



New Configurations and Techniques for Controlling Membrane Bioreactor (MBR) Fouling

Djamel Ghernaout^{1,2}

¹Chemical Engineering Department, College of Engineering, University of Ha'il, Ha'il, KSA

²Chemical Engineering Department, Faculty of Engineering, University of Blida, Blida, Algeria

Email: djamel_andalus@hotmail.com

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Abstract

At the worldwide level, with numerous full-scale plants dealing with urban and industrial wastewater, the membrane bioreactor (MBR) process is viewed as a fully developed technique. Nevertheless, membrane fouling constitutes a critical barrier in the larger diffusion of MBR application. This work aims to discuss the new research and development progresses in the MBR technology in terms of fouling mitigation. New arrangements are examined to enhance the comprehension of the latest achievements in MBRs. Employed for biological fouling control, the quorum quenching technique is briefly introduced. As clean methods used for coping with membrane fouling, the ultrasonic technique and the surface grafting methods are also suggested. Several ameliorations focused on the module arrangement, aeration procedures, control setups, surface amendments, low-energy membrane cleaning techniques, or new fouling mitigation procedures, for instance, mechanical cleaning with granular medium, membrane vibration, or electric field. Between such ameliorations, hybrid setups, merging MBR with different techniques, employing prospects of the diverse methods to get the better of regular limitations of the MBRs are the most convenient. Nonetheless, implementing such novel fouling alleviation procedures for large scale MBRs needs more study. Sustainable control of membrane fouling necessitates utilizing more than one single strategy. Even with unceasing enhancements and expansions, fouling control features remain to be fully met.

Subject Areas

Chemical Engineering & Technology

Keywords

Membrane Bioreactor (MBR), Membrane Fouling, Quorum Quenching

(QQ), Quorum Sensing (QS), Activated Sludge (AS), Extracellular Polymeric Substances (EPSs)

1. Introduction

Through the world, the membrane bioreactor (MBR) process is adopted as a firmly proved, fully developed technique with numerous full-scale plants dealing with both municipal and industrial wastewater [1] [2]. Nevertheless, some drawbacks avert the larger acceptance of such a technique, such as a membrane fouling and energy consumption [3] [4]. This is why huge research and development (R & D) attempts remain taken [5]. Such R & D endeavors have conducted to an augmentation in the number of reports during the last two years.

Several recent discussions concentrated on features, like fouling characterization, visualization and foulants identification [6] [7] [8], modeling [9] [10] [11] [12] [13], membrane cleaning [14] [15], introduction of activated carbon [16], fouling control [17] [18], process monitoring [19], osmotic MBRs [20] [21] [22], removal of pharmaceutical compounds [23] [24] [25] and treatment of industrial wastewaters [26] [27]. As a consequence, it is required to summarize methodically such novel expansions in MBR technology.

This work aims to discuss the new R & D progresses in MBR technology as for fouling mitigation, both being the fundamental dares and significant features of MBR application. New arrangements are examined to enhance the comprehension of the latest achievements in MBRs. Employed for biological fouling (bio-fouling) control, the quorum quenching (QQ) technique is briefly introduced. As a clean method used for coping with membrane fouling, the ultrasonic technique is shortly discussed. Finally, surface grafting techniques for dealing with membrane fouling are also suggested.

2. Membrane Fouling Control

Even if MBRs are presently a fully developed technique, membrane fouling stays the most significant running issue, retarding their general and wide-scale implementation [28] [29]. Membrane fouling decreases MBR productivity, augments the energy demands because of air-scouring, and needs recurrent cleaning of the membrane to reinstate its permeability [30] [31]. Repeated membrane cleaning, however, reduces the membrane's life-time and leads to bigger membrane replacement prices. Therefore, numerous reports have been dedicated to membrane fouling, with a view to interpreting the pathways in charge of its generation and to suggest strategies to relieve this [1] [32] [33].

In MBRs, fouling is generated from the interaction between the mixed liquor and the membrane [1]. There are three major pathways in charge of membrane fouling: 1) pore narrowing which is related to the sorption of dissolved

and micro-colloidal substances possessing a size much smaller than the membrane pore size, 2) pore plugging because of the deposition of solids possessing a size similar than to that membrane pores and 3) cake layer production on the membrane's surface because of the deposition of matters on the membrane's surface [34]. There are several kinds of foulant: biofilm comprising extracellular polymeric substances (EPSs), soluble organics, particulates, colloids, dissolved inorganic compounds [8] [35] [36]. Numerous factors could influence membrane fouling in MBR techniques: 1) the membrane features, 2) the mixed liquor characteristics, 3) the running circumstances and, 4) the wastewater features.

Dominating and reducing membrane fouling remains crucial in MBR technology to guarantee a cost-effective and long-term process [37]. Six important procedures are implemented to dominate membrane fouling [38]: 1) implementation of appropriate pre-treatment to the feed wastewater, 2) permeate backflushing/backwashing or relaxation, 3) chemical cleaning of membranes, 4) chemically improved backwash, 5) membrane scouring through coarse bubble aeration and, 6) chemically modifying the mixed liquor [1] [39] [40].

In backflushing, the filtration flow is reversed to eliminate the solids fixed to the membrane surface. In relaxation, the filtration operation is paused to alleviate the membrane from the formed pressure. Backflushing or relaxation is merged inside the standard working of the MBR; thus, a filtration cycle is composed of a few minutes of filtration pursued by a short backflushing or relaxation time. Backflushing/relaxation could eliminate most of the reversible fouling and is, therefore, performant in eliminating the cake layer. In a submerged MBR, the needed membrane scouring is performed via coarse bubble aeration that is realized at the bottom part of the membrane modules [41] [42]. Regulating the implementation of the coarse bubble aeration could be realized in terms of intensity and duration, with intermitted aeration also being used. Chemical cleaning can be performed via injecting mineral organic acids, caustic soda, or sodium hypochlorite. Sodium hypochlorite is frequently added to eliminate biofouling and citric acid is injected to eliminate inorganic fouling. Chemical cleaning could also be realized throughout the usual MBR running via injecting a low chemical level to the backflush water; such an operation is famous as chemically enhanced backflush. Chemical cleaning is very efficacious in dealing with irremovable fouling, which could not be reduced throughout the usual running of the MBR. Nevertheless, recurrent, intensive chemical cleaning decreases the life of the membrane [1].

Additives could be injected into the biomass with a view to change the mixed liquor properties, improving the filtration technique, and decreasing fouling. Such additives could be coagulants, polyelectrolytes, adsorbing agents, and membrane performance enhancers. Coagulants add positive ions, neutralizing the negative charges of biomass, therefore improving flocculation [43]. Adsorbents could be zeolite and activated carbon. Such products could be inserted into the mixed liquor of MBR to alleviate fouling through adsorbing colloidal and

dissolved matters [44] [45]. A natural zeolite was added to reduce the level of dissolved microbial products and so alleviate fouling [46]. An added sponge has the potential to decrease cake generation and pore blockage in a submerged MBR [47]. Injecting 1 g/L of powdered activated carbon reduced the specific resistance of the cake film that developed on the membrane's surface [48]. Introducing diverse additives has shown that the cationic polymer MPE50 and poly-aluminum chloride are so efficacious in reducing membrane fouling [48]. Nevertheless, inserting additives is not commonly utilized in full-scale MBRs because it is unknown if the price of chemical usage is approved by the membrane fouling reduction. In addition, the long term consequences of utilizing, or avoiding utilizing, additives have not been investigated in detail [1].

Modifying chemically the membrane's surface is considered as a new technique that can be implemented to ameliorate MBR efficiency. Indeed, a fresh antifouling coating is applied to commercial UF membranes, which was based on a polymerizable bicontinuous microemulsion technique [49]. These scientists [49] juxtaposed the efficacy of a fresh MBR in which such a coating was implemented to a traditional MBR and proved that the fresh MBR illustrated much lower fouling. Likewise, researchers [50] suggested a composite microfiltration membrane, which was fabricated via blending polyvinylidene fluoride (PVDF) and hydrophilic graphene oxide (GO) nanosheets. Such a PVDF/GO membrane was tried on an MBR setup and worked better as it depicted higher critical flux, lower cleaning frequency, and lower membrane resistance than a classical PVDF membrane of an MBR. Lately, quorum quenching (QQ) has been recognized as an efficient antifouling procedure [51]. Nevertheless, there are so restricted full-scale implementations and feasible problems like the cost and stability of enzymes have to be resolved [1] [52]. More details about QQ are given in Section 4.

Merging advanced oxidation processes [53] or electrocoagulation [54] with MBRs could be extremely performant in eliminating recalcitrant compounds like pharmaceuticals and reducing MBR fouling [55] [56]. Moreover, combining microbial fuel cells with MBRs (MFC-MBR) to remedy wastewater could as well reduce membrane fouling. Decreasing membrane fouling is affected to a modification in the activated sludge (AS) features because the biomass in the MFC-MBR technique is categorized by a lower quantity of loosely bound EPS, more homogenized sludge and a lower quantity of filamentous bacteria [57]. Nevertheless, in the MFC-MBR technique, the major reason for its utilization is not the decrease of membrane fouling but targets like an ameliorated reduction of organic micropollutants, energy recovery, and lower operating expenses. Further, these merged techniques stay in their premature step of expansion since they are being examined at the bench and pilot-scale levels [1] [58].

3. New Configurations for Dealing with Membrane Fouling

In terms of new configurations in the field of MBRs, fresh R & D progress con-

centrated mainly on membrane fouling control [1] [59]. Recently, several MBR setups employing dynamic shear-enhanced filtration through rotation, vibration, or reciprocation movement have been assessed to decrease membrane fouling [60]. Rotating MBRs have been furnished with flat-sheet [61] [62] [63], tubular [64], hollow fiber [65], or helical [66] membrane modules. Elevating rotation speed could conduct to better effectiveness in terms of fouling control [62]. Scientists [61] observed that rotation speed has an effect on cleaning effectiveness until a critical speed of 60 r/min was attained, after which little impact is detected. Researchers [63] proved that rotating flat-sheet MBR has a slower fouling rate juxtaposed to traditional MBRs when consuming the identical energy. Other scientists [1] evaluated via modeling investigations that the rotation efficacy in terms of fouling prevention was 12%, proposing that prevention of cake build-up and fouling is mainly realized by air-scouring. Presently, numerous kinds of rotation MBRs are at hand on the MBR market as commercial products, comprising a cross-flow MBR system with rotating ceramic discs impellers Grundfos BioBooster [67] and Huber vacuum rotation membrane VRM® bioreactor [68]. In vibrating MBR (VMBR), different motions/mechanical forces (*i.e.*, longitudinally, transversely, torsionally, or their combination) produce sheer at the membrane's surface to alleviate fouling [60]. As a fouling control solution, numerous VMBRs have been investigated like transverse vibration system [69], vertical movement [70], magnetically induced membrane vibration (MMV-MBR) [71], and high-frequency powerful vibration (HFPV-MBR) [1]. Such configurations permit a low air-scouring procedure thanks to the cyclic application of vibration. Further, they possess a capacity to lower dissolved oxygen (DO) in the AS returned from the membrane tank to the anoxic tank, which is frequently DO-rich and decreases the MBR denitrification performance [72]. Low frequency and low amplitude vertical vibrations were enough to conserve the hollow-fiber membrane practically free from fouling [73]. Critical fluxes of a bench-scale unit augmented from 15 to 27 L/m² h when membrane vibration was used, and further to 56 L/m² h when frequency of vibrations augmented from 1.7 to 8.4 Hz [74]. Further, more scientists [69] [70] noted a decreased fouling rate and improved critical flux throughout vibration enhanced filtration. Moreover, researchers [70] noted that 1% - 2% loosening of fibers could further augment the permeate flux. Scientists [71] established that MMV-MBR attained higher flux and lower levels of fouling juxtaposed to aerated setups. In the HFPV-MBR, periodic high-frequency vibrations until 223 Hz were applied throughout the relaxation of hollow fiber membranes, without stopping the work of the submerged MBR setup [1]. Then, membrane effectiveness in respect to TMP and flux were recuperated to the circumstances of an almost clean membrane [1]. Even if numerous VMBRs look so encouraging, several vibration systems were only tested at a small scale and at low MLSS levels of 4 - 5 g/L. Researchers [15] discussed the vibration/rotation MBRs data. The reciprocation MBR (rMBR) uses inertial force on the membrane fibers via the horizontal reciprocating motion of the

membrane cassette to decrease membrane fouling in the lack of air scouring [72]. The rMBR avoids the necessity of air-scouring setup and increased DO level in the return AS stream to the anoxic tank decreasing denitrification efficacy [1] [75].

The recently developed helical membrane modules boost scouring, decrease membrane fouling, and augment permeate flux thanks to vortex mixing and related intensified turbulence at the membrane surface [76] [77]. In the premature devices, the module was put vertically with a lower part loose; while in a more modern version, the module rotated counterclockwise to more elevate permeate flux by 27% [66]. In the Pentair's Helix membranes a helically-winding ridge, made of the same material as the membrane, is located on the inside of the membrane [78].

In baffled MBR (BMBR), incorporated baffles separate the bioreactor into two areas [1]. Such a division aims to alternatively generate anoxic/aerobic circumstances in the tank provided that wastewater is fed in a suitable manner [79]. Such circumstances are anticipated to catalyze concurrent nitrification and denitrification, leading to performant nitrogen elimination [80]. Throughout pilot-scale trials, the average reduction performances of total organic carbon (TOC), total phosphorous (TP), and total nitrogenous (TN) were 85%, 97%, and 77%, respectively [80]. In addition, because of the gap in a gas hold-up and fluid density in various areas, throughout aeration a cross-flow over membrane surface is generated furnishing bonus membrane cleaning [81]. As an illustration, scientists [82] suggested an airlift oxidation ditch membrane bioreactor (AOXMBR) including a submerged flat-sheet membrane and air injection setup put between two baffles furnishing aeration for biological targets, membrane scouring and AS circulation. Lately, employing baffles, incorporated in the membrane compartment of a submerged MBR, was tested to regulate hydraulic circumstances in the device with a view to ameliorating aeration effectiveness [81] and to improve the performance of mechanical cleaning with granules [83]. **Table 1** gives a global view of new MBR configurations for enhanced membrane fouling control [1].

4. Quorum Quenching (QQ) Technique for Biofouling Control

In the MBRs technology, biofouling is described as the undesirable aggregation of microorganisms on the membrane surface [51] [85] [86]. Even if it has been largely investigated during the last twenty years, it stays a crucial restricting factor to the larger MBR implementation for treating wastewater (**Table 2**) [86] [87]. Two decades ago, the idea of quorum sensing (QS)/quorum quenching (QQ) was suggested as an anti-fouling procedure for MBRs [88] (**Figure 1**). Several investigations have established the capacity of QQ for biofouling control in MBR via diverse means [89]. The progression of QQ-MBR has progressed in terms of QQ-microorganisms, QQ-media, and the size of the QQ-MBRs tried. Oh and Lee [51] focused on the QS/QQ researches concerning the explanation

Table 1. General view of fresh MBR configurations for enhanced membrane fouling control [1].

MBR type	Membrane type	Main results in matter of fouling	Reference
Rotating MBR	Flat sheet	Flux augmented from 42 L/m ² h to 47 L/m ² h when rotational speed elevated from 15 to 25 r/min	[84]
Rotating MBR	Flat sheet	Membrane fouling rate is much lower in rotating MBR juxtaposed to traditional MBR for the identical energy consumption	[64]
Rotating MBR	Tubular	The fouling rate decreased as the rotational speed of the module increased	[65]
Rotating MBR	Hollow fiber	At the tested rotational frequencies, high dispersive conditions were present and significantly larger than those observed during static operation	[66]
Reciprocal MBR	Hollow fiber	Low and stable transmembrane pressure was achieved at 40 L/m ² h by use of repetitive membrane reciprocation	[67]
Helical membrane	Filter cloth sheet	27% enhancement of stable flux can be maintained by rotating a 360° helical membrane, compared to a rotating same sized flat membrane, at a rotating speed of 160 rpm	[1]
Baffled MBR	Flat sheet	10% - 30% increase in membrane surface shear compared with the no-baffle configuration at the same aeration intensity	[71]

Table 2. Category of fouling in membrane following foulant category [87].

Type	Description	Foulants
Colloidal Fouling	Accumulation of particles on membrane surface and inside membrane pores, forming a cake layer	Suspended solids and particles such as silicate, ferric oxide, iron oxide and aluminum oxide
Inorganic Fouling	Precipitation deposits resulting in bulk and membrane crystallization	Inorganic salt such as calcium carbonate, calcium sulfate, calcium phosphate and sodium chloride
Organic Fouling	Adsorption of natural organic compounds on membrane, caused gel formation	Natural organic matter such as fulvic acid, protein, polysaccharides and polyacrylic polymer
Biofouling	Formation of biofilm on membrane surface	Aquatic organism such as fungi, algae and bacteria

and control of biofouling in MBRs, comprising the determination of QS signals, the isolation of QS signal forming or decomposing microbes, and different practical

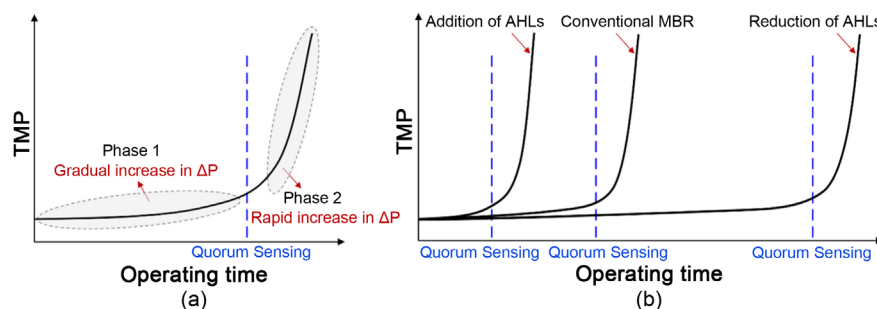


Figure 1. (a) Typical profile of trans-membrane pressure (TMP) increase during operation of MBRs for wastewater treatment, and (b) change in the point of quorum sensing (QS) and TMP increase as a function of the concentration of *N*-acyl homoserine lactone (AHL) signal molecules [51].

procedures to implement enzymatic or bacterial QQ in the form of QQ-media to alleviate membrane biofouling. They reviewed the dares facingsuch utilizations and the next trends of QQ-based biofouling control procedures for MBR [51] [90].

In the same context, Huang *et al.* [91] presented an exhaustive review on acyl-homoserine lactone (AHL)-based QS and QQ for increasing the efficiency of biological wastewater treatments. Shi *et al.* [36] focused on EPSs controlling procedures (QS systems) for effectiveness amelioration of biological wastewater treatments. Lin *et al.* [92] examined the EPSs properties and roles in membrane fouling and control procedures. Meng *et al.* [8] suggested an exhaustive and updated review on the fouling in MBRs. Lee *et al.* [93] focused on the opportunities and dares for biofouling control related to the QS and QQ in MBRs.

5. Ultrasonic Technique for Coping with Membrane Fouling

As seen above, membrane cleaning procedures could be mostly categorized into four classes comprising chemical, physical, physicochemical, and biological. Lately, ultrasonication has been discovered as an encouraging cleaning method for the MBRs membranes [94]. Indeed, ultrasonic irradiation could clean the fouled membrane by generating interesting physical processes involving micro-jets, micro-streams, and shock waves. In addition, ultrasonic technology can be integrated with different cleaning processes such as chemical cleaning and backwashing with a view to ameliorating the cleaning performance. In fact, implementing ultrasonic in the MBR system is not restricted to membrane cleaning. This is due to the fact that pretreating wastewater by ultrasonic irradiation or ultrasound merged with additional technologies (like ozonation) before the MBR setup has the potential to reduce the organic matter of the wastewater and then delay the membrane fouling. Arefi-Oskoui *et al.* [94] discussed the fresh signs of progress in utilizing ultrasound in MBR devices.

The particles could be liberated from the fouled membrane by the mentioned

physical processes and/or by forming hydroxyl radicals in a heterogeneous liquid-solid system [94]. Applying ultrasonic could be realized either in-situ (online) or ex-situ (offline) for cleaning the membrane in the MBR setups. Implementing on-line ultrasonic irradiation could efficaciously dominate the membrane fouling in the MBR devices by dominating the production of the cake film on the membrane surface. Most of the investigations concerned the utilization of ultrasonic techniques in MBR setups on a laboratory scale. As a result, more attention stays requested to follow the ultrasound implementation on an industrial level focusing on the expansion of technical-economical techniques with low energy consumption.

6. Surface Grafting Procedures for Dealing with Membrane Fouling

Surface grafting procedures have a crucial contribution in enhancing the traditional membrane setup which is mainly hydrophobic in nature [95] [96]. The hydrophobic nature of membranes is recognized to provoke fouling, leading to increased maintenance costs and shorter lifetime of MBR. Therefore, surface grafting intends to ameliorate the hydrophilicity of bio-based membrane setups. Lee *et al.* [97] revised the main surface modification methods presently utilized in membranes, comprising photo-induced grafting, plasma treatment and plasma-induced grafting, radiation-induced grafting, thermal-induced grafting, and ozone-induced grafting. The fouling trouble can be settled with the surface grafting methods to reach better effectiveness of MBRs.

7. Conclusions

In this work, modern signs of progress in terms of membrane fouling control and novel configurations in MBRs are discussed. Employed for biofouling control, the QQ technique is briefly introduced. As a clean method used for coping with membrane fouling, the ultrasonic technique is shortly discussed. Finally, surface grafting techniques for dealing with membrane fouling are also suggested. From this work, the following conclusions can be drawn:

- 1) MBR fouling troubles have drawn the interest of researchers, practitioners, and MBR suppliers, and have conducted to diverse fouling-mitigation options, optimization procedures, and fresh commercial products. Such ameliorations focused on the module arrangement, aeration procedures, control setups, surface amendments, low-energy membrane cleaning techniques, or new fouling mitigation procedures, for instance, mechanical cleaning with granular medium [98], membrane vibration, or electric field. Numerous new MBR arrangements have been suggested to ameliorate membrane fouling control. Between such ameliorations, hybrid setups, merging MBR with different techniques, employing prospects of the diverse methods to get the better of regular limitations of the MBRs were the most important [1] [99].

- 2) More research is requested to find the best design and materials of QQ-media

with a view to improving QQ activity and to decrease the price of QQ-MBR. Further, it is suggested to present a novel flat-sheet or hollow-fiber membrane modules in which part of sheets or fibers are substituted by QQ-sheets or QQ-fibers, respectively. Such QQ-membrane modules are anticipated to avoid a method for the separation of QQ-media from AS in QQ-MBR. Over the QQ-MBR, the capacity of QQ-technology can be extended to additional membrane techniques in water treatment for biofouling control, like anaerobic MBR (AnMBR) [100] [101] [102], reverse osmosis (RO), forward osmosis (FO) [103], FO-MBR [60], bioelectrochemical systems, BES-AnMBRs [104] [105], thermophilic membrane bioreactors (ThMBRs) [106], etc. [107] [108]. Indeed, the capability of QQ-AnMBR and QQ-RO has previously been established in lab-scale tests [51].

3) Even with unceasing enhancements and expansions, fouling control features remain to be fully met. Between the fouling control features, the expansion of original antifouling membranes, stable flux production for long term operation, efficient and/or low-energy membrane cleaning techniques and identification of tailored pretreatment protocols for alleviating the fouling issue stay required [1]. Fresh techniques were successfully employed to deal with the issue of membrane fouling in MBRs, such as nanomaterials, cell entrapment, biological concepts, and electrically-based processes. Nonetheless, implementing such novel fouling alleviation procedures for large scale MBRs needs more study. Sustainable control of membrane fouling necessitates utilizing more than one single strategy [109].

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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