Integrated membrane bioreactors modelling: A review on new comprehensive modelling framework

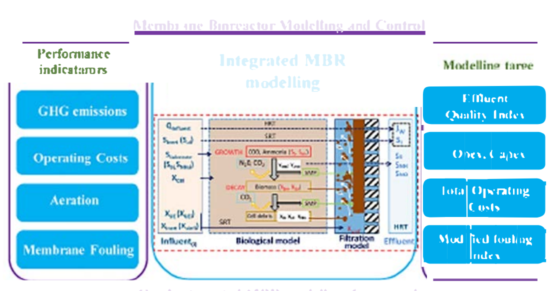
Giorgio Mannina[a,*], Marion Alliet[b], Christoph Brepols[c], Joaquim Comas[d,e], Jerome Harmand[f], Marc Heran[g], Nesrine Kalboussi[h], Jacek Makinia[i], Ángel Robles[j], Taise Ferreira Rebouças[a], Bing-Jie Ni[k], Ignasi Rodriguez-Roda[d,e], María Victoria Ruano[j], Giorgio Bertanza[l], Ilse Smets[m]

[a] *Engineering Department, Palermo University, Viale delle Scienze, Ed.8, 90128 Palermo, Italy*
[b] *Laboratoire de Génie Chimique, Université de Toulouse, CNRS, INPT, UPS, Toulouse, France*
[c] *Erftverband, Am Erftverband 6, 50126 Bergheim, Germany*
[d] *Catalan Institute for Water Research (ICRA), Emili Grahit 101, 17003 Girona, Spain*
[e] *LEQUiA, Laboratory of Chemical and Environmental Engineering, University of Girona, Campus Montilivi, 17071 Girona, Spain*
[f] *LBE, Univ. Montpellier, INRAE, Narbonne, France*
[g] *IEM, Univ. Montpellier, CNRS, ENSCM, Montpellier, France*
[h] *Université de Carthage, Institut National ds Sciences Appliquées et de Technologie & Université de Tunis El Manar, Ecole Nationale d'Ingénieurs de Tunis, Laboratoire de Modélisation Mathématique et Numérique dans les sciences d'ingénieur, Tunis, Tunisia*
[i] *Faculty of Civil and Environmental Engineering, Gdansk University of Technology, ul. Narutowicza 11/12, 80-233 Gdansk, Poland*
[j] *Departament d'Enginyeria Química, Escola Tecnica Superior d'Enginyeria (ETSE-UV), Universitat de València, Avinguda de la Universitat s/n, 46100 Burjassot, València, Spain*
[k] *Centre for Technology in Water and Wastewater, School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, New South Wales 2007, Australia*
[l] *Departament of Civil, Environmental, Architectural Engineering and Mathematics, Brescia University, via Branze 43, 25123 Brescia, Italy*
[m] *Department of Chemical Engineering, KU Leuven, Celestijnenlaan 200F Box 2424, 3001 Heverlee, Belgium*

HIGHLIGHTS

- A literature review on integrated MBR modelling and control is presented.
- The use of integrated MBR models should be more encouraged.
- A new framework was proposed to pursue good practice for MBR modelling.
- Integrated MBR modelling applications to real case studies is needed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
High environmental sustainability
Biological processes

ABSTRACT

Integrated Membrane Bioreactor (MBR) models, combination of biological and physical models, have been representing powerful tools for the accomplishment of high environmental sustainability. This paper, produced by the International Water Association (IWA) Task Group on Membrane Modelling and Control, reviews the state-of-the-art, identifying gaps for future researches, and proposes a new integrated MBR modelling framework.

* Corresponding author.
E-mail address: giorgio.mannina@unipa.it (G. Mannina).

https://doi.org/10.1016/j.biortech.2021.124828

Performance indicators
Modelling framework

In particular, the framework aims to guide researchers and managers in pursuing good performances of MBRs in terms of effluent quality, operating costs (such as membrane fouling, energy consumption due to aeration) and mitigation of greenhouse gas emissions.

1. Introduction

The application of mathematical models to wastewater treatment plants (WWTPs) or water resource recovery facilities (WRRFs) is widely used in view of providing more accurate answers for design, management, optimization and control issues (Zhang et al., 2021; Zuthi et al., 2012). Indeed, since the 80 s they have been representing a powerful tool to understand the several features related to the treatment process (Martin & Vanrolleghem, 2014; Hamedi et al., 2019). The Activated Sludge Model (ASM) series represent the highlight concerning WWTP modelling since they are considered a reliable tool to assess the main features related to wastewater treatment. They were first applied to traditional activated sludge (AS) systems, consisting of a bioreactor and a secondary clarifier, and evolved to accompany more advanced technologies, such as aerobic membrane bioreactors (MBRs). MBRs came to light as an advanced treatment technology with the ability to provide an effluent with higher quality to comply with strict regulation limits, reduce sludge production, require less space, and have potential for upgrading existing WWTPs and implementing water reuse (Judd, 2006; Krzeminski et al., 2017; Zuthi et al., 2017; Zheng et al., 2018). Recent studies have reported that the implementation of aerobic MBRs is increasing over the years due to their many advantages over conventional treatment technologies (Deng et al., 2016; Meng et al., 2017). Attempts to combine membranes with the activated sludge process were already made 50 years ago (Smith et al., 1969). The first full-scale commercial applications of aerobic MBRs were reported in the late 1970s in North America (Smith et al., 1969), and early 1980s (Japan).

MBRs use micro- or ultra-filtration membranes for the phase (solid–liquid) separation. The nominal pore size of membrane filters is typically 0.02–0.2 µm. While smaller dissolved fractions (e.g. humic and low-molecular-weight substances) pass through the membrane, larger particles are mostly retained. Typical examples of such large particles include flocs, bacteria and organic colloids (Fenu et al., 2010).

Following the spread of aerobic MBR technology, mathematical models advanced to include the unit process of membrane filtration. From a modelling point of view, MBR differs from conventional activated sludge systems (CAS) not only due to the physical separation but also due to the need for integrating the biological and physical treatment features, which is one of the biggest challenges faced by researchers (Zuthi et al., 2012; Naessens et al., 2012). To address this issue, integrated MBR models were introduced in the literature (Zarragoitia-González et al., 2008; Di Bella et al., 2008).

Despite the existence of such models, there is a pressing demand for the updating of integrated models to consider the numerous new targets that were brought into the current MBR's situation, such as fulfilment of more and more restrictive legal effluent requirements, or improvements for several key performance indicators (KPI): energy consumption and overall operating costs, greenhouse gas (GHG) emissions, land use, social acceptance, or resource consumption (Puyol et al., 2016; Bozkurt et al., 2016; Atanasova et al., 2017; Mannina et al., 2017c). However, many questions still remain about the connection between biological and physical processes, especially due to the complexity of the membrane fouling phenomenon (Hamedi et al., 2019).

Some reviews have been published in the past to provide some enlightenment regarding integrated MBR modelling (Ng & Kim, 2007; Zuthi et al., 2012, 2013), which have not been updated ever since. Additionally, as far as the authors are aware, none of these works have presented any kind of review focused on MBR multi-objective assessments through integrated modelling. Therefore, the first goal of this paper is to provide an up-to-date review of the current scenario involving integrated MBR modelling identifying gaps for future researches. The second goal focusses on establishing the basis to propose a framework focused on best modelling practice of aerobic MBRs, also highlighting future needs to achieve this goal. A framework for good MBR modelling practice can be employed for the design, operation, optimisation and management of MBR systems involving multiple-targets: effluent quality, membrane fouling, energy consumption and overall operating costs, and mitigation of GHG emissions, among others.

2. Motivation of integrated MBR modelling

In this section, we present a number of arguments to illustrate the necessity of considering coupled biological and physical principles to come up with what will be named hereafter "integrated models". Continuous MBRs do not operate "continuously" but often "intermittently" mainly due to the necessary backwash or relaxation phases subject but also due to fluctuating influent flows. Such intermittently operated processes, also known as production/regeneration systems, present the fundamental characteristic of never working at steady-state.

Thus, during the treatment phase, the biomass leads to a set of complex phenomena which may cause a progressive fouling of the membrane; during backwash/relaxation phase, the matter accumulated onto the membranes is washed off out in order, ideally, to recover its original filtering properties. In practice, the presence of "irreversible and/or irrecoverable fouling" phenomena leads to the fact that after the backwash we do not find exactly the initial filtration properties but conditions in which these properties slowly degrade backwash after backwash. In the long term, such a phenomenon must be solved by operators. However, to remain as pedagogic as possible, this is not explicitly considered in the very simple model (as the one represented above by Eqs. (1)–(6)). During these phases, complex feedbacks - of both biological and physical natures - are exerted on the variables of the system and influence their dynamics. Biological dynamics are highly dependent on different factors, such as the nature of the influent (i.e. flow and content in particulate matter), the structure of the biomass, the aeration power, etc. These characteristics highly influence the fouling propensity of the bioreactor content. Conversely, the application of a transmembrane pressure (TMP) leads to the attachment of the particulate matter and of certain molecules on the membrane and in its pores, gradually blocking the outlet flow. Due to the corresponding elevated TMPs, more severe cross flow velocities of the sludge mixture or higher air scouring flows need to be applied which affect the bioflocculation structure of the biomass and, hence, its activity and again its filterability. Indirectly, biological parameters (sludge concentration, kinetics, etc…) may also be influenced. Thus, biology – of the biological process – influences the physical phenomenon – the filtering of the medium through the membrane – and vice versa. To illustrate the direct influence of the filtration process on the dynamics of biological variables, consider the simplest school case in which a biomass *X* would grow on a single substrate *S* in a bioreactor with a perfect membrane separating soluble (*S*) and particulate matter (*X*). Assume the system is operating at constant TMP and that the flux decreases over time due to the attachment of matter onto the membrane (named *M*). The simplest model of such a situation would be written as follows during the filtration phase:

$$\dot{X} \quad \mu(S) \quad \alpha D(M))X \tag{1}$$

$$\dot{S} \quad (S_{in} \quad S_{out})D(M) \quad \frac{1}{Y}\mu(S)X \tag{2}$$

$$\dot{M} \quad \beta\alpha D(M)X \tag{3}$$

where, μ is the kinetics of the biomass, S_{in} is the input substrate concentration, Y is a yield coefficient, $D(M)$ is the flow rate going through the reactor (assumed to be a decreasing function of M bounded by 0 when M equals a limit value M^*), α and β are kinetics and scaling parameters (notice that X will rather be in concentration and M in mass).

During the backwash/relaxation phase, this simplest model would be written as follows:

$$\dot{X} \quad \rho M \tag{4}$$

$$\dot{S} \quad 0 \tag{5}$$

$$\dot{M} \quad \gamma M \tag{6}$$

where, ρ and γ are kinetics and scaling parameters.

There are many hypotheses behind this simple model (no oxygen limitation, no biomass decay, etc…), but assuming an alternating functioning of the system, we immediately see that:

1. Except X_{eq} 0, the model does not exhibit any constant steady state: whatever the initial conditions, the system evolves such that M tends towards M*, then D 0 and the system is switched to the regeneration mode until the membrane recovers (M be small enough), and then the system is switched back to the production mode, etc…
2. Because of the feedback of the membrane (the physical device) on the flux, the membrane exerts a direct feedback on the dynamics of the biological variables.
3. Notice finally that even if the biomass is considered to be at what is called a "pseudo steady state", the fact that D depends explicitly on M – which can precisely be seen as a feedback of physical phenomena on biology – introduces a "continuous dynamical behaviour".

As a consequence, such a system cannot be modelled by a "biological compartment" followed by a model describing the physical behaviour of the membrane: the coupling of both must be necessarily taken into account to finally come up with what will be named hereafter an "integrated model". Looking at Fig. 1, it can be noticed that direct feedbacks of the physical compartment on the biology of the AS could also be considered in the sense, for instance, where the quantity of attached biomass M could directly impact the biomass growth kinetics in the medium. The modelling of such feedback obviously opens up instigating research perspectives that are, however, out of the scope of the present paper.

3. Integrated MBR models

3.1. Classification

Since the MBR invention, several efforts have been employed to improve their operation strategies and to prevent their known limitations (mainly membrane fouling issues) from affecting the viability of the technology expansion. One of the challenges was to understand how the biological treatment communicates with the physical one, which led to the necessity of combining biological models with membrane filtration models (Wintgens et al., 2003; Di Bella et al., 2008). From this point and based on the available literature, four types of aerobic MBR models are generally described in the literature: biological, hybrid, physical, and integrated.

Biological models refer to the unmodified ASM models, formerly developed to describe both the kinetics and the stoichiometry for biological nutrient removal activated sludge systems (Henze et al., 1987; 1995), which are also used for modelling aerobic MBRs (Fenu et al., 2010). The called hybrid models in fact are just modified versions of the ASM family, which were adapted including new state variables to take into account mainly the soluble microbial products (SMP) and extracellular polymeric substances (EPS) formation and degradation processes (Zuthi et al., 2012), thus we will consider them as biological models in this paper. Other authors (Galinha et al., 2018) define "MBR hybrid modelling" as the combination of a mechanistic model (ASM based) with non-mechanistic models (for membrane filtration mainly), but we have focussed our review on mechanistic models, so we will not take this definition into consideration. On the other hand, the physical

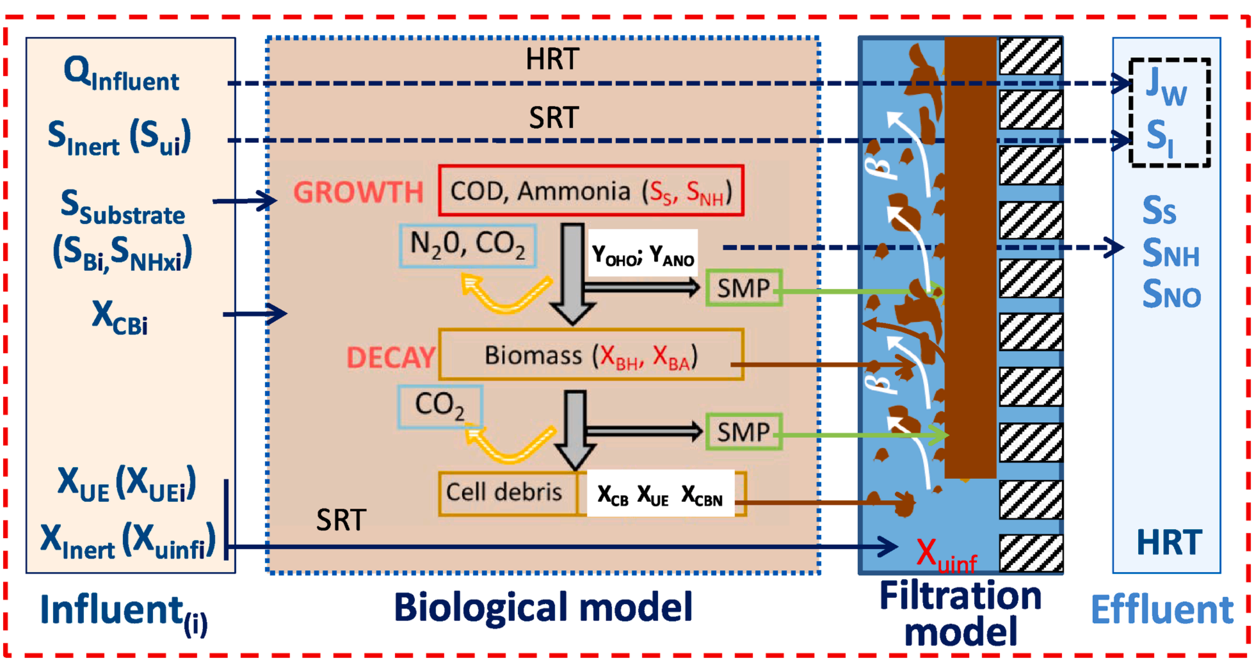


Fig. 1. Example of a schematic representation of integrated MBR models and correlations (Where S_u:= soluble undegradable organics; S_B:= soluble biodegradable organics; S_{NHx}:= soluble biodegradable ammonia; X_{CB}:= particulate biodegradable organics; X_{CB}:= particulate biodegradable organics; X_{ue}:= Particulate undegradable endogenous products ; Y_{OHO}:= yield coefficient of heterotrophic biomass; Y_{ANO}:= yield coefficient of autotrophic biomass; Xcb:= particulate biodegradable carbon, X_{UE}:= particulate substances; X_{CBN}:= particulate nitrogen.

models consider the liquid–solid separation process promoted by the membrane filtration. In particular, the following processes are generally taken into account (Mannina et al., 2011a): i) cake layer formation during the membrane filtration, permeate backwashing phases, and aeration; ii) pre-filtration throughout the cake layer (biological membrane effect) leading to removal of organic matter (COD); iii) particle retention by the membrane (physical membrane effect) leading to removal of organic matter (COD); and iv) irreversible membrane fouling (specifically pore narrowing; pore blocking; and influence of SMP on pore fouling). Finally, the integrated MBR models are the combination of the biological models (whatever the nomenclature used by the authors) with the physical model.

Despite the simplified definition provided above, the concept of integrated MBR model is controversial, since the literature still struggles with an agreement regarding their composition. Indeed, a historical overview points out that integrated MBR models were first considered to be a correlation between biological and physical models (Ng & Kim, 2007), without a clear definition regarding the concept of the first model. Indeed, according to Ng & Kim (2007), an integrated MBR model can be defined as the connection between a biological or hybrid models and a physical model. According to Di Bella et al. (2008) and Mannina et al. (2011a), the integrated MBR models are a combination of biological models to describe biomass behaviour and physical models to describe membrane fouling.

In the second part of a review paper, Naessens et al. (2012) presented three types of integrated models for MBR systems: i. models that couple biological and filtration models (with and without the estimation of SMP and EPS); ii. models that integrate population mass balances into the integrated framework; iii. models that integrate cost models into the integrated framework. No formal concept of the integrated approach was presented by Naessens et al. (2012) in this review. The major question retrieved from this work is which boundaries should be given while defining the integrated MBR models since the categorization seems to encompass several aspects related to the whole MBR technology (e.g., calibration of half-saturation coefficients and costs), instead of focusing on the biological and physical aspects that are considered by the MBR modelling. Indeed, a few years later, Mannina et al. (2018a) stated that integrated MBR models combine physical and physical models in order to predict MBR behaviour. This short definition is in agreement with previous literature (Di Bella et al., 2008; Mannina et al., 2011a; Zuthi et al., 2012).

From the aforementioned definitions, one can understand that the use of integrated MBR models is the most comprehensive way to model MBR systems. Some authors employ different approaches not simulating EPS/SMP and obtaining acceptable results (Wintgens et al., 2003; among others). For some other authors, the hybrid models are important because SMPs and EPS are considered one of the main causes of membrane fouling (Drews et al., 2008; Meng et al., 2009; among others). Their formation/degradation processes are known to happen during the biological treatment by means of substrate utilization, biomass decay and cell hydrolysis (Zuthi et al., 2012). The introduction of these aspects in a hybrid model may provide for some cases a reasonable approach to evaluate membrane fouling (Ahn et al., 2006). Some reviews were published on this matter with the aim to address the aspects of MBR biomass kinetic modelling (Zuthi et al., 2012; Scholes et al., 2016), which can be consulted to a more detailed approach.

As for the physical model, literature states that most of them were developed to address membrane fouling issues considering resistance-based equations (Wintgens et al., 2003). In fact, models related to physical aspects mostly differ in terms of complexity. While some consider aspects such as resistance-in-series (RIS) and permeate flux (Lee et al., 2002; Wintgens et al., 2003; Sarioglu et al., 2012; Robles et al., 2013), others assess carbon removal by the cake layer (deep-bed filtration theory), and the effects of reversible and irreversible fouling over permeate flux (Zuthi et al., 2013).

The idea of coupling biological and physical models in a single model leads to a comprehensive prediction of the system's behaviour. Among its main advantages, the integrated MBR models can provide credible estimations for full-scale facilities and validate results obtained on a laboratory scale (Zuthi et al., 2012). They can also surpass the limitations of experimental results, which offer a limited universe of possibilities while the model can present a wide range of scenarios to be considered during a decision-making process (Mannina & Cosenza, 2013; Monclús et al., 2012). In other words, by the use of integrated MBR models, managers are able to explore a variety of operating conditions prior to their application on-site, avoiding waste of environmental, physical and chemical resources which is reflected over plant's performance indicators (e.g., operating costs, energy consumption, effluent quality, etc.).

On the other hand, one of their major problems is related to the selection of default values for crucial information (e.g., biomass growth and decay rates, formation/degradation coefficients, compounds individual fractioning, etc.), because available literature references are scarce/limited and usually related to plants with different characteristics among them (sometimes related only to CAS processes) (Zuthi et al., 2012). Another important issue regards to the model's calibration and uncertainty, which are complex procedures that require time and trustable data (Fenu et al., 2010; Zuthi et al., 2012; Mannina et al., 2010). In addition, models that were calibrated considering lab-scale information may provide underestimated results when applied to full-scale facilities. These liabilities reflect in results that may fit with the researcher's data but fail when applied to other researches (Ni and Yuan, 2015). Sensitivity and uncertainty analysis as well as comprehensive calibration protocols are limited for MBR modelling and their application is needed in view of getting good modelling results (Freni and Mannina, 2010; Mannina et al., 2010; Mannina and Viviani, 2009). Indeed, recently Mannina et al. (2017a); (2018c;)) carried out a study on the assessment of the sensitivity and uncertainty analysis for both an ASM1 and ASM2d integrated (biological and physical) MBR model. Authors were able to pin down the source of uncertainty and most influential parameters in the MBR modelling. The study showed that for the gaseous model outputs 88–93% of the measured data lays inside the confidence bands showing an accurate model prediction. Future studies should focus on the estimation of uncertainty in order to provide a quality of model prediction as well as gaining insights in the dominated processes.

Considering the overall discussion above reported, there is a need to simplify the definition of what is called integrated modelling that has a non-clear and unique definition causing misunderstanding among modellers. In view of that, here we define integrated MBR modelling as the combination of biological and physical models to describe membrane filtration (Fig. 2), assuming that biological models refer to ASM family (adding or not state variables and other processes). Special emphasis should be given to the link between physical and biological models which define the interactions in the integrated model which are, in turns, the main features. Further, there is a continuous exchange of information from the biological to physical model and in some cases vice versa (Mannina et al., 2010). The main advantages of integrated MBR models consist in getting a more comprehensive approach and in having the possibility to better understand the overall involved phenomena (both biological and physical) in view of an optimization. On the other hand, main disadvantages of integrated MBR models are the complexity and larger data set needed for model application respect to simple modelling approaches.

3.2. Historical evolution

Fig. 3 summarises the historical evolution that led to the current integrated MBR models.

As mentioned before, integrated models derive from the ASM-types. The ASMs have evolved from the assessment of biological carbon removal, nitrification, and denitrification in the ASM1 (Henze et al.,

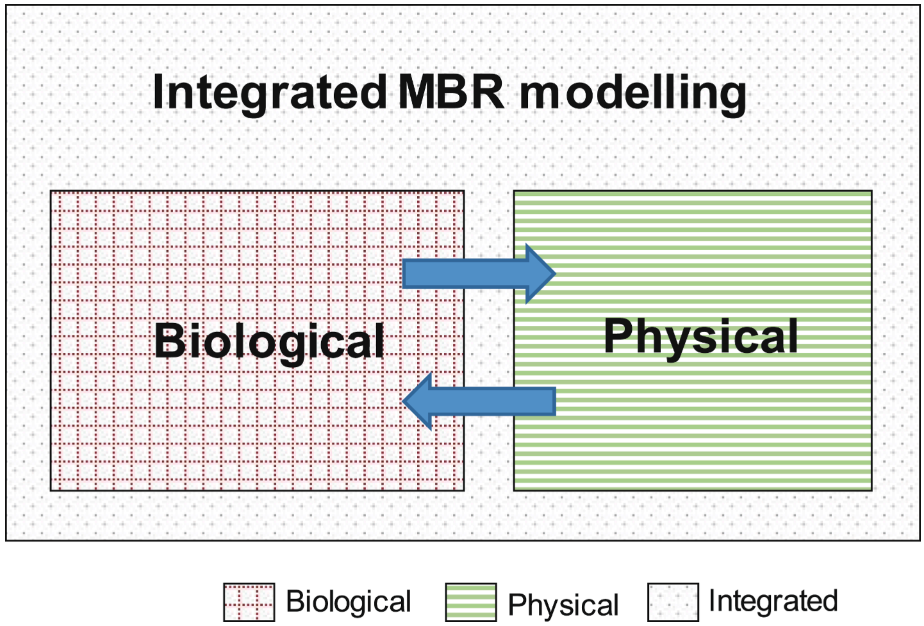


Fig. 2. Schematic representation of integrated MBR models.

1987), to assess SMP and EPS (Orhon et al., 1989), then to include biological phosphorus removal in the ASM2 (Henze et al., 1995), internal cell storage compounds within heterotrophs in the ASM3 (Gujer et al., 1999), and GHG production (ASMN) (Hiatt and Grady, 2008). When MBR started to spread as an advanced treatment technology with many advantages with respect to CAS (Suganthi et al., 2013; Xiao et al., 2014), the development of specific MBR modelling tools was stimulated.

The first concerns about modelling MBR systems arose after the breakthrough for the MBRs proposed by Yamamoto et al. (1989). Indeed, Chaize and Huyard (1991) applied an unmodified ASM1 to an MBR plant to assess its performance and found that the biological model alone provided results in disagreement with the experimental ones, since the ASMs were developed to consider the CAS systems as a reference, which rendered difficult applying an unmodified version to an MBR system. Lately, other attempts were made in view of modelling membrane processes focused on the physical aspects. Nagaoka et al. (1998) developed a mathematical model to simulate temporal changes in suction pressure, flux, and filtration resistance. Additionally, the model considered the accumulation, detachment, and consolidation of EPS on the membrane surface. Despite considering EPS results, this model may not be considered hybrid since no biological assessment was performed during model simulations.

Along with the development of the physical models, even more specific features were included in the biological ones, such as the formation of SMP and EPS (Lu et al., 2001, 2002). Indeed, the fact that SMP/EPS kinetics were already under study by modellers (Namkung and Rittmann, 1986; Orhon et al., 1989; Ahn et al., 2006; Aquino and Stuckey, 2008; Jiang et al., 2008), facilitated the integration of these features into the biological models into a hybrid approach. The modification of the ASM1 held by Lu et al. (2001) may be considered the first application of a hybrid model. Lately, Lu et al. (2002) modified an ASM3 to include the estimation of SMP and EPS. From this point, the first attempts to develop an integrated MBR model were observed (Wintgens et al., 2003; Saroj et al., 2008), although the link between the biological and the filtration models was not clear yet. For example, Saroj et al. (2008) applied an ASM3 with EPS dynamics, coupled with an EPS based filtration model (Ognier et al., 2004), without, however, linking the EPS dynamics with the filtration model. An extensive assessment among published literature demonstrates that the first complete versions of integrated MBR models including SMP/EPS were contemporaneously presented by Zarragoitia-González et al. (2008) and Di Bella et al. (2008). Zarragoitia-González et al. (2008) described a detailed hybrid ASM1-SMP model and simulated the biological-filtration link. The hybrid ASM-SMP model was based on the work of Lu et al. (2001) and Cho et al. (2003); the physical processes were modelled by the filtration model of Li and Wang (2006) where coarse bubble aeration was considered both for the effects of its cycles on the attachment and detachment of the cake layer formation and for the repartition of the fouling along the height of the membrane. The latter model (Di Bella et al., 2008) was similar to the one presented by Zarragoitia-González et al. (2008), except for the physical model, which included the influence of backwashing in the attachment and detachment forces to the cake layer formation (instead of aeration) and, for the first time in an integrated model, including hybrid EPS/SMP modelling, and the removal of COD based on deep-bed filtration theory (Bai and Tien, 2000; Kuberkar and Davis, 2000). Lately, Mannina et al. (2011a) further modified the model proposed by Di Bella et al. (2008) including the sectional approach for the resistance in series (Li and Wang, 2006) and the SMP model by replacing the Lu et al. (2002) model with Jiang et al. (2008). Further, the model calibration was enhanced by considering the protocol proposed by Mannina et al. (2011b) where the global sensitivity analysis (Saltelli et al., 2004) was included to take into account the interactions among the model parameters. In Fig. 4 the main feature of Mannina et al. (2011a) model are reported.

Additional features were added to the ASM family. For example, excess sludge production, oxygen transfer rate, oxygen consumption rate started to be considered (Fenu et al., 2010). Meanwhile, the assessment of SMP and EPS were being updated. Janus & Ulanicki (2010) divided the SMPs between soluble utilization associated products (S_{UAP}) and soluble biomass associated products (S_{BAP}) in accordance with the approach proposed by Laspidou and Rittmann (2002). Their purpose was to provide reliable values of SMP and EPS to be applied whilst modelling MBR processes. Results reported a strong correlation between SMP/EPS and mixed liquor volatile suspended solids (MLVSS) and sludge retention time (SRT), indicating a pathway to be followed in the integration of biological and physical features.

Physical models were also updated, presenting important results that led to the current versions of the integrated models. Wu et al. (2012) developed a combined cake layer and pore fouling model in view of assessing the influence of solid, colloidal and soluble components over

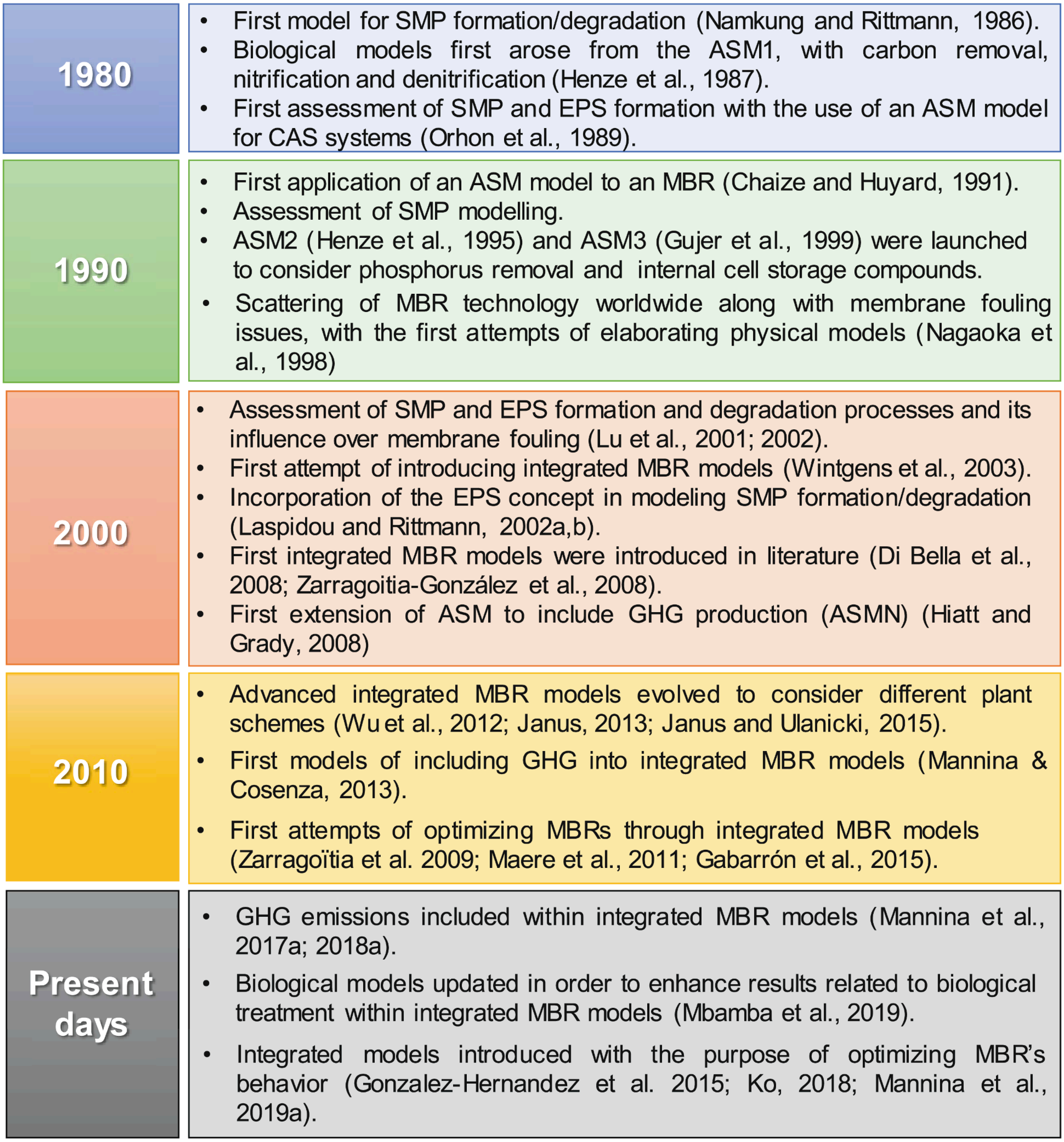


Fig. 3. Historical overview of the key developments for integrated MBR modelling evolution.

membrane fouling. The results were reported to be positive since the model successfully predicted the changes in TMP, and also in cake and pore resistance at various aeration intensities. Indeed, results reported that aeration exerted a significant influence on fouling evolution, which stimulated other modelling approaches in the future.

Since the integrated approach became more spread, several reviews were published to address some issues that still remained unclear (Naessens et al., 2012; Zuthi et al., 2012). One of the main findings of Zuthi et al. (2012) was related to the production and degradation of SMP within an MBR, which can be influenced by the operating specificities of the treatment process, such as longer SRT, feeding ratios, total suspended solids, and MLSS among others. These results not only led to the spread of the integrated MBR models but also to understand that promoting changes in the operating parameters (i.e., to optimize the range of parameters set for MBR functioning) could lead to the optimization of membrane performance. From this point, integrated MBR models started to consider other targets, such as dynamic fouling.

Considering the dynamic fouling, for example, Charfi et al. (2015) and Zuthi et al. (2017) developed a semi-empirical mathematical model that accounts for cake formation and pore-blocking as the major contributor to membrane fouling. This integrated MBR model considers the resistance due to pore blocking (R_{PB}) and the loss of porosity in accordance with the approach of Bowen et al. (1997) and Busch et al. (2007). The model also considered that a pore size reduction is expected due to the adsorption of soluble particles within the pores. The resistance due to cake layer formation (R_{CL}) is obtained by considering the attachment and detachment forces, which lead to a final thickness of the cake after the application of filtration and backwashing fluxes. In the end, the total resistance (R_T) is modelled by means of the resistance-in-series that accounts that R_T is equal to the sum of the membrane intrinsic

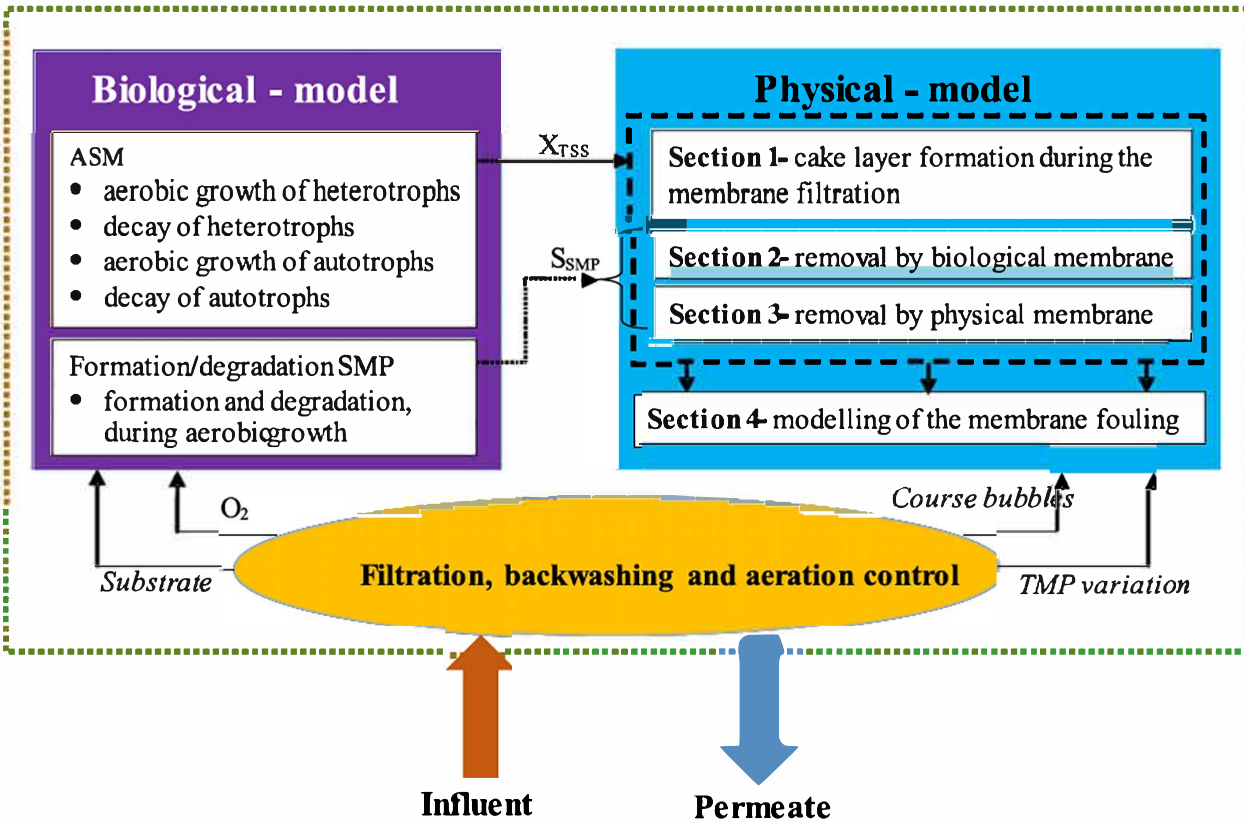


Fig. 4. Integrated MBR model as proposed by Mannina et al. (2011a).

resistance ($R_{It,M}$) plus R_{PB} and R_{CL} SMP was found to be the most important cause of the biofilm formation onto the membrane surface.

A similar physical model was applied by Mannina et al. (2011a). However, R_{CL} was divided into two complementary resistances: the resistance of the stable (and irreversible) cake layer ($R_{Iv,CL}$) and of the dynamic (and reversible) cake layer ($R_{Rv,CL}$). These resistances are also related to the presence of filtration and backwashing fluxes, but $R_{Rv,CL}$ relates to the amount of sludge that detaches from the membrane surface with the influence of aeration, whilst $R_{Iv,CL}$ represents the irreversible cake that can be removed only by means of chemical cleaning. The application of Zuthi et al. (2017) does not include the cross-sectional approach that divides the membrane into equal fractions in order to consider the probability of cake formation according to how distant the section is from the aerator (Zarragoitia-González et al., 2008; Mannina et al., 2011a). This characteristic allows the model to correlate the aeration with membrane fouling, which is a subject that demands more attention from the literature Notations of the above mentioned filtration resistances have been amended according to literature (Brepols et al., 2020).

Indeed, new applications can be found in literature considering the comprehensive physical approach previously presented, with the complete features of a hybrid model. From this point, the integrated models were also able to estimate GHG emissions, since WWTPs were revealed to be responsible for almost 3% of the GHG emissions on a global scale (IPCC, 2013; Koutsou et al., 2018). Mannina et al. (2017a) and Mannina et al. (2018a) presented the first integrated models employing ASM1 and ASM2d, respectively, and taken into account GHGs. Both models modified the nitrogen modelling by considering two steps and four steps for nitrification and denitrification processes, respectively. Further, Mannina et al. (2018b) presented the comparison among two different integrated MBR models applicable to the assessment of nutrient removal, considering two different aspects of nitrification: the Model I applied the nitrification as a one-step process (Hiatt & Grady, 2008), while Model II considered nitrification as a two-step process (Pocquet et al., 2016). The model was applied to understand the influence of both nitrification approaches on GHG emissions. Results showed that Model II had a better capacity to match experimental data as it considers a more comprehensive approach when it comes to nitrous oxide (N_2O) formation by the ammonia-oxidizing bacteria (AOB). This application is important to ensure the consideration of biomass metabolism while modelling GHG emissions and elevates the concerns regarding the application of more accurate kinetic values. Despite the advanced studies presented by Mannina's and co-workers, the models need to be applied to real WWTPs to further verify their suitability.

The historical evolution of the integrated approach led to a more consistent knowledge regarding the MBR's functioning, and the application of the integrated approach to assess MBRs operating conditions has been proved as a trustworthy method that provides reliable and realistic results (Saroj et al., 2008). Thus, the current step is to provide the models with tools that allow overcoming MBR's most important obstacles in order to optimize their performance.

Another application of the MBR modelling can be system optimization. Specifically, integrated models employed for MBR optimization are still under careful studies and there are few available in the literature (Di Bella et al., 2008; Zarragoïtia et al., 2009; Jang et al., 2006; Zuthi et al., 2013; González Hernández et al., 2015; Yang et al., 2017). Among the available tools, an even smaller amount has assessed the optimization of an MBR by considering multi-objective targets, such as energy demand, operating costs, etc. (Maere et al., 2011; Dalmau et al., 2013; 2014;; Gabarrón et al., 2015). For this reason, multi-objective performance assessment has become imperative to the development of the MBR technology and the use of integrated MBR models may be an applicable solution. Further studies are thus needed in order to provide a more comprehensive approach in MBR optimization and control. Future studies should focus on the studying the interplay role among biological and physical processes for enhancing design and operation of MBR systems.

. oards a frameor for good MBR integrated modelling ractice

An integrated modelling and simulation study involving MBR requires a stepwise procedure to take into account all relevant phases of a modelling project in a similar way as activated sludge modelling is guided through the GMP guidelines (Rieger et al. 2013). Therefore, this protocol is taken as the key guidance to develop a framework for good practices in MBR integrated modelling projects. The rationale behind consists on identifying the needs for extension or adaption of the activated sludge GMP framework due to the particular characteristics of MBRs. The MBR Modelling and Control Task Group from the International Water Association (IWA) is working towards the development of such a framework but some key ideas are already indicated here. The framework for MBR integrated modelling practice will be composed of five steps: project definition, data collection and reconciliation, model set-up, calibration and validation, and, simulation and results interpretation.

The project definition step includes defining the objective of the MBR modelling study (e.g. design, operation/optimisation, control or operators training), the state variables, the modelling targets and the performance indices to be used (permeate quality, membrane fouling or cost evaluation criteria). Fig. 5 contains a schematic representation of how the modelling targets can be considered by the integrated MBR models in order to reflect on the results of each KPI presented in this paper.

Some specific examples of MBR modelling projects include the design of the required membrane surface or the specific aeration demand device, the optimisation of biological nutrient removal and filtration processes in an integrated way, the control of membrane fouling (by regulating filtration cycles and air scouring) or sludge residence time. Similarly, additional performance criteria such as membrane fouling index or operational cost index, including air scouring, may be considered.

The second step, data collection and reconciliation, includes collecting the different type of data (influent and permeate quality, physical data related to the membrane compartment, and operational parameters, such as filtration cycles or TMP set points for membrane cleanings) and identify the data requirements (e.g. quantity and frequency of the data), which might be very different depending on the modelling purpose and the dynamics of biological and filtration processes. The data reconciliation step should allow to identify gaps and errors in the collected data and thus need for additional measuring campaigns for a proper validation. Typical additional data requirement would be dissolved oxygen and nutrient concentrations in the membrane compartment to optimise nutrient removal and aeration control (Fenu et al., 2010).

The third step requires the selection and set up of the models needed to describe MBR layout and performance; it means deciding on an

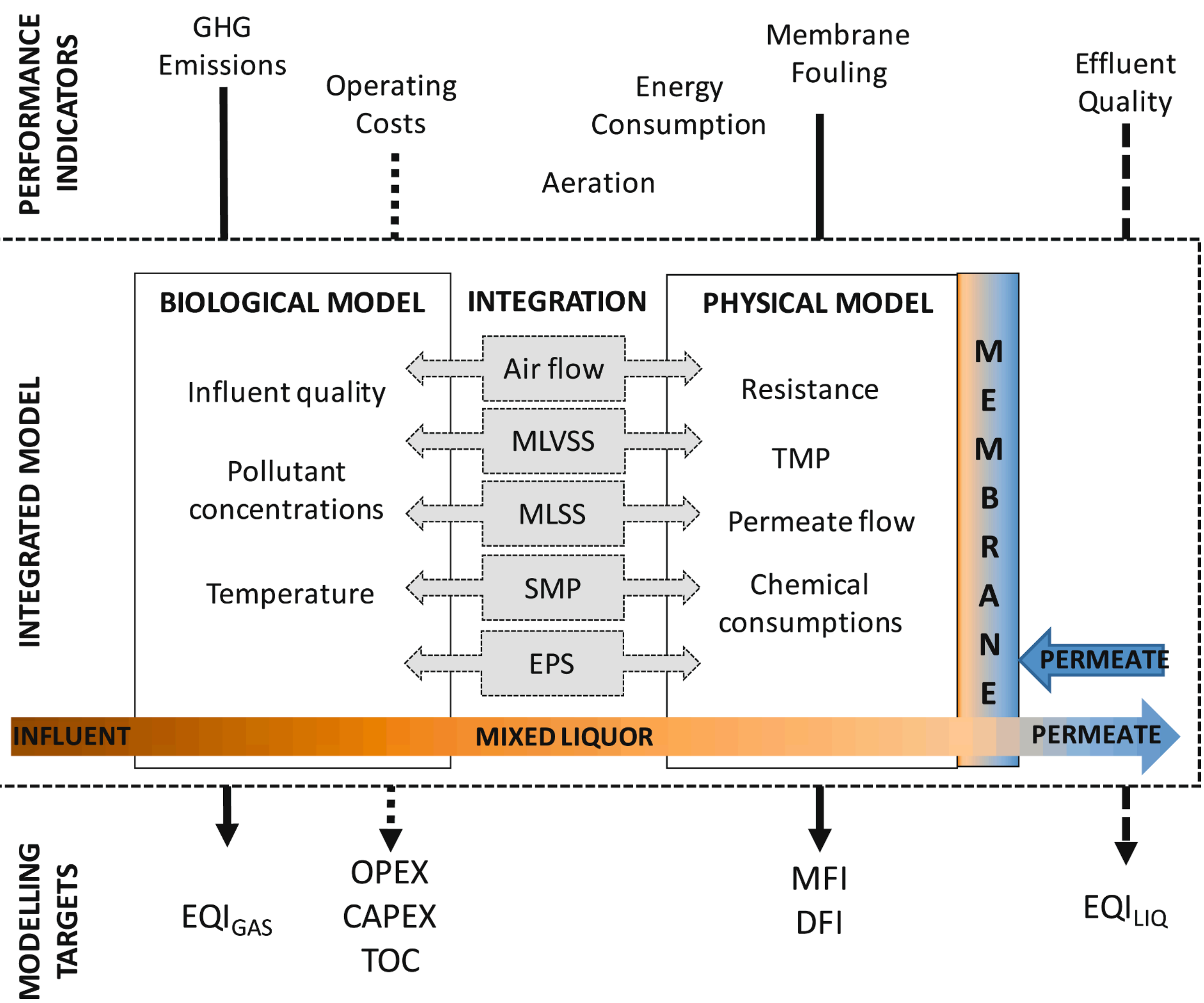


Fig. 5. Schematic representation of part of the framework for good MBR modelling practices. Where EQIgas = effluent quality index including the gas products (i.e., nitrous oxide, methane and CO_2), OPEX = operating expenditure; CAPEX = Capital expenditure; TOC = total operating costs; MFI = modified fouling index; DFI = Dimensionless Fouling Index; EQI_{LIQ} = Effluent Quality Index of the liquid phase).

influent model, reactor hydraulics, biological models, aeration and filtration models. As stated before, integrated models will be preferred here when results concerning the whole process are required. These modelling studies usually require additional state variables (with respect to activated sludge modelling) for both the biological and physical models (i.e. air flow rate for membrane scouring, SMP, EPS, resistance, TMP, permeate flow rate and chemical used for membrane cleaning). Integrated MBR models have already shown a huge potential in developing engineering solutions for MBR application and assessing various interactions between biological and physical models. As can be seen in Fig. 5, the integrated approach represents an important aspect of the modelling process, because it can correlate the biological and physical treatment by considering the most important operating variables that govern the MBR. In this case, a target can be set for the MBR modelling within a treatment plant reality and it can be assessed by the KPIs. It is necessary to select the most important KPIs, mainly related to operating variables, depending on the aim of the modelling approach: design, operation optimization, or management.

For model selection, the general rule would be to keep model complexity as simple as possible to answer the modelling question. However, the feasibility of the framework application is related to the available data set in order to balance among model accuracy and complexity. Sensitivity and uncertainty analysis can provide a good response in finding a trade-off between model complexity and available data for model application (among others, Mannina et al., 2020a).

The fourth step, calibration and validation, has special features in MBR modelling exercises. Depending on the complexity of the model, many model parameters may be adjusted (namely, 122 from Mannina et al. 2018c). Some of these parameters may be adjusted with external experiments as respirometer or dead-end filtration test (Zarragoitia-González et al., 2008), however most of them are taken from the literature. Still some are "manually adjusted" or just given (Janus, 2013), others may be partially calibrated with optimisation protocols (Vanrolleghem et al., 2003). A procedure advising to calibrate each target process (first biological nutrient removal processes, then filtration process or altogether simultaneously) and the default parameters for new processes encountered in MBRs is needed.

The final step, simulation and results interpretation, refers to the definition, running and analysis of typical steady-state or dynamic scenarios in MBR modelling. It really depends on the objective of the project.

The final framework for good MBR modelling practice will also to highlight the most relevant aspects in each step and provide guidelines to support the application of this framework for different MBR modelling applications. For example, suggesting the target variables, performance indicators, acceptable errors (for calibration), model type or modelling scenarios as a function of the modelling objective. This suggestion may be illustrated with the application/benchmarking of different MBR models for different data bases and case studies. This proposed framework would benefit from including a discussion on the potential benefits and limitations of using MBR models. Despite a first attempt to apply a simplified scheme of the above proposed framework has been provided for MBR pilot plants (i.e., Mannina et al., 2020b) there is a need of more comprehensive applications to MBR systems in real WWTPs.

5. New perspectives

Despite a lot has been done, further work to make plant evaluation as wide (holistic) as possible is needed. Efforts may be addressed in two different areas: 1) process performance assessment (which is more properly linked to the main topic of this paper), and 2) evaluation of the general plant suitability and sustainability.

As for the first point, instead of focusing on a few items (e.g. GHG emissions, effluent quality index – EQI – based on a few parameters, etc.), a broader environmental footprint analysis should be performed, by integrating Life Cycle Assessment (LCA) based methodologies within the integrated MBR modelling. This poses a series of challenges. First, the necessity to estimate a number of mass and energy flows throughout the plant, to build the input data set for LCA-based calculations. Secondly, the need of taking into account emerging contaminants of environmental concern (both in the sludge and the effluent wastewater). This topic indeed hides another issue related to the growing consciousness that chemical characterisation may fail in giving the real picture of effluent properties, as measuring thousands of compounds and predicting the effect of their mixture is unfeasible (Pedrazzani et al., 2019a). This led to the development of bioassays for a more suitable characterisation (Escher and Leusch, 2011; Gonzalez-Gil et al., 2016; Papa et al., 2016a; Pedrazzani et al., 2020). Nevertheless, the direct use of bioassays results in LCA-based procedures is not possible, unless proper conversion into equivalent pollutants mass flows is made (as suggested by Pedrazzani et al., 2019b; Di Trapani et al., 2015). Alternative approaches have also been proposed for overcoming this limitation (Papa et al., 2013; 2016b).

As for the second issue, which could be indeed considered as another step in the decision making process, for assessing the plant suitability, other areas should be taken into account and included: e.g. plant complexity and reliability; process flexibility; need of skilled personnel; administrative and legal constraints, etc. Procedures for including these items in a general evaluation and decision making framework, in the case of MBR plants, are reported in the literature (Bertanza et al., 2017).

6. Conclusion

This review presented the remarks retrieved from peer-reviewed papers regarding the integrated MBR modelling. On this behalf, a clear simplified definition and a framework were proposed to pursue good practice for MBR modelling taking into account key process indicators such as effluent quality, membrane fouling, aeration, operating costs, energy consumption, and mitigation of GHG emissions. Literature review shows that the use of integrated mathematical models should be more encouraged since they have the ability to provide comprehensive results to gain more understanding concerning the functioning of an MBR system.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Giorgio Mannina holds the Chair of the Task Group on Membrane Bioreactor Modelling and Control of the International Water Association. This work is part of the activities carried out by the Task Group (http://www.iwa-network.org/groups/membrane-bioreactor-modelling-and-control/).

References

Ahn, Y.T., Choi, Y.K., Jeong, H.S., Shin, S.R., 2006. Modeling of extracellular polymeric substances and soluble microbial products production in a submerged MBR at various SRTs. Water Sci. Technol. 53 (7), 209–216.

Aquino, S.F., Stuckey, D.C., 2008. Integrated model of the production of soluble microbial products (SMP) and extracellular polymeric substances (EPS) in anaerobic chemostats during transient conditions. Biochem. Eng. J. 38, 138–146.

Atanasova, N., Dalmau, M., Comas, J., Poch, M., Rodriguez-Roda, I., Buttiglieri, G., 2017. Optimized MBR for greywater reuse systems in hotel facilities. J. Environ. Manage. 193, 503–511.

Bai, R., Tien, C., 2000. Effect of deposition in deep-bed filtration: determination and search of rete parameters. J. Colloid Interface Sci. 231, 299–311.

Bertanza, G., Canato, M., Laera, G., Vaccari, M., Svanstrom, M., Heimersson, S., 2017. A comparison between two full-scale MBR and CAS municipal wastewater treatment

plants: techno-economic-environmental assessment. Environ. Sci. Pollut. Res. 24 (21), 17383–17393.
Bowen, W.R., Mohammad, A.W., Hilai, N., 1997. Characterization of nanofiltration membranes for perspective purposes – use of salts, uncharged solutes and atomic force microscopy. J. Membr. Sci. 126, 91–105.
Bozkurt, H., van Loosdrecht, C.M., Gernaey, V., Sin, G., 2016. Optimal WWTP process selection for treatment of domestic wastewater – A realistic full-scale retrofitting study. Chem. Eng. J. 286, 447–458.
Brepols, C., Comas, J., Harmand, J., Heran, M., Robles, Á., Rodriguez-Roda, I., Ruano, M. V., Smets, I., Mannina, G., 2020. Position paper – progress towards standards in integrated (aerobic) MBR modelling. Water Sci. Technol. 81 (1), 1–9.
Busch, J., Cruse, A., Marquardt, W., 2007. Modeling submerged hollow-fiber membrane filtration for wastewater treatment. J. Membr. Sci. 288 (1–2), 94–111.
Chaize, S., Huyard, A., 1991. Membrane bioreactor on domestic wastewater treatment sludge production and modelling approach. Water Sci. Technol. 23, 1591–1600.
Charfi, A. Yang, Y. Harmand, Ben Amar J. N., Heran, M., Grasmick A. (2015). Soluble microbial products and suspended solids influence in membrane fouling dynamics and interest of punctual relaxation and/or backwashing. Journal of Membrane Science, 475, pp 156-166.
Cho, J., Ahn, K.H., Seo, Y., Lee, Y., 2003. Modification of ASM No. 1 for a submerged membrane bioreactor system: including the effects of soluble microbial products on membrane fouling. Water Sci. Technol. 47, 177–181.
Dalmau, M., Monclús, H., Gabarrón, S., Rodriguez-Roda, I., Comas, J., 2014. Towards integrated operation of membrane bioreactors: Effects of aeration on biological and filtration performance. Bioresour. Technol. 171, 103–112.
Dalmau, M., Rodriguez-Roda, I., Ayesa, E., Odriozola, J., Sancho, L., Comas, J., 2013. Development of a decision tree for the integrated operation of nutrient removal MBRs based on simulation studies and expert knowledge. Chem. Eng. J. 217, 174–184.
Deng, L., Guo, W., Ngo, H.H., Zhang, H., Wang, J., Li, J., Wu, Y., 2016. Biofouling and control approaches in membrane bioreactors. Bioresour. Technol. 221, 656–665.
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. Membr. Sci. 322, 1–12.
Di Trapani, D., Di Bella, G., Mannina, G., Torregrossa, M., Viviani, G., 2015. Effect of C/N shock variation on the performances of a moving bed membrane bioreactor. Bioresour. Technol. 189, 250–257.
Drews, A., Vocks, M., Bracklow, U., Iversen, V., Kraume, M., 2008. Does fouling in MBRs depend on SMP? Desalination 231 (1–3), 141–149.
Fenu, A., Guglielmi, G., Jimenez, J., Sperandio, M., Saroj, D., Lesjean, B., Brepols, C., Thoeye, C., Nopens, I., 2010. Activated sludge model (ASM) based modeling of membrane bioreactor (MBR) processes: a critical review with special regard to MBR specificities. Water Res. 44, 4272–4294.
Escher, B., Leusch, F. (2011). Bioanalytical Tools in Water Quality Assessment. IWA Publishing.ISBN13: 9781843393689.
Fenu, A., Guglielmi, G., Jimenez, J., Sperandio, M., Saroj, D., Lesjean, B., Brepols, C., Thoeye, C., Nopens, I., 2010. Activated sludge model (ASM) based modeling of membrane bioreactor (MBR) processes: a critical review with special regard to MBR specificities. Water Res. 44, 4272–4294.
Freni, G., Mannina, G., 2010. Uncertainty in water quality modelling: The applicability of Variance Decomposition Approach. J. Hydrol. 394 (3–4), 324–333.
Gabarrón, S., Dalmau, M., Porro, J., Rodriguez-Roda, I., Comas, J., 2015. Optimization of full-scale membrane bioreactors for wastewater treatment through a model-based approach. Chem. Eng. J. 267, 34–42.
Galinha, C, Sanches, S, Crespo, J. (2018). Fundamental Modelling of Membrane Systems. Elsevier, 2018.
González Hernández, Y., Jáuregui Haza, U., Albasi, C., Alliet, M., 2015. Understanding the Influence of Operating Parameters through in Silico Optimization of Energy Consumption of Submerged Membrane Bioreactor for Urban Wastewater Treatment. Desalin. Water Treat. 12, 1–13.
Gonzalez-Gil, L. Papa, M. Feretti D., Ceretti, E. Mazzoleni, G. Steimberg, N. Pedrazzani, R. Bertanza, G.Juan M Lema, Carballa M. (2016): "Is anaerobic digestion effective for the removal of organic micropollutants and biological activities from sewage sludge?" Water Research, 102, 211-220.
Gujer, W., Henze, M., Mino, T., van Loosdrecht, M. (1999). Activated sludge model No. 3. Water Sci. Technol. 39 (1), 183–193.
Hamedi, H., Ehteshami, M., Mirbagheri, Rasouli, S. A., Zendehboudi, S. (2019). Current status and future prospects of membrane bioreactors (MBRs) and fouling phenomena: a systematic review. Can. J. Chem. Eng. 97, 32–58.
Henze, M., Grady, C.P.L.J., Gujer, W., Marais, G.v.R., Matsuo, T. (1987). Activated Sludge Model No. 1. IAWPRC Scientific and Technical Report No. 1, IAWPRC, London.
Henze, M., Gujer, W., Mino, T., Matsuo, T., Wentzel, M.C.M., Marais G.V.R. (1995). Activated sludge model No. 2. IWA Scientific and Technical Report No. 3, London, England.
Hiatt, W.C., Grady, C.P.L., 2008. An updated process model for carbon oxidation, nitrification, and denitrification. Water Environ. Res. 80, 2145–2156.
IPCC, Climate Change (2013) The physical science basis. In: Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, New York, p 1535.
Jang, N., Ren, X., Cho, J., Kim, I.S., 2006. Steady-state modeling of bio-fouling potentials with respect to the biological kinetics in the sMBR. J. Membr. Sci. 284, 352–360.
Janus, T., Ulanicki, B., 2010. Modeling SMP and EPS formation and degradation kinetics with an extended ASM3 model. Desalination 261, 117–125.
Janus, T., 2013. Modelling and Simulation of Membrane Bioreactor for Wastewater Treatment (Ph.D. thesis). De Montfort University.
Jiang, T., Myngheer, S., De Pauw, D.J.W., Spanjers, H., Nopens, I., Kennedy, M.D., Amy, G., Vanrolleghem, P.A., 2008. Modeling the production and degradation of soluble microbial products (SMP) in membrane bioreactors (MBR). Water Res. 42 (20), 4955–4964.
Judd, S., 2006. The MBR Book: Principles and Applications of Membrane Bioreactors. Elsevier, Amsterdam.
Koutsou, O.P., Gatidou, G., Stasinakis, A.S., 2018. Domestic wastewater management in Greece: greenhouse gas emissions estimation at country scale. J. Clean. Prod. 188, 851–859.
Krzeminski, P., Leverette, L., Malamis, S., Katsou, E., 2017. Membrane bioreactors – A review on recent developments in energy reduction, fouling control, novel configurations, LCA and market prospects. J. Membr. Sci. 527, 207–227.
Kuberkar, V.T., Davis, R.H., 2000. Modeling of fouling reduction by secondary membranes. J. Membr. Sci. 168, 243–257.
Laspidou, C.S., Rittmann, B.E., 2002. A unified theory for extracellular polymeric substances, soluble microbial products, and active and inert biomass. Water Res. 36, 2711–2720.
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.
Li, X., Wang, X., 2006. Modelling of membrane fouling in a submerged membrane bioreactor. J. Membr. Sci. 278, 151–161.
Lu, S.G., Imai, T., Ukita, M., Sekine, M., Higuchi, T., 2002. Modeling prediction of membrane bioreactor process with the concept of soluble microbial product. Water Sci. Technol. 46 (11–12), 63–70.
Lu, S.G., Imai, T., Ukita, M., Sekine, M., Higuchi, T., Fukagawa, M., 2001. A model for membrane bioreactor process based on the concept of formation and degra- dation of soluble microbial products. Water Res. 35, 2038–2048.
Maere, T., Verrecht, B., Moerenhout, S., Judd, S., Nopens, I., 2011. BSM-MBR: A benchmark simulation model to compare control and operational strategies for membrane bioreactors. Water Res. 45, 2181–2190.
Mannina, G., Capodici, M., Cosenza., A., Di Trapani, A., Olsson, G. (2017c) Greenhouse gas emissions and the links to plant performance in a fixed-film activated sludge membrane bioreactor – Pilot plant experimental evidence, Bioresource and Technology, 241, 1145-1151.
Mannina, G., Cosenza, A., 2013. The fouling phenomenon in membrane bioreactors: Assessment of different strategies for energy saving. J. Membr. Sci. 444, 332–344.
Mannina, G., Viviani, G., 2009. Separate and combined sewer systems: A long-term modelling approach. Water Sci. Technol. 60 (3), 555–565.
Mannina, G., Cosenza, A., Vanrolleghem, P., Viviani, G., 2011b. A practical protocol for calibration of nutrient removal wastewater treatment models. J. Hydroinform. 13 (4), 575–595.
Mannina, G., Cosenza, A., Ekama, G., 2017a. Greenhouse gases from membrane bioreactors: Mathematical modelling, sensitivity and uncertainty analysis. Bioresour. Technol. 239, 353–367.
Mannina, G., Cosenza, A., Ekama, G., 2018a. A comprehensive integrated membrane bioreactor model for greenhouse gas emissions. Chem. Eng. J. 334, 1563–1572.
Mannina, G., Cosenza, A., Ekama, G., 2018b. Mathematical modeling of greenhouse gas emissions from membrane bioreactors: A comprehensive comparison of two mathematical models. Bioresour. Technol. 268, 107–115.
Mannina, G., Cosenza, A., Viviani, G., Ekama, G., 2018c. Sensitivity and uncertainty analysis of an integrated ASM2d MBR model for wastewater treatment. Chem. Eng. J. 351, 579–588.
Mannina, G., Di Bella, G., Viviani, G., 2011a. An integrated model for biological and physical process simulations in membrane bioreactors (MBR). J. Membr. Sci. 376 (1–2), 56–69.
Mannina, G., Di Bella, G., Viviani, G., 2010. Uncertainty assessment of a membrane bioreactor model using the GLUE methodology. Biochem. Eng. J. 52 (2–3), 263–275.
Mannina, G., Ni, B.-J., Ferreira Reboucas, T., Cosenza, A., Olsson, G., 2020b. Minimizing membrane bioreactor environmental footprint by multiple objective optimization. Bioresour. Technol. 302, 122824.
Mannina, G., Cosenza, A., Ferreira Reboucas, T., 2020a. Uncertainty and sensitivity analysis for reducing greenhouse gas emissions from wastewater treatment plants. Water Sci Technol 82 (2), 339–350.
Martin, C., Vanrolleghem, P., 2014. Analysing, completing, and generating influent data for WWTP modelling: A critical review. Environ. Modell. Software 60, 188–201.
Meng, F., Zhang, S., Oh, Y., Zhou, Z., Shin, H., Chae, S., 2017. Fouling in membrane bioreactors: An updated review. Water Res. 114, 151–180.
Meng, F., Chae, S., Drews, A., Kraume, M., Shin, H., Yang, F., 2009. Recent advances in membrane bioreactors (MBRs): membrane fouling and membrane material. Water Res. 43, 1489–1512.
Monclus, H., Buttiglieri, G., Ferrero, G., Rodriguez-Roda, I., Comas, Q., 2012. Knowledge-based control module for start-up of flat sheet MBRs. Biore. Tech. 106, 50–54.
Naessens, W., Maere, T., Ratkovich, N., Vedantam, S., Nopens, I., 2012. Critical review of membrane bioreactor models – Part 2: Hydrodynamic and integrated models. Bioresour. Technol. 122, 107–118.
Nagaoka, H., Yamanishi, S., Miya, A., 1998. Modeling of biofouling by extracellular polymers in a membrane separation activated sludge system. Water Sci. Technol. 39, 497–504.
Namkung, E., Rittmann, B.E., 1986. Soluble microbial products (SMP) formation kinetics by biofilms. Water Res. 20, 795–806.
Ng, A.N.L., Kim, A.S., 2007. A mini-review of modeling studies on membrane bioreactor (MBR) treatment for municipal wastewaters. Desalination 212 (1–3), 261–281.
Ni, B., Yuan, Z., 2015. Recent advances in mathematical modeling of nitrous oxides emissions from wastewater treatment processes. Water Res. 87, 336–346.

Ognier, S., Wisniewski, C., Grasmick, A., 2004. Membrane bioreactor fouling in sub-critical filtration conditions: a local critical flux concept. J. Membr. Sci. 229, 171–177.
Orhon, D., Artan, N., Cimcit, Y., 1989. The concept of soluble residual product formation in the modelling of activated sludge. Water Sci. Technol. 21, 339–350.
Papa, M., Ceretti, E., Viola, G.C.V.D., Feretti, I., Zerbini, G., Mazzoleni, N., Steimberg, R. Pedrazzani, Bertanza, G., 2016a. The assessment of WWTP performance: towards a jigsaw puzzle evaluation Chemosphere 145, 291–300.
Papa, Pedrazzani, R., Bertanza, G., 2013. How green are environmental technologies A new approach for a global evaluation: the case of WWTP effluents ozonation" -. Water Res. 47, 3679–3687.
Pedrazzani R., Baroni P., Feretti D., Mazzoleni G.,Steimberg N., Urani C., Viola G., Zerbini I., Ziliani E., Bertanza G. (2020) Methodological Protocol for Assessing the Environmental Footprint by Means of Ecotoxicological Tools: Wastewater Treatment Plants as an Example Case. In: Ecotoxicological QSARs, Methods in Pharmacology and Toxicology, Kunal Roy (ed.), https://doi.org/10.1007/978-1-0716-0150-1_14, © Springer Science+Business Media, LLC, part of Springer Nature 2020.
Pedrazzani, E., Ziliani, I., Cavallotti, E., Bollati, M., Ferreri, G. Bertanza, 2019b. Use of ecotoxicology tools within the environmental footprint evaluation protocols: the case of wastewater treatment plants. Desalin. Water Treat. 172, 2–14.
Pedrazzani, G., Bertanza, I., Brnardić, Z., Cetecioglu, J., Dries, J., Dvarioniene, A.J., García-Fernández, A., Langenhoff, G., Libralato, G., Lofrano, B., Škrbić, E., Martínez-López, S., Meriç, D. Mutavdžić, Pavlović, M., Papa, P., Schroder, K.P., Tsagarakis, C. Vogelsang, 2019a. Opinion paper about organic trace pollutants in wastewater: Toxicity assessment in a European perspective. Sci. Total Environ. 651, 3202–3221. https://doi.org/10.1016/j.scitotenv.2018.10.027.
Pocquet, M., Wu, Z., Queinnec, I., Spérandio, M., 2016. A two pathway model for N2O emissions by ammonium oxidizing bacteria supported by the NO/N2O variation. Water Res. 88, 948–959.
Puyol, D., Batstone, D.J., Hülsen, T., Astals, S., Peces, M., Kromer, J.O., 2016. Resource Recovery from Wastewater by Biological Technologies: Opportunities, Challenges, and Prospects. Front. Microbiol. 7, 1–23.
Rieger, L., Gillot S., Langergraber, G., Ohtsuki, T., Shaw, A., Takács, I., and Winkler, S. (2013) Guidelines for Using Activated Sludge Models. Scientific and Technical Report 22. London [u.a]: IWA Publ.
Robles, A., Ruano, M.V., Ribes, J., Ferrer, J., 2013. A filtration model applied to submerged anaerobic MBRs (SAnMBRs). J. Membr. Sci 444, 139–147.
Saltelli, A., Tarantola, A., Campolongo, F., 2004. Ratto (2004) Sensitivity analysis in practice. John Wiley & Sons, Chichester, UK, A guide to assessing scientific models Probability and Statistics Series.
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.
Saroj, D., Guglielmi, G., Chiarani, D., Andreottola, G., 2008. Modeling and simulation of membrane bioreactors by incorporating simultaneous storage and growth concept: an especial attention to fouling while modeling the biological process. Desalination 221, 475–482.
Scholes, E., Verheyen, V., Brook-Carter, P., 2016. A review of practical tools for rapid monitoring of membrane bioreactors. Water Res. 102, 252–262.
Smith, C. W., Di Gregorio, D., and Talcott, R. M. (1969). The use of ultrafiltration membrane for activated sludge separation. Proceedings of the 24th Annual Purdue Industrial Waste Conference, Purdue University, West Lafayette, Indiana, USA. 1300–1310.
Suganthi, V., Mahalakshmi, M., Balasubramanian, N., 2013. Development of hybrid membrane bioreactor for tannery effluent treatment. Desalination 309, 231–236.
Vanrolleghem, P.A., Insel, G., Petersen, B., Sin, G., De Pauw, D., Nopens, I., Weijers, S., Gernaey, K., 2003. A comprehensive model calibration procedure for activated sludge models. In: Proceedings: WEFTEC 2003, 76th Annual Technical Exhibition and Conference. October 11–15, 2003, Los Angeles, CA, USA (on CD-ROM).
Wintgens, T., Rosen, J., Melin, T., Brepols, C., Drensla, K., Engelhardt, N., 2003. Modelling of a membrane bioreactor system for municipal wastewater treatment. J. Membr. Sci 216, 55–65.
Wu, J., He, C., Zhang, Y., 2012. Modeling membrane fouling in a submerged membrane bioreactor by considering the role of solid, colloidal and soluble components. J. Membr. Sci. 397–398, 102–111.
Xiao, K., Xu, Y., Liang, S., Lei, T., Sun, J., Wen, X., Zhang, H., Chen, C., Huang, X., 2014. Engineering application of membrane bioreactor for wastewater treatment in China: current state and future prospect. Front. Environ. Sci. Eng. 8, 805–819.
Yamamoto, K., Hiasa, M., Mahmood, T., Matsuo, T., 1989. Direct solid-liquid separation using hollow fiber membrane in activated sludge aeration tank. Water Sci. Technol. 30, 21–27.
Yang, M., Yu, D., Liu, M., Zheng, L., Zheng, X., Wei, Y., Wang, F., Fan, T., 2017. Optimization of MBR hydrodynamics for cake layer fouling control through CFD simulation and RSM design. Bioresour. Technol. 227, 102–111.
Zarragoïtia, A., Schetrite, S., Jáuregui-Haza, U., Lorain, O., Albasi, C., 2009. Optimization of Wastewater Filtration Process in Submerged Membrane Bioreactors: Applicability of a Dynamic Model to Scale Up. Computer Aided Chemical Engineering 27, 1545–1550.
Zarragoitia-González, A., Schetrite, S., Alliet, M., Jáuregui-Haza, U., Albasi, C., 2008. Modelling of submerged membrane bioreactor: Conceptual study about link between activated slugde biokinetics, aeration and fouling process. J. Membr. Sci. 325, 612–624.
Zhanga, G., Ngo, H.H., Peng, Y., Bux, F., Mannina, G. (2021) Biological nutrients removal and recovery, Bioresource Technology, Volume 320, Part B, 124377.
Zheng, F., Huang, L., Pan, J., Fan, L., Wang, S., Tan, C., 2018. Does influent surface organic loading and aeration mode affect nitrogen removal and N2O emission in subsurface wastewater infiltration systems? Ecol. Eng. 123, 168–174.
Zuthi, M.F.R., Guo, W.S., Ngo, H.H., Nghiem, L.D., Hai, F.I., Xia, S., Li, J., Li, J., Liu, Y., 2017. New and practical mathematical model of membrane fouling in an aerobic submerged membrane bioreactor. Bioresour. Technol. 238, 86–94.
Zuthi, M.F.R., Ngo, H.H., Guo, W.S., 2012. Modeling bioprocesses and membrane fouling in membrane bioreactor (MBR): A review towards finding an integrated model framework. Bioresour. Technol. 122, 119–129.
Zuthi, M.F.R., Ngo, H.H., Guo, W.S., Zhang, J., Liang, S., 2013. A review towards finding a simplified approach for modeling the kinetics of the soluble microbial products (SMP) in an integrated mathematical model of membrane bioreactor (MBR). Int. Biodeterior. Biodegrad. 85, 466–473.