from entire WWTPs (Brannock *et al.* 2009) to microscopic levels (Lohaus *et al.* 2018), such as the importance of fluid dynamics for MBR fouling mitigation (Böhm *et al.* 2012; Liu *et al.* 2019) or optimization of MBR design and operation (Liu *et al.* 2018). A proposal towards good modelling practice has been described by Wicklein *et al.* (2016).

### Integrated models

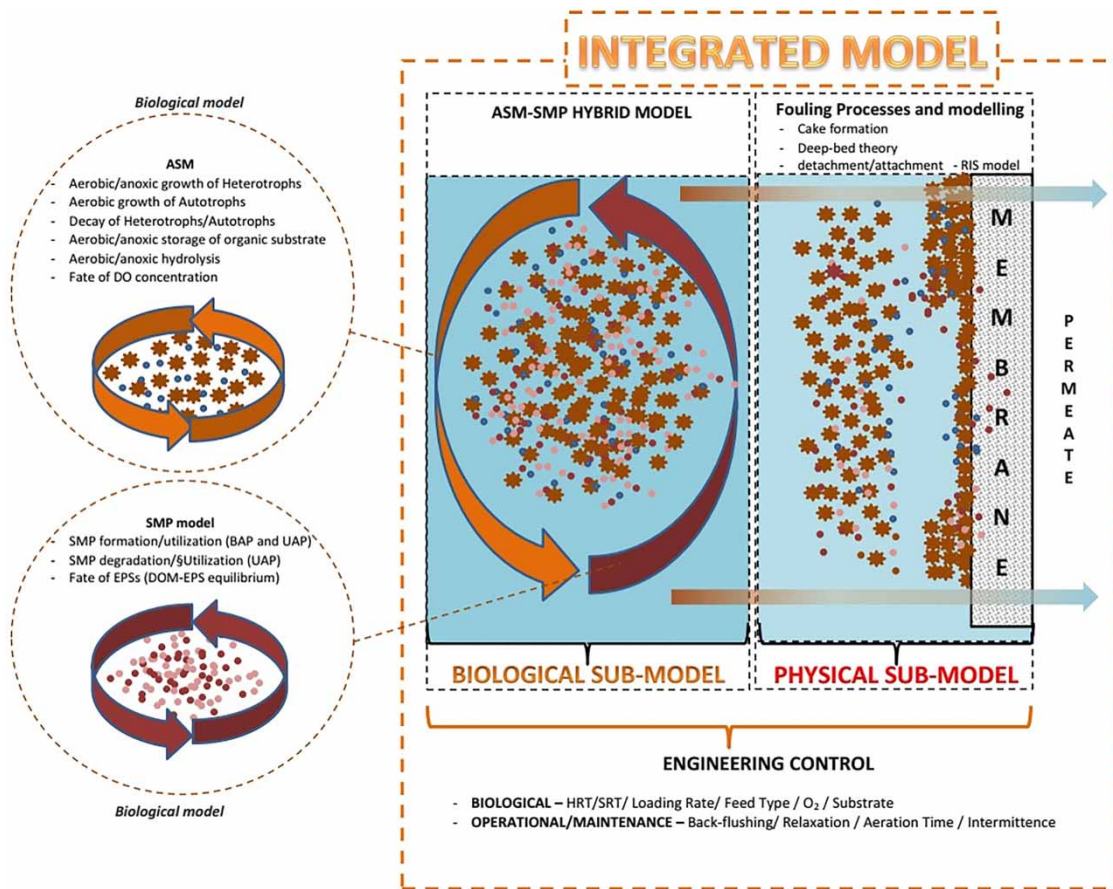
Combinations of hybrid models with physical filtration models (mostly RIS models) have been denoted as integrated models (Mannina *et al.* 2011; Zuthi *et al.* 2013). These models allow combined simulations of several of

the abovementioned crucial aspects that are important in MBR operations (Table 1). Currently these models seem to represent the most complete and complex level for the modelling of MBR systems, considering interactions among the different parts of the system (see Figure 1), despite their limitations.

Alternative models are based on particle size distribution (PSD). Given that the cake layer on the membrane consists of deposited particles of which the sub-micron-sized particles have a negative effect on the structure and porosity of the layer, models have been proposed that take into account the particle size distribution and its impact on cake layer build-up and the resulting membrane fouling (Lu & Hwang 1993; Yoon *et al.* 1999; Picioreanu *et al.* 2004; Broeckmann *et al.* 2006; Park *et al.* 2006; Shin *et al.* 2013; Cao *et al.* 2015). Due to the complex and somehow still unknown mechanisms for fouling development, there have also been approaches for data-driven modelling of fouling in MBRs (Araujo Pimentel *et al.* 2015; Dalmau *et al.* 2015; Ahmad Yasmin *et al.* 2017; Schmitt & Do 2017).

**Table 1** | Feature comparison of selected MBR modelling studies using an integrated RIS model approach

Reference/Model features	Lee <i>et al.</i> (2002)	Wintgens <i>et al.</i> (2003)	Di Bella <i>et al.</i> (2008)	Zarragoitia-González <i>et al.</i> (2008)	Zarragoitia <i>et al.</i> (2009)	Mannina <i>et al.</i> (2011)	Sarioglu <i>et al.</i> (2012)	Zuthi <i>et al.</i> (2012)	Janus & Ulanicki (2016)	Mannina <i>et al.</i> (2018a, b)
<b>Biological sub-model</b>										
Biomass growth (e.g. $X_{TSS}$ )							x	x		x
ASM (SMP hybrid)	x	x	x	x	x	x			x	x
SMP	x		x	x	x	x		x		x
EPS									x	x
<b>Process sub-models</b>										
Process control				x					x	
Energy		x			x				x	x
<b>Experimental set-up</b>										
Laboratory-scale				x	x	x		x		
Pilot-scale			x		x		x			x
Full-scale		x								
Short time series (<1 week)		x					x			
Long time series (>1 week)		x	x	x	x	x	x	x		x
<b>Calibration method</b>										
Heuristic		x					x	x		
Stochastic (e.g. sensitivity analysis)						x		x		x



**Figure 1** | Integrated approach for MBR modelling (RIS: resistance in series, HRT: hydraulic retention time, SRT: sludge retention time).

## Model-based control

Several other authors have theoretically analysed and experimentally validated energy savings of different types of advanced control in aerobic MBR technology based on models or knowledge-based approaches (Drews *et al.* 2007; Ferrero *et al.* 2011, 2012; Huyskens *et al.* 2011; Monclús *et al.* 2012; Villarroel *et al.* 2013; González *et al.* 2018). Process improvements and optimized MBR control strategies (improvement of effluent quality, reduction of fouling and energy costs) can be achieved through model-based methodologies (Yusuf *et al.* 2016; Odriozola *et al.* 2017; Kalboussi *et al.* 2018). Different open-loop and closed-loop control systems have thus been developed and validated for MBRs, even at full-scale (Smith *et al.* 2006; Vargas *et al.* 2008; Vera *et al.* 2014; Mannina *et al.* 2020b). Model-based approaches are a cost-efficient means to explore operational strategies for both control of biological processes (e.g. nitrification/denitrification) and membrane filtration (Robles *et al.* 2014; Sun *et al.* 2016; Perera *et al.* 2017). Additionally, model-based

optimizations are tools in sensitivity and uncertainty analysis of the MBR process operation.

Depending on their experimental set-up, the spatial and temporal scale and the intention of their work, authors have promoted various concepts for fouling modelling or RIS aggregation (see Table 1). The abovementioned papers reveal difficulties in identifying filtration resistances, their combinations and dynamics. Model calibration methods are not likely to be documented or are carried out on constrained data-sets. Models are seldom validated on alternative set-ups or time-lines. Uncertainties in experimental set-ups, analytical methods and model assumptions are generally not evaluated or discussed (Mannina & Di Bella 2012; Mannina *et al.* 2017).

## TERMINOLOGY AND NOTATION

Terminologies and notations of model parameters are a source of difficulties in comparing concepts and results across reported models. RIS models show overlaps and

inconsistencies in their model nomenclature (Di Bella & Di Trapani 2019), and terminology among these models can be ambiguous. These findings resemble the conclusions from an earlier examination of activated sludge models (Corominas et al. 2010; Rieger et al. 2013). It is thus attempted within this paper to draw outlines of a notational framework, while a full and unabridged framework description would exceed the limits of this publication. Still this draft is meant to be undemanding, distinctive, complete and flexible towards future requirements.

One group of state variables is used to describe bulk components which are relevant in the model and which are used in the mass balances of the model. When variables are derived from the biological (ASM) model it is recommended that their notational framework follows existing guidelines (Rieger et al. 2013). In integrated MBR models these are usually linking elements between the biological and filtration model. They can be discriminated by their nature and particle size as well as their degradability, their organic or inorganic origin, the name of the compound and other specifications. Components which are responsible for membrane fouling can be distinguished by their actual size and nature, between particulate, colloidal and soluble compounds whose definition may depend on the actual pore-size, permeation and separation characteristics of the membrane filters in use. It is thus important that particle sizes which are relevant for the underlying theories on fouling and the model are clearly specified in the model documentation. Lumped state variables which can be obtained by grouping several variables,

as e.g. the total suspended solids concentration  $X_{TSS}$ , eventually need to be discriminated from composite variables which are used to compare model data with experimental data. Table 2 exemplifies the framework. Variables can be named by their main symbol and a lineage of comma-separated subscripts.

## NOTATION OF FILTRATION RESISTANCES

RIS models generally employ more or less large numbers of additive resistances which are distinguished according to the applied theories on membrane fouling. Di Bella & Di Trapani (2019) have provided a list of some of the most abundant resistances presented in the technical literature and come to the conclusion that despite many of the reported resistances having the same definition, they are identified with a different nomenclature due to the specific approach used. Furthermore, in some cases, the same nomenclature has been adopted to describe different fouling mechanisms. As a consequence, a more explicit notation is proposed to define the filtration resistance components of the model (Table 3). As examples, intrinsic membrane resistance would be denoted  $R_{It,M}$  and reversible cake layer resistance depending on total suspended solids (TSS) concentration could be denoted as  $R_{Rv,CL,TSS}$ . Other model parameters describe physical and chemical bulk properties, like viscosity or pH-value, while other state variables describe filtration properties like flux, transmembrane pressure (TMP), and permeability. The main symbol can be used to

**Table 2** | Notation of state variables describing bulk components

Main symbol Size	Subscript correction factor	Nature	Name of compound	Specifications
X – particulate	U – undegradable	Org – organic,	e.g.	e.g.
C – colloidal	B – biodegradable	Ig – inorganic	TSS	Origin, size-compartment,
S – soluble	A – abiotically convertible		EPS	sub-compound,
			SMP	valence

**Table 3** | Proposed notation of subscripts for filtration resistance R in RIS models

Classification	Mechanism	Element, compound, state variable	Further specification
Intrinsic – It	Membrane – M	TSS	Origin
Irreversible – Iv	Cake layer formation – CL	EPS	Compartment
Irremovable – Im	Intermediate blocking – IB	SMP	Sub-compound
Reversible – Rv	Concentration polarization – CP		
	Pore blocking – PB		
	Pore narrowing – PN		

specify the parameter or correction factors, while a lineage of subscripts can be used to specify compound or reaction products and other specifications. Model parameters like hydrodynamic variables, rate coefficients and reduction factors require a notational frame of their own.

## CONCLUSIONS AND FUTURE PERSPECTIVES

A common RIS model framework does not exist so far. The development of a mutually accepted notation framework is thus a step towards improved exchange between researchers, modellers and practitioners longing to apply MBR models. However, the outline of a notational framework as proposed here for the biodegradation-related state variables and the different resistances in the RIS-based filtration model is still a work in progress.

In accordance with previous conclusions (Naessens et al. 2012b), it can be stated also that RIS simulation studies show weaknesses regarding good modelling practice and uncertainties in MBR modelling have not been addressed systematically. Uncertainties in wastewater treatment modelling occur during all stages of model development beginning from the scope and definition of a project through data collection and reconciliation, plant model set-up, calibration and validation to simulation and interpretation of results (Belia et al. 2009). A structured discussion on the validity of MBR models and an evaluation of possible sources, locations and levels of uncertainties seem to be inevitable. The assessment of uncertainty for MBR models needs further application to better balance model complexity between biological and physical processes.

## ACKNOWLEDGEMENTS

This work has been carried out under the umbrella of the Task Group on Membrane Bioreactor Modelling and Control of the International Water Association (IWA) (<http://www.iwa-network.org/groups/membrane-bioreactor-modelling-and-control/>).

## REFERENCES

- Ahmad Yasmin, N. S., Abdul Wahab, N. & Yusuf, Z. 2017 Modeling of membrane bioreactor of wastewater treatment using support vector machine. In: *Modeling, Design and Simulation of Systems* (M. S. Mohamed Ali, H. Wahid, N. A. M. Subha, S. Sahlan, M. A. M. Yunus & A. R. Wahap, eds), Springer, Singapore, pp. 485–495. [https://doi.org/10.1007/978-981-10-6502-6\\_42](https://doi.org/10.1007/978-981-10-6502-6_42).
- Araujo Pimentel, G., Dalmau, M., Vargas, A., Comas, J., Rodriguez-Roda, I., Rapaport, A. & Vande Wouwer, A. 2015 Validation of a simple fouling model for a submerged membrane bioreactor. *IFAC-PapersOnLine* **48**, 737–742. <https://doi.org/10.1016/j.ifacol.2015.05.031>.
- Belia, E., Amerlinck, Y., Benedetti, L., Johnson, B., Sin, G., Vanrolleghem, P. A., Gernaey, K. V., Gillot, S., Neumann, M. B., Rieger, L., Shaw, A. & Villez, K. 2009 Wastewater treatment modelling: dealing with uncertainties. *Water Sci. Technol.* **60**, 1929–1941. <https://doi.org/10.2166/wst.2009.225>.
- Böhm, L., Drews, A., Prieske, H., Bérubé, P. R. & Kraume, M. 2012 The importance of fluid dynamics for MBR fouling mitigation. *Bioresour. Technol.* **122**, 50–61. <https://doi.org/10.1016/j.biortech.2012.05.069>.
- Brannock, M. W. D., De Wever, H., Wang, Y. & Leslie, G. 2009 Computational fluid dynamics simulations of MBRs: inside submerged versus outside submerged membranes. *Desalination* **236**, 244–251. <https://doi.org/10.1016/j.desal.2007.10.073>.
- Brepols, C., Drensla, K., Janot, A., Beyerle, L. & Schäfer, H. 2017 Future perspectives for MBR applications at the Erftverband. In: *Frontiers in Wastewater Treatment and Modelling* (G. Mannina, ed.), Springer, Cham, Switzerland, pp. 149–152. [https://doi.org/10.1007/978-3-319-58421-8\\_22](https://doi.org/10.1007/978-3-319-58421-8_22).
- Broeckmann, A., Busch, J., Wintgens, T. & Marquardt, W. 2006 Modeling of pore blocking and cake layer formation in membrane filtration for wastewater treatment. *Desalination* **189**, 97–109. <https://doi.org/10.1016/j.DESAL.2005.06.018>.
- Cao, T. A., Van De Staey, G. & Smets, I. Y. 2015 Integrating activated sludge floc size information in MBR fouling modeling. *Water Sci. Technol.* **71**, 1073–1080. <https://doi.org/10.2166/wst.2015.070>.
- Chang, I.-S., Field, R. & Cui, Z. 2009 Limitations of resistance-in-series model for fouling analysis in membrane bioreactors: a cautionary note. *Desalin. Water Treat.* **8**, 31–36. <https://doi.org/10.5004/dwt.2009.687>.
- Corominas, L., Rieger, L., Takács, I., Ekama, G., Hauduc, H., Vanrolleghem, P. A., Oehmen, A., Gernaey, K. V., van Loosdrecht, M. C. M. & Comeau, Y. 2010 New framework for standardized notation in wastewater treatment modelling. *Water Sci. Technol.* **61**, 841–857. <https://doi.org/10.2166/wst.2010.912>.
- Dalmau, M., Atanasova, N., Gabarrón, S., Rodriguez-Roda, I. & Comas, J. 2015 Comparison of a deterministic and a data driven model to describe MBR fouling. *Chem. Eng. J.* **260**, 300–308. <https://doi.org/10.1016/j.cej.2014.09.003>.
- Di Bella, G. & Di Trapani, D. 2019 A brief review on the resistance-in-series model in membrane bioreactors (MBRs). *Membranes* **9**, 24. <https://doi.org/10.3390/membranes9020024>.
- Di Bella, G., Mannina, G. & Viviani, G. 2008 An integrated model for physical–biological wastewater organic removal in a submerged membrane bioreactor: model development and parameter estimation. *J. Memb. Sci.* **322**, 1–12. <https://doi.org/10.1016/j.memsci.2008.05.036>.

- Di Bella, G., Di Trapani, D. & Judd, S. 2018 Fouling mechanism elucidation in membrane bioreactors by bespoke physical cleaning. *Sep. Purif. Technol.* **199**, 124–133. <https://doi.org/10.1016/j.seppur.2018.01.049>.
- Drews, A. 2010 Membrane fouling in membrane bioreactors – characterisation, contradictions, cause and cures. *J. Memb. Sci.* **363**, 1–28. <https://doi.org/10.1016/J.MEMSCI.2010.06.046>.
- Drews, A., Arellano-Garcia, H., Schöneberger, J., Schaller, J., Kraume, M. & Wozny, G. 2007 Improving the efficiency of membrane bioreactors by a novel model-based control of membrane filtration. *Comput. Aided Chem. Eng.* **24**, 345–350. [https://doi.org/10.1016/S1570-7946\(07\)80081-2](https://doi.org/10.1016/S1570-7946(07)80081-2).
- Fenu, A., Guglielmi, G., Jimenez, J., Spèrandio, M., Saroj, D., Lesjean, B., Brepols, C., Thoeve, C. & Nopens, I. 2010 Activated sludge model (ASM) based modelling of membrane bioreactor (MBR) processes: a critical review with special regard to MBR specificities. *Water Res.* **44**, 4272–4294. <https://doi.org/10.1016/J.WATRES.2010.06.007>.
- Ferrero, G., Monclús, H., Sancho, L., Garrido, J. M., Comas, J. & Rodríguez-Roda, I. 2011 A knowledge-based control system for air-scour optimisation in membrane bioreactors. *Water Sci. Technol.* **63**, 2025–2031.
- Ferrero, G., Rodríguez-Roda, I. & Comas, J. 2012 Automatic control systems for submerged membrane bioreactors: a state-of-the-art review. *Water Res.* **46** (11), 3421–3433.
- González, E., Díaz, O., Vera, L., Rodríguez-Gómez, L. E. & Rodríguez-Sevilla, J. 2018 Feedback control system for filtration optimisation based on a simple fouling model dynamically applied to membrane bioreactors. *J. Memb. Sci.* **552**, 243–252. <https://doi.org/10.1016/J.MEMSCI.2018.02.007>.
- Grau, P., de Gracia, M., Vanrolleghem, P. A. & Ayesa, E. 2007 A new plant-wide modelling methodology for WWTPs. *Water Res.* **41**, 4357–4372. <https://doi.org/10.1016/j.watres.2007.06.019>.
- Hamed, H., Ehteshami, M., Mirbagheri, S. A., Rasouli, S. A. & Zendejboudi, S. 2019 Current status and future prospects of membrane bioreactors (MBRs) and fouling phenomena: a systematic review. *Can. J. Chem. Eng.* **97**, 32–58. <https://doi.org/10.1002/cjce.23345>.
- Huyskens, C., Brauns, E., Van Hoof, E., Diels, L. & De Wever, H. 2011 Validation of a supervisory control system for energy savings in membrane bioreactors. *Water Res.* **45**, 1443–1453. <https://doi.org/10.1016/J.WATRES.2010.11.001>.
- Janus, T. & Ulanicki, B. 2016 Integrated benchmark simulation model of an immersed membrane bioreactor. *Process Saf. Environ. Prot.* **104**, 24–37. <https://doi.org/10.1016/j.psep.2016.08.005>.
- Kalboussi, N., Harmand, J., Rapaport, A., Bayen, T., Ellouze, F. & Ben Amar, N. 2018 Optimal control of physical backwash strategy – towards the enhancement of membrane filtration process performance. *J. Memb. Sci.* **545**, 38–48. <https://doi.org/10.1016/J.MEMSCI.2017.09.053>.
- Langergraber, G., Rieger, L., Winkler, S., Alex, J., Wiese, J., Owerdieck, C., Ahnert, M., Simon, J. & Maurer, M. 2004 A guideline for simulation studies of wastewater treatment plants. *Water Sci. Technol.* **50** (7), 131–138. <https://doi.org/10.2166/wst.2004.0436>.
- Lee, Y., Cho, J., Seo, Y., Lee, J. W. & Ahn, K.-H. 2002 Modeling of submerged membrane bioreactor process for wastewater treatment. *Desalination* **146**, 451–457. [https://doi.org/10.1016/S0011-9164\(02\)00543-X](https://doi.org/10.1016/S0011-9164(02)00543-X).
- Liu, M., Yang, M., Chen, M., Yu, D., Zheng, J., Chang, J., Wang, X., Ji, C. & Wei, Y. 2018 Numerical optimization of membrane module design and operation for a full-scale submerged MBR by computational fluid dynamics. *Bioresour. Technol.* **269**, 300–308. <https://doi.org/10.1016/j.biortech.2018.08.089>.
- Liu, X., Wang, Y., Shi, Y., Li, Q., Dai, P., Guan, J., Waite, T. D. & Leslie, G. 2019 CFD modelling of uneven flows behaviour in flat-sheet membrane bioreactors: from bubble generation to shear stress distribution. *J. Memb. Sci.* **570–571**, 146–155. <https://doi.org/10.1016/j.memsci.2018.10.040>.
- Lohaus, J., Perez, Y. M. & Wessling, M. 2018 What are the microscopic events of colloidal membrane fouling? *J. Memb. Sci.* **553**, 90–98. <https://doi.org/10.1016/j.memsci.2018.02.023>.
- Lu, W.-M. & Hwang, K.-J. 1993 Mechanism of cake formation in constant pressure filtrations. *Sep. Technol.* **3**, 122–132. [https://doi.org/10.1016/0956-9618\(93\)80012-G](https://doi.org/10.1016/0956-9618(93)80012-G).
- Mannina, G. & Di Bella, G. 2012 Comparing two start-up strategies for MBRs: experimental study and mathematical modelling. *Biochem. Eng. J.* **68**, 91–103.
- Mannina, G., Di Bella, G. & Viviani, G. 2011 An integrated model for biological and physical process simulation in membrane bioreactors (MBRs). *J. Memb. Sci.* **376**, 56–69. <https://doi.org/10.1016/J.MEMSCI.2011.04.005>.
- Mannina, G., Cosenza, A. & Ekama, G. A. 2017 Greenhouse gases from membrane bioreactors: mathematical modelling, sensitivity and uncertainty analysis. *Bioresour. Technol.* **239**, 353–367.
- Mannina, G., Cosenza, A. & Ekama, G. A. 2018a A comprehensive integrated membrane bioreactor model for greenhouse gas emissions. *Chem. Eng. J.* **334**, 1563–1572.
- Mannina, G., Cosenza, A., Viviani, G. & Ekama, G. A. 2018b Sensitivity and uncertainty analysis of an integrated ASM2d MBR model for wastewater treatment. *Chem. Eng. J.* **351**, 579–588.
- Mannina, G., Cosenza, A. & Ekama, G. 2018c Mathematical modelling of greenhouse gas emissions from membrane bioreactors: a comprehensive comparison of two mathematical models. *Bioresour. Technol.* **268**, 107–115. <https://doi.org/10.1016/J.BIORTECH.2018.07.106>.
- Mannina, G., Pandey, A., Larroche, C., Ng, H. Y. & Ngo, H. H. 2020a *Current Developments in Biotechnology and Bioengineering: Advanced Membrane Separation Processes for Sustainable Water and Wastewater Management – Case Studies and Sustainability Analysis*. Elsevier, Amsterdam, The Netherlands.
- Mannina, G., Ni, B.-J., Rebouças, T. F., Cosenza, A. & Olsson, G. 2020b Minimizing membrane bioreactor environmental footprint by multiple objective optimization. *Bioresour. Technol.* **302**, 122824.

- Massara, T. M., Solís, B., Guisasola, A., Katsou, E. & Baeza, J. A. 2018 Development of an ASM2d-N<sub>2</sub>O model to describe nitrous oxide emissions in municipal WWTPs under dynamic conditions. *Chem. Eng. J.* **335**, 185–196. <https://doi.org/10.1016/j.cej.2017.10.119>.
- Monclús, H., Buttiglieri, G., Ferrero, G., Rodriguez-Roda, I. & Comas, J. 2012 Knowledge-based control module for start-up of flat sheet MBRs. *Bioresour. Technol.* **106**, 50–54. <https://doi.org/10.1016/J.BIORTECH.2011.12.001>.
- Naessens, W., Maere, T. & Nopens, I. 2012a Critical review of membrane bioreactor models – part 1: biokinetic and filtration models. *Bioresour. Technol.* **122**, 95–106. <https://doi.org/10.1016/J.BIORTECH.2012.05.070>.
- Naessens, W., Maere, T., Ratkovich, N., Vedantam, S. & Nopens, I. 2012b Critical review of membrane bioreactor models – part 2: hydrodynamic and integrated models. *Bioresour. Technol.* **122**, 107–118. <https://doi.org/10.1016/J.BIORTECH.2012.05.071>.
- Ng, A. N. L. & Kim, A. S. 2007 A mini-review of modeling studies on membrane bioreactor (MBR) treatment for municipal wastewaters. *Desalination* **212**, 261–281. <https://doi.org/10.1016/J.DESAL.2006.10.013>.
- Odrizola, J., Beltrán, S., Dalmau, M., Sancho, L., Comas, J., Rodríguez-Roda, I. & Ayesa, E. 2017 Model-based methodology for the design of optimal control strategies in MBR plants. *Water Sci. Technol.* **75**, 2546–2553. <https://doi.org/10.2166/wst.2017.135>.
- Park, P.-K., Lee, C.-H. & Lee, S. 2006 Permeability of collapsed cakes formed by deposition of fractal aggregates upon membrane filtration. *Environ. Sci. Technol.* **40**, 2699–2705. <https://doi.org/10.1021/es0515304>.
- Perera, M. K., Englehardt, J. D., Tchobanoglous, G. & Shamskhorzani, R. 2017 Control of nitrification/denitrification in an onsite two-chamber intermittently aerated membrane bioreactor with alkalinity and carbon addition: model and experiment. *Water Res.* **115**, 94–110. <https://doi.org/10.1016/j.watres.2017.02.019>.
- Picioreanu, C., Kreft, J.-U. & van Loosdrecht, M. C. M. 2004 Particle-based multidimensional multispecies biofilm model. *Appl. Environ. Microbiol.* **70**, 3024–3040. <https://doi.org/10.1128/AEM.70.5.3024-3040.2004>.
- Rieger, L., Gillot, S., Langergraber, G., Ohtsuki, T., Shaw, A., Takacs, I. & Winkler, S. 2013 *Guidelines for Using Activated Sludge Models*. IWA Publishing, London, UK.
- Robles, A., Ruano, M. V., Ribes, J., Seco, A. & Ferrer, J. 2014 Model-based automatic tuning of a filtration control system for submerged anaerobic membrane bioreactors (AnMBR). *J. Memb. Sci.* **465**, 14–26. <https://doi.org/10.1016/j.memsci.2014.04.012>.
- Sarioglu, M., Insel, G. & Orhon, D. 2012 Dynamic in-series resistance modeling and analysis of a submerged membrane bioreactor using a novel filtration mode. *Desalination* **285**, 285–294. <https://doi.org/10.1016/J.DESAL.2011.10.015>.
- Schmitt, F. & Do, K.-U. 2017 Prediction of membrane fouling using artificial neural networks for wastewater treated by membrane bioreactor technologies: bottlenecks and possibilities. *Environ. Sci. Pollut. Res.* **24**, 22885–22913. <https://doi.org/10.1007/s11356-017-0046-7>.
- Shin, J., Kim, K., Kim, J. & Lee, S. 2013 Development of a numerical model for cake layer formation on a membrane. *Desalination* **309**, 213–221. <https://doi.org/10.1016/j.desal.2012.10.018>.
- Smith, P. J., Vigneswaran, S., Ngo, H. H., Ben-Aim, R. & Nguyen, H. 2006 A new approach to backwash initiation in membrane systems. *J. Memb. Sci.* **278**, 381–389. <https://doi.org/10.1016/J.MEMSCI.2005.11.024>.
- Sun, J., Liang, P., Yan, X., Zuo, K., Xiao, K., Xia, J., Qiu, Y., Wu, Q., Wu, S., Huang, X., Qi, M. & Wen, X. 2016 Reducing aeration energy consumption in a large-scale membrane bioreactor: process simulation and engineering application. *Water Res.* **93**, 205–213. <https://doi.org/10.1016/j.watres.2016.02.026>.
- Vargas, A., Moreno-Andrade, I. & Buitrón, G. 2008 Controlled backwashing in a membrane sequencing batch reactor used for toxic wastewater treatment. *J. Memb. Sci.* **320**, 185–190. <https://doi.org/10.1016/J.MEMSCI.2008.03.073>.
- Vera, L., González, E., Díaz, O. & Delgado, S. 2014 Application of a backwashing strategy based on transmembrane pressure set-point in a tertiary submerged membrane bioreactor. *J. Memb. Sci.* **470**, 504–512. <https://doi.org/10.1016/j.memsci.2014.07.069>.
- Verrecht, B., Judd, S., Guglielmi, G., Brepols, C. & Mulder, J. W. 2008 An aeration energy model for an immersed membrane bioreactor. *Water Res.* **42**, 4761–4770. <https://doi.org/10.1016/j.watres.2008.09.013>.
- Villarroel, R., Delgado, S., González, E. & Morales, M. 2013 Physical cleaning initiation controlled by transmembrane pressure set-point in a submerged membrane bioreactor. *Sep. Purif. Technol.* **104**, 55–63. <https://doi.org/10.1016/J.SEPPUR.2012.10.047>.
- Wang, Z., Ma, J., Tang, C. Y., Kimura, K., Wang, Q. & Han, X. 2014 Membrane cleaning in membrane bioreactors: a review. *J. Memb. Sci.* **468**, 276–307. <https://doi.org/10.1016/j.memsci.2014.05.060>.
- Wicklein, E., Batstone, D. J., Ducoste, J., Laurent, J., Griborio, A., Wicks, J., Saunders, S., Samstag, R., Potier, O. & Nopens, I. 2016 Good modelling practice in applying computational fluid dynamics for WWTP modelling. *Water Sci. Technol.* **73**, 969–982. <https://doi.org/10.2166/wst.2015.565>.
- Wintgens, T., Rosen, J., Melin, T., Brepols, C., Drensla, K. & Engelhardt, N. 2003 Modelling of a membrane bioreactor system for municipal wastewater treatment. *J. Memb. Sci.* **216**, 55–65. [https://doi.org/10.1016/S0376-7388\(03\)00046-2](https://doi.org/10.1016/S0376-7388(03)00046-2).
- Wisniewski, K., Kowalski, M. & Makinia, J. 2018 Modeling nitrous oxide production by a denitrifying-enhanced biologically phosphorus removing (EBPR) activated sludge in the presence of different carbon sources and electron acceptors. *Water Res.* **142**, 55–64. <https://doi.org/10.1016/j.watres.2018.05.041>.
- Xiao, K., Liang, S., Wang, X., Chen, C. & Huang, X. 2019 Current state and challenges of full-scale membrane bioreactor applications: a critical review. *Bioresour. Technol.* **271**,



- 473–481. <https://doi.org/10.1016/J.BIORTECH.2018.09.061>.
- Yoon, S.-H., Lee, C.-H., Kim, K.-J. & Fane, A. G. 1999 Three-dimensional simulation of the deposition of multi-dispersed charged particles and prediction of resulting flux during cross-flow microfiltration. *J. Memb. Sci.* **161**, 7–20. [https://doi.org/10.1016/S0376-7388\(99\)00049-6](https://doi.org/10.1016/S0376-7388(99)00049-6).
- Yusuf, Z., Abdul Wahab, N. & Sahlan, S. 2016 Fouling control strategy for submerged membrane bioreactor filtration processes using aeration airflow, backwash, and relaxation: a review. *Desalin. Water Treat.* **57**, 17683–17695. <https://doi.org/10.1080/19443994.2015.1086893>.
- Zarragoitia-González, A., Schetrite, S., Alliet, M., Jáuregui-Haza, U. & Albasi, C. 2008 Modelling of submerged membrane bioreactor: conceptual study about link between activated sludge biokinetics, aeration and fouling process. *J. Memb. Sci.* **325**, 612–624. <https://doi.org/10.1016/J.MEMSCI.2008.08.037>.
- Zarragoitia, A., Schetrite, S., Jáuregui-Haza, U. J., Lorain, O. & Albasi, C. 2009 Optimization of wastewater filtration process in submerged membrane bioreactors: applicability of a dynamic model to scale up. *Comput. Aided Chem. Eng.* **27**, 1545–1550. [https://doi.org/10.1016/S1570-7946\(09\)70648-0](https://doi.org/10.1016/S1570-7946(09)70648-0).
- Zhang, J., Chua, H. C., Zhou, J. & Fane, A. G. 2006 Factors affecting the membrane performance in submerged membrane bioreactors. *J. Memb. Sci.* **284**, 54–66. <https://doi.org/10.1016/J.MEMSCI.2006.06.022>.
- Zuthi, M. F. R., Ngo, H. H. & Guo, W. S. 2012 Modelling bioprocesses and membrane fouling in membrane bioreactor (MBR): a review towards finding an integrated model framework. *Bioresour. Technol.* **122**, 119–129. <https://doi.org/10.1016/J.BIORTECH.2012.04.090>.
- Zuthi, M. F. R., Ngo, H. H., Guo, W. S., Zhang, J. & Liang, S. 2013 A review towards finding a simplified approach for modelling the kinetics of the soluble microbial products (SMP) in an integrated mathematical model of membrane bioreactor (MBR). *Int. Biodeterior. Biodegrad.* **85**, 466–473. <https://doi.org/10.1016/j.ibiod.2013.03.032>.

First received 6 November 2019; accepted in revised form 3 February 2020. Available online 18 February 2020