



Position Paper - Progress towards standards in integrated (aerobic) MBR modelling

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Abstract: Membrane bioreactor 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 a 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.

Keywords: MBR modelling, integrated model, terminology

Introduction

Worldwide membrane bioreactors (MBR) 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). 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 products (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.

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

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8 Building upon previous and recent literature reviews (Chang et al., 2009; Di Bella and
9 Di Trapani, 2019; Hamedi et al., 2019; Naessens et al., 2012a, 2012b) a brief
10 summary and update is given to identify current trends in MBR modelling with
11 special regard to integrated MBR models and the temporal and spatial scale of
12 modelling applications in research and engineering.
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14 In modelling of biological wastewater treatment processes issues with ambiguous
15 terminologies and nomenclature have been addressed previously (Corominas et al.,
16 2010; Rieger et al., 2013). It is examined which of these issues persist in the used
17 MBR models. Based upon the approach of Rieger et al. (2013) a way to provide a
18 common and unambiguous terminology for variables, parameters and processes is
19 proposed.
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22 23 **Updated Literature Review**

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25 **Physico-chemical or mechanical unit operations.** Various computational models
26 have been used to describe and master (physico-chemical or mechanical) unit
27 processes of MBR operations under dynamic conditions. Simple mechanistic
28 approaches have been used to model energy consumption of MBRs based on heuristic
29 rules and models on pumping and aeration energy (Verrecht et al., 2008). Although
30 they can provide information on various design options, these models generally do not
31 predict filtration performance based on membrane fouling.
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34 **Biodegradation.** Activated sludge models (ASM) are well established and widely
35 used (Langergraber et al., 2004; Rieger et al., 2013) and have been applied to simulate
36 biomass kinetics in MBR systems (Fenu et al., 2010). Additional sub-processes or
37 complementary models on different or additional biological pathways can be
38 implemented to describe e.g. greenhouse-gas (GHG) emissions (Mannina et al., 2018;
39 Massara et al., 2018; Wisniewski et al., 2018) and energy consumption (Grau et al.,
40 2007). ASMs have also been modified to include the presence and fate of Soluble
41 Microbial Products (SMPs) which allegedly play an important role in membrane
42 fouling, in so-called hybrid ASM models (Zuthi et al., 2012). Hybrid ASM models
43 could also be used to model the fate of extracellular polymeric substances (EPS) or
44 diluted organic matter.
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48 **Filtration.** Different MBR models have been focusing on the physical aspects of the
49 fouling process by various methods with the aim of describing several processes
50 involved in membrane fouling. Among them, mathematical models are the most
51 widely developed which include empirical hydrodynamic models, conventional mass
52 transfer and tangential filtration models; fractal permeation models, sectional
53 resistance models and RIS Models (Chang et al., 2009; Naessens et al., 2012a; Ng and
54 Kim, 2007).
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57 Regarding the number of publications, RIS models seem to be highly popular.
58 Based on an application of Darcy's law non-stationary mathematical equations are
59 used to describe the total hydraulic resistance. The filtering system (physical
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membrane plus internal and external fouling) is characterized by different resistance contributions which can be correlated to local parameters (cross flow velocity, 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 sum of different resistances-in-series, each related to a specific fouling mechanism: the so-called resistance decomposition (Di Bella and Di Trapani, 2019).

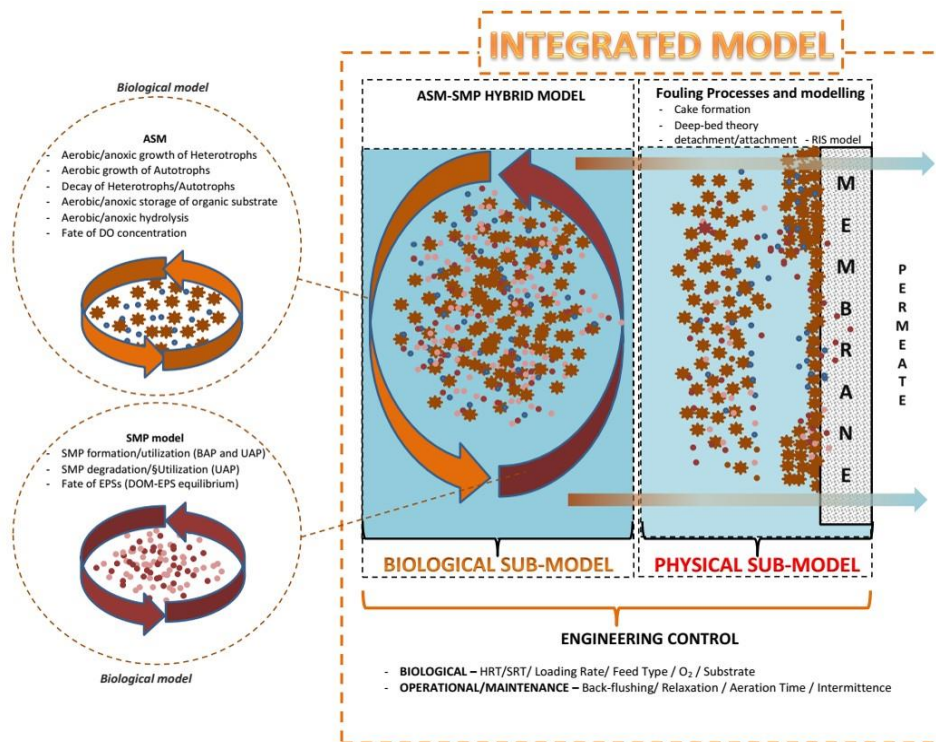


Figure 1 Integrated approach for MBR modelling (RIS: Resistance in Series, HRT: hydraulic retention time, SRT: sludge retention time).

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 pores clogging). The analytical detection and identification of foulants is challenging. Fouling classifications and fouling mechanisms reported in 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 the 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 (Di Bella et al., 2018; Drews, 2010; Wang et al., 2014).

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 above mentioned 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.

Table1 Feature comparison of selected MBR modelling studies using an integrated RIS model approach

Reference / Model features	(Lee et al., 2002)	(Wintgens et al., 2003)	(Di Bella et al., 2008)	(Zarragoitia-González et al., 2008)	(Zarragoitia et al., 2009)	(Mannina et al., 2011)	(Sarıoğlu et al., 2012)	(Zuthi et al., 2012)	(Janus and Ulanicki, 2016)	Mannina et al. 2018a-b
Biological sub-model										
Biomass growth (e.g. X_{rSS})				x	x		x	x		x
ASM (SMP hybrid)	x	x	x			x			x	x
SMP	x		x	x		x		x		x
EPS									x	x
Process sub-models										
Process control				x	x				x	
Energy		x							x	x
Experimental set-up										
Lab-scale					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
Calibration method										
heuristic		x					x	x		
stochastic (e.g. sensitivity analysis)						x		x		x

Alternative models are based on particle size distribution (PSD). Given that the cake layer on the membrane consists of deposited particles of which the submicron sized particles have a negative effect on the structure and porosity of the layer, models are proposed that take into account the particle size distribution and its impact on cake

1 layer build up and the resulting membrane fouling (Broeckmann et al., 2006; Cao et
2 al., 2015; Lu and Hwang, 1993; Park et al., 2006; Picioreanu et al., 2004; Shin et al.,
3 2013; Yoon et al., 1999). Due to the complex and somehow still unknown
4 mechanisms for fouling development, there have been also approaches for data-driven
5 modelling of fouling in MBRs (Ahmad Yasmin et al., 2017; Araujo Pimentel et al.,
6 2016; Dalmau et al., 2015; Schmitt and Do, 2017).

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8 **Model based control.** Several other authors have theoretically analysed and
9 experimentally validated energy savings of different types of advanced control in
10 aerobic MBR technology based on models or knowledge based approaches (Drews et
11 al., 2007; Ferrero et al., 2011; González et al., 2018; Huyskens et al., 2011; Monclús
12 et al., 2012; Villarroel et al., 2013). Process improvements and optimized MBR
13 control strategies (improvement of effluent quality, reduction of fouling and energy
14 costs) can be achieved through model-based methodologies (Kalboussi et al., 2018;
15 Odriozola et al., 2017; Yusuf et al., 2016). Different open-loop and closed-loop
16 control systems have thus been developed and validated for MBRs, even at full-scale
17 (Smith et al., 2006; Vargas et al., 2008; Vera et al., 2014). Model-based approaches
18 are a cost-efficient means to explore operational strategies for both control of
19 biological processes (e.g. nitrification/denitrification) and membrane filtration (Perera
20 et al., 2017; Robles et al., 2014; Sun et al., 2016). Additionally, model-based
21 optimizations are tools in sensitivity and uncertainty analysis of the MBR process
22 operation.
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27 Depending on their experimental set-up, the spatial and temporal scale and the
28 intention of their work authors promote various concepts for fouling modelling or RIS
29 aggregation (see Table 1). The abovementioned papers reveal difficulties in
30 identifying filtration resistances, their combinations and dynamics. Model calibration
31 methods are not likely to be documented or are carried out on constrained data-sets.
32 Models are seldom validated on alternative set-ups or time-lines. Uncertainties in
33 experimental set-ups, analytical methods and model assumptions are generally not
34 evaluated or discussed (Mannina and Di Bella, 2012; Mannina et al., 2017).
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38 **Terminology and Notation**

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40 Terminologies and notations of model parameters are a source of difficulties in
41 comparing concepts and results across reported models. RIS models show overlaps
42 and inconsistencies in their model nomenclature (Di Bella and Di Trapani, 2019),
43 terminology among these models can be ambiguous. These findings resemble the
44 conclusions from an earlier examination of activated sludge models (Corominas et al.,
45 2010; Rieger et al., 2013). It is thus attempted to draw outlines of a notational
46 framework within this paper, while a full and unabridged framework description
47 would exceed the limits of this publication. Still this draft is meant to be
48 undemanding, distinctive, complete and flexible towards future requirements.
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52 One group of state variables is used to describe bulk components which are relevant
53 in the model and which are used in the mass balances of the model. When variables
54 are derived from the biological (ASM) model it is recommended that their notational
55 framework follows existing guidelines (Rieger et al., 2013). In integrated MBR
56 models these are usually linking elements between the biological and filtration model.
57 They can be discriminated by their nature and particle size as well as their
58 degradability, their organic or inorganic origin, the name of the compound and other
59 specifications. Components, which are responsible for membrane fouling can be
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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.

Table 2: Notation of state variables describing bulk components

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

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 and Di Trapani (2019) 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 have 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 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, TMP, permeability. The main symbol can be used to 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.

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 polarisation - CP Pore blocking - PB Pore narrowing- PN		

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 that also RIS simulation studies show weaknesses regarding a 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 seems 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. *Commun. Comput. Inf. Sci.* 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., 2016. Validation of a simple fouling model for a submerged membrane bioreactor. *IFAC-PapersOnLine* 28, 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.* <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. *Lect. Notes Civ. Eng.* 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>

- 1 Corominas, L., Rieger, L., Takács, I., Ekama, G., Hauduc, H., Vanrolleghem, P.A., Oehmen, A.,
2 Gernaey, K. V., Van Loosdrecht, M.C.M., Comeau, Y., 2010. New framework for standardized
3 notation in wastewater treatment modelling. *Water Sci. Technol.*
4 <https://doi.org/10.2166/wst.2010.912>
- 5 Dalmau, M., Atanasova, N., Gabarrón, S., Rodríguez-Roda, I., Comas, J., 2015. Comparison of a
6 deterministic and a data driven model to describe MBR fouling. *Chem. Eng. J.* 260, 300–308.
7 <https://doi.org/10.1016/j.cej.2014.09.003>
- 8 Di Bella, G., Di Trapani, D., 2019. A brief review on the resistance-in-series model in membrane
9 bioreactors (MBRs). *Membranes (Basel)*. 9. <https://doi.org/10.3390/membranes9020024>
- 10 Di Bella, G., Di Trapani, D., Judd, S., 2018. Fouling mechanism elucidation in membrane bioreactors
11 by bespoke physical cleaning. *Sep. Purif. Technol.* 199, 124–133.
12 <https://doi.org/10.1016/j.seppur.2018.01.049>
- 13 Di Bella, G., Mannina, G., Viviani, G., 2008. An integrated model for physical-biological wastewater
14 organic removal in a submerged membrane bioreactor: Model development and parameter
15 estimation. *J. Memb. Sci.* <https://doi.org/10.1016/j.memsci.2008.05.036>
- 16 Drews, A., 2010. Membrane fouling in membrane bioreactors—Characterisation, contradictions, cause
17 and cures. *J. Memb. Sci.* 363, 1–28. <https://doi.org/10.1016/J.MEMSCI.2010.06.046>
- 18 Drews, A., Arellano-Garcia, H., Schöneberger, J., Schaller, J., Kraume, M., Wozny, G., 2007.
19 Improving the efficiency of membrane bioreactors by a novel model-based control of membrane
20 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)
- 21 Fenu, A., Guglielmi, G., Jimenez, J., Spèrandio, M., Saroj, D., Lesjean, B., Brepols, C., Thoeye, C.,
22 Nopens, I., 2010. Activated sludge model (ASM) based modelling of membrane bioreactor
23 (MBR) processes: A critical review with special regard to MBR specificities. *Water Res.* 44,
24 4272–4294. <https://doi.org/10.1016/J.WATRES.2010.06.007>
- 25 Ferrero, G., Monclús, H., Sancho, L., Garrido, J.M., Comas, J., Rodríguez-Roda, I., 2011. A
26 knowledge-based control system for air-scour optimisation in membrane bioreactors. *Water Sci.*
27 *Technol.* 63, 2025–2031.
- 28 Ferrero, G., Rodríguez-Roda, I., Comas, J., 2012. Automatic control systems for submerged membrane
29 bioreactors: a state-of-the-art review. *Water Res.* 46(11), 3421–3433.
- 30 González, E., Díaz, O., Vera, L., Rodríguez-Gómez, L.E., Rodríguez-Sevilla, J., 2018. Feedback
31 control system for filtration optimisation based on a simple fouling model dynamically applied to
32 membrane bioreactors. *J. Memb. Sci.* 552, 243–252.
33 <https://doi.org/10.1016/J.MEMSCI.2018.02.007>
- 34 Grau, P., de Gracia, M., Vanrolleghem, P.A., Ayesa, E., 2007. A new plant-wide modelling
35 methodology for WWTPs. *Water Res.* 41, 4357–4372.
36 <https://doi.org/10.1016/j.watres.2007.06.019>
- 37 Hamed, H., Ehteshami, M., Mirbagheri, S.A., Rasouli, S.A., Zendehboudi, S., 2019. Current Status
38 and Future Prospects of Membrane Bioreactors (MBRs) and Fouling Phenomena: A Systematic
39 Review. *Can. J. Chem. Eng.* 97, 32–58. <https://doi.org/10.1002/cjce.23345>
- 40 Huyskens, C., Brauns, E., Van Hoof, E., Diels, L., De Wever, H., 2011. Validation of a supervisory
41 control system for energy savings in membrane bioreactors. *Water Res.* 45, 1443–1453.
42 <https://doi.org/10.1016/J.WATRES.2010.11.001>
- 43 Janus, T., Ulanicki, B., 2016. Integrated benchmark simulation model of an immersed membrane
44 bioreactor. *Process Saf. Environ. Prot.* 104, 24–37. <https://doi.org/10.1016/j.psep.2016.08.005>
- 45 Kalboussi, N., Harmand, J., Rapaport, A., Bayen, T., Ellouze, F., Ben Amar, N., 2018. Optimal control
46 of physical backwash strategy - towards the enhancement of membrane filtration process
47 performance. *J. Memb. Sci.* 545, 38–48. <https://doi.org/10.1016/J.MEMSCI.2017.09.053>
- 48 Langergraber, G., Rieger, L., Winkler, S., Alex, J., Wiese, J., Owerdieck, C., Ahnert, M., Simon, J.,
49 Maurer, M., 2004. A guideline for simulation studies of wastewater treatment plants. *Water Sci.*
50 *Technol.*
- 51 Lee, Y., Cho, J., Seo, Y., Lee, J.W., Ahn, K.-H., 2002. Modeling of submerged membrane bioreactor
52 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)
- 53 Liu, M., Yang, M., Chen, M., Yu, D., Zheng, J., Chang, J., Wang, X., Ji, C., Wei, Y., 2018. Numerical
54 optimization of membrane module design and operation for a full-scale submerged MBR by
55 computational fluid dynamics. *Bioresour. Technol.* 269, 300–308.
56 <https://doi.org/10.1016/j.biortech.2018.08.089>
- 57 Liu, X., Wang, Y., Shi, Y., Li, Q., Dai, P., Guan, J., Waite, T.D., Leslie, G., 2019. CFD modelling of
58 uneven flows behaviour in flat-sheet membrane bioreactors: From bubble generation to shear
59
60
61
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63
64
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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/https://doi.org/10.1016/0956-9618\(93\)80012-G](https://doi.org/https://doi.org/10.1016/0956-9618(93)80012-G)
- Mannina, G., Cosenza, A., Ekama, G., 2018. 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., 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.2011.04.003>
- Massara, T.M., Solís, B., Guisasaola, A., Katsou, E., Baeza, J.A., 2018. Development of an ASM2d-N2O 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., Rodríguez-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>
- Odroizola, 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., Lagergraber, G., Ohtsuki, T., Shaw, A., Takacs, I., 2013. Guidelines for Using Activated Sludge Models, Scientific. ed. IWA Publishing, London.
- 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, in: *Computer Aided Chemical Engineering*. [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>