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Pawel Krzeminski, Lance Leverette, Simos Malamis, Evina Katsou

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Membrane bioreactors – a review on recent developments in energy reduction, fouling control, novel configurations, LCA and market prospects.

Pawel Krzeminski[a,*], Lance Leverette[b], Simos Malamis[c], Evina Katsou[d]

[a]Section of Systems Engineering and Technology, Norwegian Institute for Water Research (NIVA), Gaustadalléen 21, N-0349 Oslo, Norway.

[b]Industrial Strategic Market Consultant, 257 Gano Street #7 Providence, Rhode Island 02906 United States.

[c]Department of Water Resources and Environmental Engineering, School of Civil Engineering, National Technical University of Athens, 5 Iroon Polytechniou St., GR-15780, Athens, Greece.

[d]Department of Mechanical, Aerospace and Civil Engineering, Brunel University, Institute of Environment, Health and Societies, Kingston Lane, Uxbridge Middlesex UB8 3PH, UK.

[*]Corresponding author – Tel: +47 (0) 982 15 464, E-mail: pawel.krzeminski@niva.no

Abstract

Membrane bioreactor (MBR) technology is considered a well-established, mature technology with many full-scale plants around the world treating municipal and industrial wastewater. However, membrane fouling and energy consumption still remain serious obstacles and challenges in the wider spread of the MBR technology. Therefore, considerable research and development efforts are still underway. Recent developments are primarily focused on aspects related to energy reduction, fouling control and novel configurations for enhanced process performance. This review addresses the recent work on the above mentioned aspects and it discusses the overall life cycle of MBRs and the market prospects for MBR technology. Novel MBR configurations and integrations with other technologies are also reviewed. Finally, the challenges that need to be addressed in order to facilitate market penetration of MBR technology are highlighted.

Abbreviations: A^{2}O MBR, anaerobic–anoxic–oxic membrane bioreactor; AnMBR, anaerobic membrane bioreactor; AO or A/O, anoxic–oxic membrane bioreactor; AOXMBR, airlift oxidation ditch membrane bioreactor; BEMR, bioelectrochemical membrane reactor or bio-entrapped membrane reactor; BG-MBR, batch granulation membrane bioreactor; BMBR; baffled membrane bioreactor; e-MBR, electro-membrane bioreactor; EMBR, electrochemical membrane bioreactor; CAGR, compound annual growth rate; CAS, conventional activated sludge; COD, chemical oxygen demand; DO, dissolved oxygen; EPS, extracellular polymeric substances; FO, forward osmosis; GAC, granular activated carbon; HFPV-MBR, high frequency powerful vibration membrane bioreactor; HG-MBR, hybrid growth membrane bioreactor; HO MBR, hypoxic/oxic membrane bioreactor; LCA, life cycle assessment; MB, moving bed bioreactor; MBR, membrane bioreactor; MCP, mechanical cleaning process; MEBR, membrane electro-bioreactor; MF, microfiltration; MFC, microbial fuel cells; MLE, modified Ludzacke Ettinger; MLSS, mixed liquor suspended solids; MMV-MBR, magnetically induced membrane vibration membrane bioreactor; MPBR, membrane photobioreactor; OG, graphene oxide; OMBR, osmotic membrane bioreactor; PAC, powdered activated carbon; PBM, polymerisable bicontinuous microemulsion; PVDF, polyvinylidene fluoride; QQ, quorum quenching; rMBR, reciprocation membrane bioreactor; SADp, specific aeration demand per permeate volume; SADm, specific aeration demand per membrane area; SBAR, sequencing batch airlift reactor; SED, specific energy demand; SMP, soluble microbial products; TN, total nitrogen; TMP, trans membrane pressure; TOC, total organic carbon; TP, total phosphorous; UCT, University Cape Town; UF, ultrafiltration; VMBR, vibrating membrane bioreactor or vertical membrane bioreactor; WWTP, wastewater treatment plant

Keywords: membrane bioreactors (MBRs); energy consumption; fouling mitigation; novel configurations; LCA; market analysis;

1. Introduction

Membrane bioreactor (MBR) technology is considered a well-established, mature technology with many full-scale plants around the world treating municipal and industrial wastewater. However, as membrane fouling and energy consumption still remain serious operational obstacles and challenges in the wider spread of the MBR technology, considerable research and development efforts are still underway. These R&D efforts and continuous interest in MBR technology has led to an increased number of academic publications and MBR-related reviews in the recent years.

Current reviews focused on aspects, such as fouling characterization, visualization and foulants identification [1, 2], modelling [3-5], membrane cleaning [6], addition of activated carbon [7], fouling control [8], process monitoring [9], osmotic MBRs [10-12], removal of pharmaceutical compounds/CECs [13] and treatment of industrial

wastewaters [14, 15]. However, recent developments often resulting in novel configurations or focused on aspects related to energy reduction has attracted little attention. Therefore, it is necessary to review these new developments in MBR technology in a systematic and comprehensive study.

To this end, the purpose of this review is to address the recent R&D advances in MBR technology with regard to energy demand reduction and membrane fouling mitigation, both being the technology key challenges and important aspects of MBR functioning. Novel configurations are also discussed, based on the recent literature on the subject in order to improve the understanding of the recent advances in MBRs.

This review starts with an update on the current technology status and discussion on the cases where MBR makes sense to be applied. Following sections highlight and discuss available fouling control and energy reduction measures. Afterwards, novel MBR configurations developed in the recent years are revised. Subsequently, the paper addresses the overall life cycle of MBRs and the market prospects for MBR technology providing discussion beyond the technical aspects. Finally, the challenges that need to be addressed in order to facilitate the further penetration of the MBR technology are outlined.

2. Current status and application potential of MBRs

In Europe by the end of 2008, 37 MBR plants having a capacity higher than 5,000 m^3/d were operating, while more than 800 commercial MBR applications were in use [16, 17]. It is expected that by 2019 more than 5 million m^3 of wastewater per day will be treated by MBR plants in the world (Table 1). The Henriksdal wastewater treatment plant (WWTP) in Stockholm will be upgraded to an MBR that will treat 864,000 m^3/d of wastewater, making it the largest MBR plant in the world, when it will be commissioned in 2018[1]. In 2004, when the Nordkanal MBR plant was commissioned, it was at the time the largest MBR plant in the world having a design capacity of 45,000 m^3/d. This increase in the design capacity between the Nordkanal and the Henriksdal WWTPs demonstrates the significant growth of MBR technology. Table 1 summarizes the MBR plants in the world which have been commissioned during the last 6 years or are expected to be commissioned within the next 3 years having a design capacity higher than 100,000 m^3/d. Overall the last years, several MBR plants having a design capacity much higher than that of Nordkanal have been developed and are operating.

Table 1. Summary of large MBR plants treating municipal wastewater which have been commissioned during the last 6 years or are expected to be commissioned within the next 3 years having a design capacity higher than 100,000 m^3/d. Adopted from [2] and from Abass et al. [18].

MBR plant	Peak daily flow (m^3/d)	Year of commissioning	Location/Country	New/Upgrade	MBR company
Henriksdal	864,000	2018	Stockholm / Sweden	Upgrade	GE WPT
Seine Aval	357,000	2016	Acheres / France	Upgrade	GE WPT
Canton	333,000	2015	Ohaio / USA	Upgrade	Ovivo
Water Affairs Integrative EPC	307,000		Xingyi, Guizhou / China	New	OW
Euclid	250,000	2020	Ohaio / USA	Upgrade	GE WPT
Yunnan	250,000	2013	Kunming / China	Upgrade	OW
Shunyi	234,000	2016	Beijing / China	New	GE WPT
Macau	210,000	2017	Macau Special Administrative Region / China	New	GE WPT
Fuzhou Yangli	200,000	2015	Fujian / China	New	Memstar / United Enviro
Wuhan, Sanjiang	200,000	2015	Hubei Province / China	Upgrade	OW
Brussels Sud	190,000	2017	Brussels / Belgium	Upgrade	GE WPT
Macau	189,000	2014	Macau / China	New	GE WPT
Riverside	186,000	2014	California / USA	Upgrade	GE WPT
Brightwater	175,000	2011	Washington / USA	New	GE WPT
Visalia	171,000	2014	California / USA	Upgrade	GE WPT
Cox Creek	170,000	2016	Maryland / USA	Upgrade	GE WPT

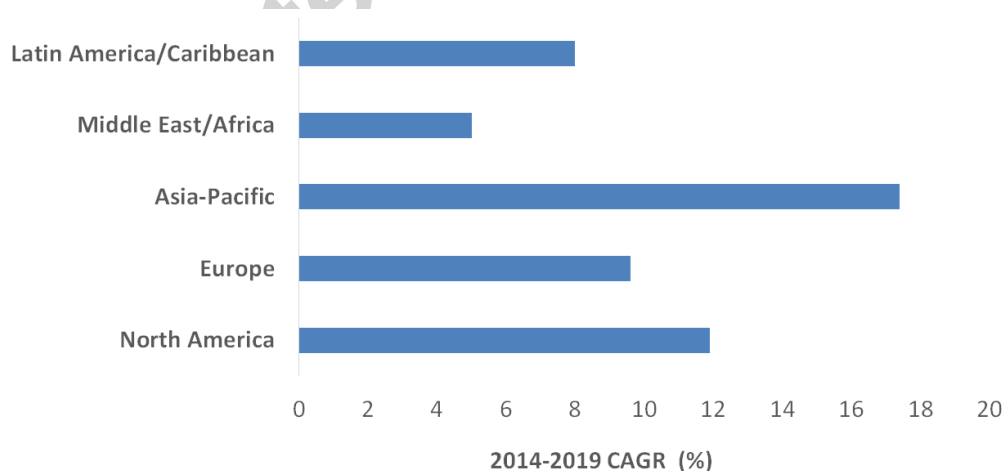[1] http://www.waterworld.com/articles/2015/03/stockholm-to-upgrade-wastewater-treatment-plant-with-ge-technology.html

[2] http://www.thembrsite.com/about-mbrs/largest-mbr-plants/

Qinghe	150,000	2012	Beijing / China	New	OW/MRC
Jilin (Phase I)	150,000	2015	Jilin Province / China	Upgrade	OW
Jilin (Phase II)	150,000	2014	Jilin Province / China	New	OW
Yantai Taoziwan	150,000	2014	Shandong Province / China	New	OW
Nanjing Chengdong	150,000	2013	Jiangsu Province / China	New	OW
Carré de Reunion	144,000	2015	Versailles / France	Upgrade	KMS
Changsha 2nd	140,000	2014	Hunan Province / China	New	OW
North Las Vegas	136,000	2011	Nevada / USA	New	GE WPT
Assago	125,000	2016	Milan / Italy	New	GE WPT
Daxing Huangcun	120,000	2013	Beijing / China	Upgrade	OW
Jinyang	120,000	2015	Shanxi / China	New	OW
Daxing Huangcun	120,000	2013	Beijing / China	Upgrade	OW
SBGE	120,000	2018	Brussels / Belgium	Upgrade	GE WPT
Ballenger McKinney	135,000	2015	Maryland / USA	Upgrade	GE WPT
Yellow River	114,000	2011	Georgia / USA	Upgrade	GE WPT
Aquaviva	108,000	2013	Cannes / France	New	GE WPT
Urumqi Ganquanpu	105,000	2014	Xinjiang Uygur / China	New	OW
Busan	102,000	2012	Busan / Korea	New	GE WPT

GE WPT – General Electric Water and Process Technologies; OW – Origin Water; MRC – Mitsubishi Rayon Corporation; KMC – Koch Membrane Systems.

As membrane prices have significantly decreased over the last 15 years, MBR technology has become a more attractive solution for medium sized plants, having a population equivalent of 10,000-100,000. Furthermore, during the last 15 years significant progress has been accomplished in the design and operation of MBR systems. Design and process optimization has helped to reduce the capital and operating expenses of MBR plants. The current growth of the MBR market is significant, but not as high as forecasted in previous years. In 2008, a 22.4% compound annual growth rate (CAGR) was predicted for the world MBR market for the period 2008-2018[3]. According to the recent report from BCC Research, the global market for MBRs was $425.7 million in 2014 and is projected to approach $777.7 million by 2019, registering a CAGR of 12.8% in the period 2014-2019[4]. Figure 1 shows the 2014-2019 projected CAGR for different areas worldwide. The CAGR is expected to be 9.6% in Europe and 11.9% in North America, while the Asia-Pacific is a fast growing MBR market with a CAGR of 17.4%, mainly due to China.

Figure 1. Projected compound annual growth rate (CAGR) for MBRs for the period 2014-2019.

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[3]http://www.waterworld.com/articles/wwi/print/volume-27/issue-2/regulars/creative-finance/membrane-multiplier-mbr.html
[4]http://www.prweb.com/releases/2015/07/prweb12827585.htm

However, MBR plants still remain more expensive compared to the conventional activated sludge (CAS) process, particularly for most of the small and decentralized schemes. This is also reflected by the level of penetration of MBR technology, which still remains low. In 2009, only 0.5% of the population in Europe was serviced by MBRs for municipal wastewater treatment [17]. This figure is expected to remain below 1% in the coming years. In the cases of low strength municipal wastewater the annualised investment costs of MBRs are still approximately 50% higher than those of a CAS. This is due to the cost of installing, maintaining and replacing the membranes, the need for more extensive pre-treatment, higher degree of automation and higher energy requirements [19]. Operational costs related to energy requirements for membrane fouling control and chemical costs required for membrane cleaning still heavily burden the economic feasibility of MBRs. It is therefore unlikely that the MBR will widely replace the CAS process [20] unless a high quality treated effluent is required. MBR offers equivalent treatment to combined CAS–Microfiltration (MF) / Ultrafiltration (UF) processes; however the latter is at the expense of higher energy cost compared to the CAS process.

The average specific energy requirements concerning MBR operation which have been reported are usually in the range of 0.6-2.3 kWh/m^3 of treated effluent, depending on the size and operating conditions of the plant and on the level of plant optimization [21, 22]. At optimal operating conditions, large MBR plants can reach as low as 0.4 kWh/m^3 in terms of their specific energy requirements. However, in many cases this figure cannot be accomplished. Combined sewer systems and high seasonal variations adversely affect MBR energy efficiency. The reduction of energy consumption of MBRs is highly important for their wider implementation. The selection of adequate equipment coupled with the implementation of strict aeration control based on online monitoring of various process parameters can contribute to lowering the specific energy requirements. Aeration control strategy in aerobic tanks is of particular significance to reduce the overall energy requirements. The use of dissolved oxygen (DO) based on automatic aeration control has attracted attention as a way to reduce energy consumption [23]; recent studies have shown promising results (20% and 4% reduction of aeration and energy consumption respectively) by applying ammonia-N-based aeration control strategy in full-scale MBRs [24]. The difference in investment costs between MBR and CAS processes can further reduce in the future. The continuous competition among the membrane suppliers may drive the membrane module prices even lower.

In small and decentralized systems, MBR suffer from "down-scale" design approach of large MBRs resulting in high specific energy requirements (often higher than 3 kWh/m^3). As noted by Lesjean et al. [20] the viability of MBR plants in the range of 50-2000 PE is restricted mainly due to high specific energy requirements. On the other hand, Tai et al. [25] listed a number of reasons based on which MBR technology was selected as the best available technology for decentralised applications: compact footprint; treated effluent water quality equivalent or superior to tertiary treatment; fully automatic operation allowing for remote monitoring and control of the system; minimal operator attention; silent and odourless operation; modular design allowing for future expansion of the system; aesthetic integration into the surrounding environment and pre-engineering and pre-testing of the MBR system suitable for the fast-track project schedule.

Overall, the growth of MBR technology is driven by: (i) the high quality of produced water, (ii) increased water scarcity, (iii) the increasingly strict discharge and reuse quality legislation, (iv) the decreasing investment costs, (v) the acceptance of the technology and (vi) the potential for upgrading existing WWTPs [26, 27].

MBRs are recognized for the production of excellent and stable quality of treated effluent, and their potential to implement water reuse. Therefore, the main market driver for MBRs is the requirement to comply with strict treated effluent discharge or reuse limits (i.e. discharge of the treated effluent into a sensitive water body) (Figure 2). The introduction of more stringent discharge and reuse limits and environmental quality standards (EDS) such as those specified in the EU Water Framework Directive (WFD), the EU Urban Waste Water Treatment Directive (91/271/EEC), the revised EU Bathing Water Directive (2006/7/EC), the Directive on Environmental Quality Standards (2008/105/EC), or the Clean Water Protection Act (2009), the Pollution Prevention Act (1990), the Clean Water Act (1983) in the USA, were of the most importance in relation to the MBR market growth. Table 2 shows some more specific examples of strict legislation in terms of treated effluent discharge and reclaimed water reuse which have or are expected to enhance the application of MBR technology. Following the adoption of strict legislation in 1999 by the Italian Ministry of Environment several (>40) small scale MBRs were installed at the historical centre of Venice for the treatment of domestic wastewater. Furthermore, the largest petrochemical MBR plant in the world is located in the industrial zone of Porto-Marghera in Mestre having a design capacity of 40,000 m^3/d [28, 29]. The treated industrial effluent is discharged into the Lagoon of Venice. The adoption of MBR can

enhance water reuse applications due to its superior performance with respect to pathogen removal. In Stockholm, Henriksdal WWTP is upgraded with MBR in order to expand the plant capacity and to comply with EU WFD and the Baltic Sea Action Plan. Several Mediterranean countries (Italy, Spain, Greece, Cyprus, Israel) have in place limits for reclaimed water reuse which cannot be met by the typical activated sludge process coupled with disinfection [30, 31]. Specifically, the limit of 10 mg/L for total suspended solids, which is usually adopted cannot be ensured by the typical activated sludge process, but it is definiletly met by the MBR processes. In addition, the MBR process results in physical disinfection of the wastewater so that the subsequent disinfection process is much more effective ensuring the compliance with the microbiological limits. Water reuse is an important measure to simultaneously address fresh water scarcity and environmental pollution [32].
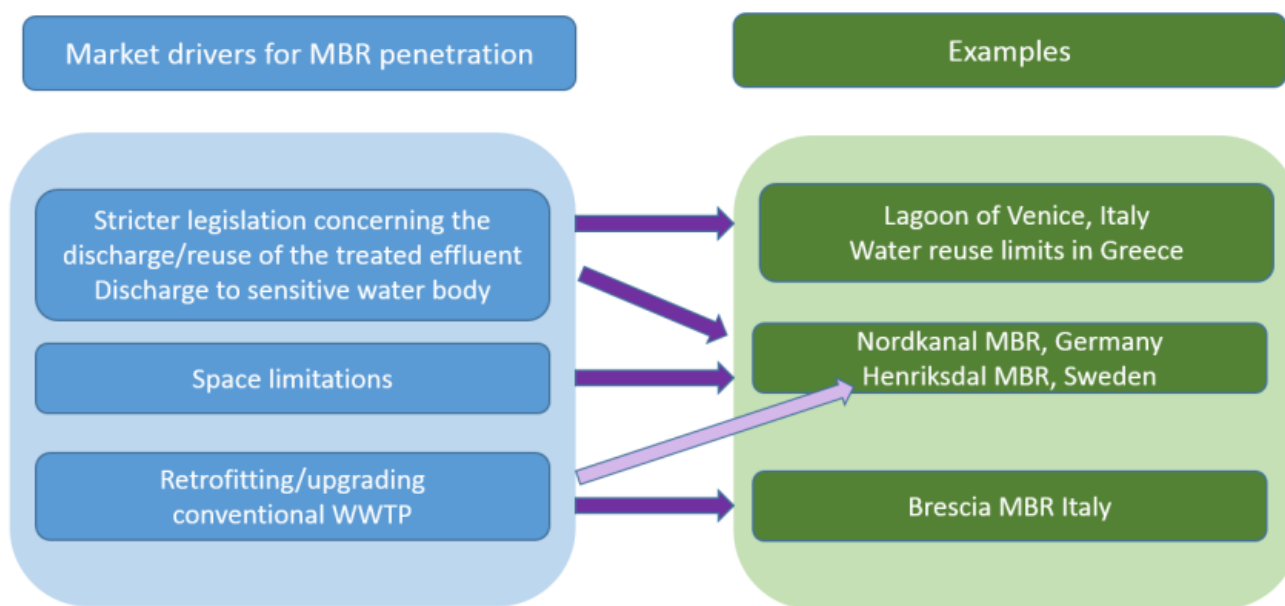
Figure 2. Market drivers for MBR technology and examples of MBR plants which were implemented for these reasons.

Table 2. Examples of stringent legislation which promotes the use of MBR technology

Legislation	Type	Country	Application
Common ministerial decision, 145116/2011	Reclaimed water reuse	Greece	Restricted and unresrtricted irrigation, urban and peri-urban
Decreto Ministeriale	Discharge of treated effluent into water body	Italy	Lagoon of Venice
State of Vermont statute	Phosphorus limit for discharge of treated effluent	USA	Lake Champlain
K.D.P. 269/2005	Reclaimed water reuse	Cyprus	Irrigation of reclaimed water from agglomerations < 2000 population equivalent
Baltic Sea Action Plan	Nitrogen and phosphorous limits for discharge of treated effluent	9 countries from Baltic Sea area	Nutrient reduction scheme for Baltic Sea

Other potential drivers for MBR technology can be space limitations and settling problems encountered in the CAS process. For example, in the case of the Nordkanal MBR plant, this technology was selected in order to save space, since the plant is adjacent to a forest. Furthermore, treated effluent of high quality is required as it is discarded into a canal which flows into a lake used for amenities and swimming. Space limitations were also of importance in retrofitting Henriksdal WWTP, which is located underground in the centre of Stockholm inside a rock. Therefore, to avoid the challenge of laborious and expansive works in the rock structure, MBR was selected for the retrofit and upgrade[5]. The increase in land price will favour MBR development since such systems require much less space than

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[5]http://www.thembrsite.com/news/henriksdal-wastewater-treatment-plant-stockholm-will-become-worlds-largest-mbr-facility

CAS. Furthermore, retrofitting the existing, conventional treatment plant into an MBR system can increase the treatment capacity up to three times without additional space requirements [19]. As pointed out by Kraemer et al. [33], industry practice has evolved towards re-using the bioreactors, while constructing new membrane basins. This is mainly due to the fact, that significant modifications are needed to the tanks to achieve the necessary geometry, number of basins, and provisions for high mixed liquor recycle flow rates.

Often in research works, the presence of membranes in MBR is overemphasized, shadowing the importance of the biological processes. The main function of the membrane is to achieve complete rejection of suspended particles. However, in the biological reactors of MBRs the processes of biodegradation, nitrification/denitrification precipitation and adsorption are the prominent ones as in other biological treatment process [20]. In fact, it is the combined biological treatment with effective filtration that can ensure the desirable treated effluent quality. Thus, MBR is a biological process designed to remove organic matter and potentially nitrogen and phosphorus, combined with a membrane separation able to enhance the performance of the biological processes. Yet, typically it has not been designed to remove targeted organic and inorganic micropollutants. Therefore, any reported superiority of the MBR compared to CAS process with respect to micropollutants cannot justify its implementation solely for that purpose.

Katsou et al. [34] have summarized the most important studies concerning the removal of metals/metalloids from municipal wastewater using MBR. MBRs have a small superiority in the removal of heavy metals over the CAS process. The processes of metal adsorption on activated sludge and precipitation in conjunction with the complete rejection of suspended solids and of colloidal matter can enhance metal removal by MBR compared to CAS process. In addition, the metals that have higher affinity to soluble macromolecular ligands may also be rejected to a certain extent by MBR [35, 36]. Recently, the role of problematic biofilm (fouling and clogging layers) has been investigated and its effect on metal removal was outlined [29, 37].

In terms of MBR performance with respect to organic micropollutant removal, recent literature shows that there is no significant advantage of the MBR compared to the CAS process for similar operating conditions [38-42]. The advantage of operating the MBR at very high SRT to promote the biodegradation of recalcitrant compounds is usually offset by the increased operating expenses associated with the higher oxygen requirements of biomass. However, MBRs are able to effectively remove a wide spectrum of organic micropollutants including compounds that are resistant to activated sludge processes [43, 44]. In contrast to the previously mentioned literature, the results of the AMPERES project [45] showed that the MBR process increases the removal of 22 quantified substances by approximately 25% compared to the removal achieved by six CAS plants with comparable sludge age; this is particularly the case for substances which are partially degraded. However, the large confidence interval associated to the activated sludge data does not allow the authors to confirm this observation. Regardless of the applied technology, the removal of micropollutants depends on the treatment conditions and the physicochemical properties of the substances. MBRs must be coupled to post-treatment processes for the elimination of organic micropollutants [46, 47]. A number of research works have reported that the effectiveness of MBR technology in the removal of xenobiotics and persistent organic compounds is not sufficiently pronounced to serve as the sole justification for employing MBRs in municipal wastewater treatment [39, 48]. Another important aspect that can promote the wider MBR application is related to staff expertise. The lessons learned by the application of the Nordkanal and other MBR plants for municipal wastewater treatment, showed that staff training is very important. MBRs require a skilful and motivated workforce, particularly with respect to membrane module operation and maintainance. Thus, the organization of dissemination and training activities as well as the discussion of operating experiences and control practices is important in order to familiarise the operators with MBR application and challenges.

Concluding, MBRs have become an accepted option to consider for applications requiring a high quality of treated effluent, small footprint, particularly in situations with stringent suspended solids, nutrient and microbiological limits or when water reuse is required [33, 49].

3. Fouling and fouling control

Although MBRs are currently a mature technology, membrane fouling remains the most important operational problem, hindering their universal and wide scale application. Membrane fouling reduces MBR productivity, increases the energy requirements due to air scouring and requires frequent cleaning of the membrane to restore its permeability; the latter shortens the membrane's lifespan and results in higher membrane replacement costs. It is thus not surprising that an immense amount of literature has been devoted to membrane fouling, trying to explain the mechanisms responsible for its formation and to develop ways to mitigate this in order to make the technology even more attractive.

Fouling in MBR processes results from the interaction among the mixed liquor and the membrane. The three main mechanisms responsible for membrane fouling are: (a) pore narrowing which is attributed to the sorption of soluble and micro-colloidal substances having a size much smaller than the membrane pore size, (b) pore plugging due to the deposition of particles having a size similar than to that membrane pores and (c) cake layer formation on the membrane's surface due to the deposition of substances on the membrane's surface [50]. The type of foulants which occur are: biofilm including extracellular polymeric substances (EPS), soluble organics, particulates, colloids, dissolved inorganic compounds [51]. The parameters which impact on membrane fouling in MBR processes can be grouped in four main categories, which include (a) the membrane characteristics, (b) the mixed liquor properties, (c) the operating conditions and (d) the properties of sewage.

The control and mitigation of membrane fouling is essential in MBR systems in order to ensure a cost effective and long-term operation. The main strategies that are applied to control fouling and clogging in full-scale MBRs, include [52]:
- Application of suitable pre-treatment to the feed wastewater
- Permeate backflushing/backwashing or relaxation
- Chemical cleaning of membranes
- Chemically enhanced backwash
- Membrane scouring through coarse bubble aeration
- Chemically modifying the mixed liquor

In backflushing, the filtration flow is reversed in order to remove the particles attached to the membrane surface. In relaxation, the filtration process stops to relieve the membrane from the generated pressure. Backflushing or relaxation are integrated within the normal operation of the MBR so that a filtration cycle consists by a few minutes of filtration followed by a short backflushing or relaxation period. Backflushing/relaxation can remove most of the reversible fouling and is thus effective in removing the cake layer. In a submerged MBR the required membrane scouring is accomplished through coarse bubble aeration which is introduced at the bottom part of the membrane modules. Efforts have concentrated on optimizing the operation of the coarse bubble aeration in terms of intensity and duration, with internmitted aeration also being applied. Chemical cleaning is carried out using mineral organic acids, caustic soda or sodium hypochlorite, and can be carried out either in situ and/or ex situ. Usually sodium hypochlorite is applied to remove biofouling and citric acid is used to remove inorganic fouling. Chemical cleaning can also be carried out during the normal MBR operation by adding a low chemical concentration to the backflush water; this is known as chemically enhanced backflush. Chemical cleaning is particularly effective for combating irremovable fouling, which cannot be removed during the normal operation of the MBR. The suppliers of MBRs propose their own chemical cleaning protocol. However, frequent, intensive chemical cleaning reduces the life span of the membrane.

Additives can be inserted to the biomass in order to modify the mixed liquor characteristics, favouring the filtration process and reducing fouling. Such substances can be coagulants, polyelectrolytes, adsorbing agents and membrane performance enhancers. Coagulants introduce positive charges, neutralizing the negative charges of biomass, thus enhancing flocculation [53]. Zeolite and activated carbon are adsorbents which have been added into the mixed liquor of MBR to mitigate fouling by adsorbing colloidal and soluble substances [54, 55]. Rezaei and Mehrnia [56] added natural zeolite to decrease the concentration of soluble microbial products and thus mitigate fouling. Deng et al. [57] concluded that the added sponge can reduce cake formation and pore blockage in a submerged MBR. Ng et al. [58] found that the addition of 1 g/L of powdered activated carbon decreased the specific resistance of the cake

layer which developed on the membrane's surface. The testing of different additives has shown that the cationic polymer MPE50 and poly-aluminium chloride are very effective in decreasing membrane fouling [59]. However, the use of additives is not usually practiced in full-scale MBRs since it is uncertain whether the cost of chemical use is justified by the membrane fouling decrease. Furthermore, the long term implications of using, or stopping to use, additives have not been researched in detail.

A novel method which can be applied to improve MBR performance is the chemical modification of the membrane's surface. Deowan et al. [60] applied a novel antifouling coating to commercial UF membranes, which was based on a polymerisable bicontinuous microemulsion (PBM) technique. The authors compared the performance of a novel MBR in which this coating was applied to a conventional MBR and concluded that the novel MBR exhibited much lower fouling. Similarly, Zhao et al. [61] developed a composite microfiltration membrane, which was made by blending polyvinylidene fluoride (PVDF) and hydrophilic graphene oxide (GO) nanosheets. This PVDF/GO membrane was tested on an MBR system and performed better since it exhibited higher critical flux, lower cleaning frequency and lower membrane resistance than a conventional PVDF membrane of an MBR. Quorum quenching (QQ) has recently been acknowledged as an effective antifouling strategy. However, there are very limited full scale applications and practical issues such as the cost and stability of enzymes need to be tackled [62].

The integration of advanced oxidation processes with MBRs [63] or electrocoagulation with MBRs [64] can be very effective in removing recalcitrant compounds such as pharmaceuticals and also decreases MBR fouling [65]. Furthermore, the integration of microbial fuel cells to MBRs (MFC-MBR) to treat wastewater can also decrease membrane fouling. The latter is attributed to a change in the activated sludge properties, since the biomass in the MFC-MBR process is characterized by lower amount of loosely bound EPS, more homogenized sludge and lower amount of filamentous bacteria [66]. However, in the aforementioned process the main drive for their implementation is not the reduction of membrane fouling but issues such as enhanced removal of organic micropollutants, energy recovery and lower operating expenses. In addition, such integrated processes are still in their early stage of development as they are being investigated at bench and pilot scale level.

4. Energy reduction

4.1. Current state of full-scale MBRs

Energy demand and related costs issues have, together with membrane fouling issues, become an essential focus point in the full-scale MBR design and operation. According to the recently reported data from full-scale municipal MBRs, the yearly average specific energy consumption varies between: 0.8-2.4 kWh/m^3 in France [67], 0.8-3.0 kWh/m^3 in Japan [68], 0.4-0.6 kWh/m^3 in China [69], 0.4-2.1 kWh/m^3 in Spain [70], 0.8-1.1 kWh/m^3 in the Netherlands [27], and 0.7-1.8 kWh/m^3 in Germany [71].

Recent developments in MBR energy reduction concentrated on the module configuration, aeration strategies, control systems, low-energy membrane cleaning methods or novel fouling mitigation methods such as mechanical cleaning with granular medium, membrane vibration, electric field, and others [1, 72].

4.2. Energy-savings solutions

MBR energy issues have attracted the attention of researchers, practitioners and MBR suppliers, and have led to a number of studies on energy consumption and efficiency of the MBRs. This in turn resulted in several energy-saving solutions, optimization strategies and new commercial products. Table 3 provides an overview of the potential energy optimization measures for MBRs, based on measures implemented at pilot- and full-scale or identified during energy audits at full-scale MBRs.

Many authors [27, 67, 70, 73, 74] stressed the importance of hydraulic capacity utilization of the membranes and operation at optimal flow conditions, i.e., hydraulic load close to the design flow rate, for energy efficient operation of MBRs. Since operation below optimal flow conditions is associated with energy penalty, implementation of flow equalization or adjusting operational settings to the incoming flow was proposed. Coupling of the number of membrane lines or modules in use, intensity of membrane aeration, duration of filtration and relaxation/backwash intervals, and recirculation rates to the incoming loading especially at low flow conditions have a potential to reduce energy consumption. However, these actions are not always permitted by membrane manufacturers. Furthermore,

filtration process optimization could be implemented with frequent activated sludge filterability measurements at an MBR installation [74, 75]. For example, during periods of good activated sludge filterability, operators could prolong the filtration and/or shorten relaxation/backwash intervals to reduce energy consumption and to improve energy efficiency. Moreover, operating close but lower than critical flux is important in order to accomplish hudraulic and energy efficiency. Additionally, frequent filterability measurements could also act as an early warning system for operators and as a membrane aeration energy optimization tool. Pellegrin and Kinnear [76] evaluated energy efficiency of nine full-scale MBRs located mostly in North America and proposed implementation of new air scour strategies, influent flow equalization, operation closer to design fluxes to maximize membrane utilization, and designing MBRs with modular construction with multiple trains to reduce energy consumption. Barillon et al. [67] evaluated energy efficiency of selected full-scale MBRs located in France, Spain and the USA and identified a number of energy-saving solutions: optimized aeration control systems of activated sludge, coupling of sludge recirculation to the influent flow, implementation of variable speed drives on the main electrochemical equipment, and reduction of MLSS concentration. Tolkou et al. [77] highlight the biological aeration adjustment, intermittent denitrification, application of primary clarification ahead of the MBR, flow equalization, solids adjustment between the aeration and the membrane basins, intermittent air scouring or coupling of air scouring to the flux, use of flux enhancers, and pump configuration as the energy-savings solutions. Xiao et al. [69] proposed the utilization of membrane aeration for biological purposes, implementation of simulation modelling and automatic control for biological aeration optimization, improving configuration of membrane module, aeration system, and tank geometry, as well as aeration patterns (e.g., pulsed aeration) to improve efficiency for membrane air scouring as the energy-savings solutions. Gabarron et al. [70] evaluated operational costs of seven full-scale MBRs located in Spain and application of energy-saving strategies. Implementation of intermittent aeration for biological purposes and reduction of MLSS concentration decreased the specific energy demand in a flat-sheet stand-alone MBR from 1.12 to 0.71 kWh/m^3. Implementation of control systems for biological aeration, use of alternative air blower for membrane air scouring, together with modification of the filtration protocol (prolonged filtration, shorter backwash and more frequent relaxation periods) reduced the specific energy demand in hollow-fibre stand-alone MBR from 1.54 to 1.12 kWh/m^3. Finally, optimization of biological aeration and membrane air-scouring together with equalization of influent flow and reduction of permeate flux from 27 to 23 L/m^2·h to lower excessive membrane fouling rates and, subsequently, reduction of the airflow to the membranes, reduced the specific energy demand in hollow-fibre hybrid MBR by an average 14%.

The role of the membrane flux in the energy related aspects is of importance since the flux is directly linked with the hydraulic utilization of the membranes and indirectly with the strategy applied for the membrane air-scouring. Both are the most important operating parameters influencing the MBR energy consumption and energy efficiency [74]. Often, the actual fluxes during normal operation are lower than the design fluxes leading to a less efficient operation, for example due to over-aeration applied for the membrane cleaning, in respect to the specific energy demand per cubic meter of treated water. In such cases, operation with a stable flux close to the design flux should be examined to improve hydraulic utilization of the membranes. If not possible, adapting of operational settings to the incoming flow (e.g. lower aeration at lower flows) or alternate operation of the membrane lines (to increase flux) may be considered. For example, Palmowski et al. [71] proposed filtration at high flux over short time periods as a potential approach to improve specific energy demand. On the other hand, operation with the flux rates exceeding the critical flux will likely lead to increased fouling and/or clogging of the membranes, which in turn is linked with the energy penalty associated with the fouling mitigation measures. In such case, operation with a flux lower than the critical flux may be beneficial also from the energy efficiency point of view.

Table 3. Overview of potential energy optimization measures for MBRs based on measures implemented at pilot- and full-scale or identified during energy audits at full-scale MBRs

MBR type	Measure related to	Energy optimization measure	Energy reduction potential	Reference
Pilot-scale flat-sheet and hollow fibre MBRs (Singapore)	Operation, equipment	Flux increase; lowering air supply by installing variable frequency drivers (VFDs) for the air blowers;	SED from 1.3 to 0.8 kWh/m^3	[79]
Full-scale hollow-fibre MBR (Singapore)	Design, operation, equipment	Designing multiple treatment lines; energy efficient equipment with VFDs; treatment of the settled sewage; gravity driven flow between bioreactor compartments; high throughput filtration	SED from 0.8 to 0.37 kWh/m^3	[79]

		protocol; operation at stable net flux; MLSS reduction to 6 g/L; optimization of MLSS recirculation streams; implementation of biological aeration control; introduction of cyclic membrane aeration (10 sec on/30 sec off);		
Large Pilot-plant hollow-fibre MBR (Singapore)	Design	Installation of a more compact membrane module with higher packing density;	70% reduction of membrane air flow; 40% reduction of SED down to 0.37 kWh/m^3	[80]
Full-scale flat-sheet MBR (Spain)	Operation	Intermittent aeration for biological purposes; MLSS reduction;	SED from 1.12 to 0.71 kWh/m^3	[71]
Full-scale hollow-fibre MBR (Spain)	Operation, equipment	Control systems for biological aeration; filtration protocol modification; lower capacity air blower for membrane air scouring;	SED from 1.54 to 1.12 kWh/m^3	[71]
Full-scale hollow-fibre MBR (Spain)	Design, operation	Aeration control system for biological aeration; inflow equalization; mitigation of excessive fouling rates by permeate flux reduction; membrane air-scouring reduction;	14% reduction of SED	[71]
Pilot-scale flat-sheet UCT-MBR (Spain)	Operation	Over-aeration reduction by lowering aerobic DO set point from 1.5 to 0.5 mgO$_2$/L and membrane airflow SADm from 1.25 to 1.0 m/h;	Up to 81% and 20% reduction of biological and membrane aeration, respectively. 42% reduction of average airflow rate (energy savings of 75%)	[91]
Full-scale hollow-fibre MBR (Spain)	Operation	DO control strategy (lowering the DO set point for biological aeration from 1.2 to 0.8 mgO$_2$/L);	7% saving on biological aeration costs	[22]
Pilot-scale hollow-fibre MBR (France)	Operation	Sequenced aeration (5 sec on/25 sec off); low aeration during filtration and high during backwash;	~50% reduction of membrane aeration flows, further 12% reduction when aeration coupled with filtration/ backwash cycles	[82]
Pilot- and full-scale hollow-fibre MBRs (US, Canada, EU)	Operation	Sequenced membrane aeration (10 sec on/10 sec off; 10 sec on/30 sec off)	50-75% reduction of filtration and air-scour energy	[95]
Small full-scale hollow-fibre MBR, (UK)	Operation	Sequenced membrane aeration (10 sec on/10 sec off; 10 sec on/30 sec off)	Up to 75% reduction of membrane aeration energy (for 10:30 aeration)	[96]
Pilot-scale flat-sheet MBR (Belgium)	Operation	Membrane aeration control system coupled with on-line fouling measurement tool (based on permeate production at given TMP)	22% reduction of membrane aeration flow rate	[98]
Pilot-scale hollow-fibre MBR, Spain	Operation	Membrane aeration control system based on permeability trends	13-21% reduction of membrane aeration energy	[99-101]
Full-scale hollow-fibre MBR (Spain)	Operation	Membrane aeration closed-loop control system based on permeability evolution	13-20% reduction of air scour flow rate, corresponding to 14-22% reduction of membrane aeration energy (by 0.025-0.04 kWh/m^3)	[90]
9 full-scale MBRs (US, Netherlands)	Design, operation	Implementation of new air scour strategies; influent flow equalization; operation closer to design fluxes to maximize membrane utilization; designing MBRs with modular construction with multiple trains;	N.A. (Recommendations from energy audit)	[77]

| 6 flat-sheet and hollow-fibre full-scale MBRs (France, Spain, US) | Operation, equipment | Optimized aeration control systems; coupling of sludge recirculation to the influent flow; implementation of variable speed drives on the main electrochemical equipment; reduction of MLSS concentration; | N.A. (Recommendations from energy audit) | [68] |

DO – dissolved oxygen; N.A. – not applicable; SADm – specific aeration demand per membrane area; SADp – specific aeration demand per permeate volume; SED – specific energy demand [kWh/m^3]; UCT – University Cape Town;

4.3. Success stories

In the recent years, successful optimization strategies demonstrated that energy consumption of a fully optimized MBR can be in the range of 0.4-0.5 kWh/m^3 and efforts are made to establish case-studies with energy consumption lower than 0.4 kWh/m^3. Tao et al. [78] demonstrated, through a six-year long pilot and demonstration scale studies, the reduction of energy consumption in a municipal full-scale MBR from 1.3 kWh/m^3 down to 0.37 kWh/m^3. The actions towards energy reduction consist of: increasing flux, lowering air supply by installing variable frequency drivers for the air blowers, designing multiple treatment lines, gravity driven flow between bioreactor compartments, high throughput filtration protocol (9 min filtration, 1 min relaxation and backwash every 10 filtration cycles), operation at stable net flux of 25.3 L/m^2·h, treatment of the settled sewage, reduction of MLSS to 6 g/L, optimization of MLSS recirculation streams, implementation of biological aeration control and, finally, introduction of 10 sec on/30 sec off cyclic membrane aeration mode.

In another study, Kitagawa et al. [79] estimated a minimum energy demand of a large pilot-plant MBR to be 0.37 kWh/m^3, based on 40% energy reduction through a more compact membrane module with higher packing density allowing reduction of membrane aeration down to specific aeration demand per permeate volume (SADp) of 1.5 m^3 air/m^3 permeate and specific energy demand for membrane air scouring of 0.08 kWh/m^3. Itokawa et al. [68] reported specific energy consumption for a demonstration MBR in Japan to be 0.47 kWh/m^3 on an annual average and 0.39 kWh/m^3 under the full capacity operation. In 2012, new studies were initiated in Japan with the aim to reduce energy consumption of municipal MBRs below 0.4 kWh/m^3 [68].

4.4. Commercial developments

Recent commercial developments include the introduction of new generation membranes, membrane modules and complete MBR systems. In 2011, Koch Membrane Systems introduced new Puron PSH1800 modules, which according to the company offers 10% lower aeration requirements at 10% higher surface area [80]. The module uses a single header with reinforced hollow fibres fixed at the bottom, while the sealed upper end of the fibre floats freely. The new design, similar to the one proposed by Polymem [81], eliminates the build-up of hair and fibrous material that could cause clogging of the upper end of hollow fibre membranes [82]. In 2011, GE WPT introduced a new system, LEAPmbr with ZeeWeed membranes, which according to the company reduces the energy consumption by 30%, while providing 15% higher productivity with a 20% smaller footprint compared to previous company products [83, 84]. The energy reduction arises from a more efficient membrane air scouring system. The LEAPmbr system has been selected for full-scale applications by a number of customers around the world [85-87]. In 2012, Mitsubishi Rayon introduced a new hollow fibre MBR with 30% lower energy consumption compared to previous company products [88]. In 2015, Pentair brought to the market 'Helix', a new flux-enhancing technology with a helically-winding ridge on the inside of the X-flow tubular membrane[6]. The ridge is made of the same material as the membrane which takes part in the filtration process, and is backwashable. Introduction of secondary flows (Dean vortices) and increased wall crossflow velocity have the effect of increasing the shear stress at the membrane wall and, subsequently, promoting flux. Pilot- and full-scale testing demonstrated an increase of operational flux by 15-20% for the airlift MBR and by 40% for the crossflow MBR, at increased pressure drop and reduced specific energy demand by ca. 20% and 35% for airlift and crossflow MBR processes, respectively.

Furthermore, the air scour systems have evolved so that the energy requirements of the leading manufacturers are often comparable [33]. In addition, recent developments have resulted in considerable aeration improvements, e.g., intermittent or cyclic aeration for membrane air scouring, sparger and module geometry, reusing the air scour between different modules [1, 89].

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[6]http://www.thembrsite.com/features/improving-mbr-flux-ultrafiltration-with-a-twist/

However, despite recent developments, the membrane air scour flow rates applied in practice are generally very conservative relative to the MBR manufacturers' recommendations [89]. For example, Dalmau et al. [90] was able to experimentally demonstrate the reduction of aeration for biological and membrane purposes in a pilot scale MBR by 81% and 20%, respectively. During successful optimisation of MBR aeration, over-aeration was limited by reducing aerobic DO set-point from 1.5 to 0.5 mgO_2/L and specific aeration demand per membrane area (SADm) from 1.25 to 1.0 m/h. The average airflow rate was reduced by 42%, which represents an energy savings of 75% compared to initial conditions, without comprising filtration performance, sludge characteristics or nutrient removal efficiency over a course of 35-day experiments.

Therefore, since aeration remains the largest individual cost factor in MBR operation, a large number of studies have been focused on aeration reduction including, aeration control systems, aeration strategies, alternative cleaning methods, etc.

4.5. Control systems

Automation and control presents a wide range of opportunities for optimisation and is a promising alternative to reduce energy consumption of MBRs. Therefore, in the past years different model-based approaches and aeration control systems have been developed and implemented [91].

4.5.1. Model-based approach

Mannina and Cosenza [92] reported energy saving of 20% for a pilot plant MBR by applying a simulation-based approach with a control system based on TMP and treated effluent quality. Gabarrón et al. [23] identified optimization strategies to improve treated effluent quality and reduce energy/operational costs for full-scale MBRs through the model-based approach. For a full-scale MBR, lowering the DO set point from 1.2 to 0.8 mg/L resulted in an increase in nitrogen removal efficiencies by up to 27% and a decrease of biological aeration by up to 7%, without affecting filtration performance or sludge characteristics.

4.5.2. Open-loop control systems

Lorain et al. [81] tested a pilot scale MBR with sequenced aeration with cycles of 5 sec on and 25 sec off and a strategy of low aeration during filtration and high aeration during backwash. The sequenced aeration reduced the membrane aeration flows by nearly 50% (from SADm of 0.5 $m^3/m^2 \cdot h$ to 0.260 $m^3/m^2 \cdot h$), whereas coupling of aeration with filtration/backwash cycles reduced the membrane aeration flows by another 12% (SADm of 0.19 $m^3/m^2 \cdot h$). Braak et al. [93] also pointed out that intermittent aeration, especially working with intermittent filtration, enables to save energy. Adams et al. [94] optimized alternating aeration strategies of GE's membrane system, i.e., 10 sec on – 10 sec off (10:10 aeration) and 10 sec on – 30 sec off (10:30 aeration), reducing the amount of air-scouring and achieving, respectively, between 50% and 75% energy consumption reductions. Verrecht et al. [95] also investigated different membrane aeration strategies: continuous aeration, 10 sec on – 10 sec off (10:10 aeration), and 10 sec on – 30 sec off (10:30 aeration). The study has revealed that 10:30 aeration may provide membrane aeration energy savings of up to 75% compared to continuous aeration, with no significant impact on the fouling rate. With new aeration protocols already in use at some of the large scale plants, these findings are corroborated by recent industrial practice [95, 96]. However, as pointed out by Monclús et al. [89], these strategies are open loop strategies where an aeration rate is independent from operational or environmental conditions and always follows the same pattern. Further energy reduction can be achieved by implementation of closed-loop aeration strategies.

4.5.3. Closed loop control systems

Huyskens et al. [97] applied an on-line fouling measurement tool (measuring permeate production at given TMP) as an automatic control system for air-scour reduction and validated it at pilot scale. An average 22% reduction in membrane aeration flows was achieved without negative impact on filtration performance. Ferrero et al. [98-100] demonstrated an average energy reduction for membrane aeration of 13% and a maximum of 20%, in pilot scale MBRs through an automatic control system based on permeability trends without interfering with membrane fouling and biological nutrient removal. Recently, Monclús et al. [89] developed a closed-loop air scour control system, 'Smart Air MBR®', based on permeability evolution and validated at full-scale over a 1-year period. The aeration control system working in real time was able to reduce the air scour flow rate on average by 13%, corresponding to

a decrease in the average energy consumption for membrane aeration of 14% (0.025 kWh/m^3), without affecting permeability, fouling rate trends, biological nitrogen removal efficiency or sludge characteristics.

However, to evaluate the effective gain of the applied control system, it is important to consider potential implications related to the control system introduction, such as the increasing plant complexity, investment, and maintenance costs.

4.6. Hydrodynamics

A number of studies have been devoted to hydrodynamic sheer stress generation on the membrane surface to reduce membrane fouling and provide an alternative to the air scouring membrane cleaning technique. Traditionally, hydrodynamic sheer stress on the membrane surface is achieved by intense air-scouring with coarse air bubbles to move the fluid next to the membrane. Over the years, in order to increase hydrodynamic forces and thus reduce energy demand, several operational and geometrical approaches have been proposed: intermittent aeration, alternating aeration with different bubbling regimes (e.g., large spherical cap bubble, slug flow), introduction of granules/carriers, and turbulence promoters (e.g., membrane spacer, helical baffles) [101]. Zhang et al. [102] studied two bubbling regimes, free bubbling and slug bubbling, in parallel flat sheet lab-scale MBRs. The average aeration energy induced by free bubbling was estimated to be 2.07 kWh/m^3 compared to 1.41 kWh/m^3 for a slug bubble, highlighting the slug flow potential to save energy in flat sheet MBRs. In addition, the slug flow controls fouling better compared to the free bubble technique. Furthermore, according to Prieske et al. [103] modification of the shape and location of membrane aerators, i.e., smoother draft tube edge, increased the liquid circulation by 30-50%, likely resulting in lower requirements for air-scouring rates. Additionally, Xia et al. [104] observed, during air sparging of hollow fibre membranes, that aeration when located at the two sides of the membrane module and alternately operating air spargers was more energy efficient compared to one centrally located air sparger. Different researchers studied the introduction of a granular medium into submerged MBRs to mitigate membrane fouling, and thus reduce aeration requirements for membrane air-scouring, by providing mechanical cleaning to the membrane surface [105-108]. According to Krause and Dickerson [109] and Krause et al. [110], the implementation of granules for the mechanical cleaning process (MCP) and optimized PLC programming, allows for an operation of municipal MBRs with SED of 0.5 kWh/m^3. According to Kurita et al. [111, 112] the introduction of granules reduced aeration by 50% during bench-scale experiments with continuously aerated flat-sheet MBRs. However, an important aspect of mechanical cleaning with granules or carriers that requires further study is the promotion of physically irreversible fouling and the risk of membrane surface damage [112]. In baffled membrane bioreactors (BMBR), baffles divide the membrane tank into sections that during aeration, due to difference in gas hold-up and fluid density, create a cross flow over the membrane's surface [113]. Recently, the use of baffles, inserted into the membrane compartment of submerged MBRs, were investigated to optimize hydraulic conditions in the reactor in order to improve aeration efficiency [113] and to enhance the efficiency of mechanical cleaning with granules [112].

In alternative methods of low-energy membrane cleaning, the sheer at the membrane surface is generated by mechanical vibration [114-118], rotation [6] or reciprocation of the membrane surface itself [119, 120]. Different vibration systems were recently proposed, namely, transverse vibration [115], vertical reciprocating movement [116], magnetically induced membrane vibration (MMV) [114], and high frequency powerful vibration (HFPV) [117, 118]. All can overcome the hydrodynamic limitations of air scouring and contribute to a low air-scouring operation due to the periodic implementation of mechanical movement. Additional benefit is the potential to lower DO in the activated sludge returned from the membrane tank to the anoxic tank, which is often DO rich and decreases the denitrification efficiency of the anoxic reactor of the MBR. The reciprocation MBR (rMBR), described in *5.1*, provides a step-further. The rMBR eliminates the need for an air scouring system and elevated DO concentration in the return stream to the anoxic tank at a low specific energy consumption for membrane reciprocation of 0.072 kWh/m^3. This is 75% less than conventional membrane air scouring systems which are in the range of 0.29-0.31 kWh/m^3 [27, 96]. In 2015, the rMBR called LENA MBR was introduced to the market by Doosan [121]. Finally, in another approach, Akamatsu et al. [122] proposed the application of intermittent electric fields for fouling mitigation as an energy-saving alternative to energy intensive air scouring.

As the MBR is an energy intensive process, it is expected that innovative ways to decrease energy requirements will be transferred to practice. For example, the application of intermitted coarse bubble aeration which was tested in

demonstration scale MBRs, is already implemented in practice. It is expected that new air scouring and filtration strategies as well as control and automation processes that limit the supply of air without adversely affecting the permeate quality or membrane fouling will find their way into the market. Specifically, closed loop aeration strategies are expected to be applied in full scale MBRs; in these cases the coarse bubble aeration or the filtration pattern can be continuously adjusted based on online measurements of filterability, fouling or other recorded parameters.

5. Novel configurations

Recent R&D advances in MBRs with respect to novel configurations have focused on membrane fouling control, energy demand reduction, enhanced nutrient removal or removal of refractory compounds [2, 12, 77].

5.1. Membrane fouling control

A number of MBR systems utilizing dynamic shear-enhanced filtration through **rotation, vibration or reciprocation movement** have been studied in the last years to reduce membrane fouling, concentration polarization and to provide low-energy alternative to intense air-scouring membrane cleaning. **Rotating MBRs** have been equipped with flat-sheet [123-127], tubular [128], hollow fibre [129], or helical [130] membrane modules. Increase in rotation speed can lead to better performance in terms of fouling control [124]. Wu et al. [123] found that rotation speed has an influence on cleaning efficiency until a critical speed of 60 r/min was reached, after which little effect is observed. Jiang et al. [127] demonstrated that rotating flat-sheet MBR have a slower fouling rate compared to conventional MBRs when consuming the same energy. Paul and Jones [131] estimated through the modelling studies that, the rotation efficiency in terms of fouling prevention was 12%, suggesting that prevention of cake build-up and fouling is mostly accomplished by air scouring. Various types of rotation MBRs are currently available on the MBR market as commercial products, including a cross-flow MBR system with rotating ceramic discs impellers Grundfos BioBooster [132] and Huber vacuum rotation membrane VRM® bioreactor [133]. In **vibrating MBR (VMBR)** different motions/mechanical forces, i.e., longitudinally, transversely, torsionally or their combination, generates sheer at the membrane surface to mitigate fouling. Different VMBR have been studied as a fouling control option, e.g., transverse vibration system [115], vertical movement [116], magnetically induced membrane vibration (MMV-MBR) [114], and high frequency powerful vibration (HFPV-MBR) [117, 118]. These designs allow a low air-scouring operation due to the periodic implementation of vibration and have a potential to lower DO in the activated sludge returned from the membrane tank to the anoxic tank, which is often DO rich and decreases the denitrification efficiency of MBR [120]. Low frequency and low amplitude vertical vibrations were sufficient to keep the hollow-fibre membrane almost free from fouling [134]. Critical fluxes of a bench-scale unit increased from 15 $L/m^2 \cdot h$ to 27 $L/m^2 \cdot h$ when membrane vibration was implemented, and further to 56 $L/m^2 \cdot h$ when frequency of vibrations increased from 1.7 to 8.4 Hz [135]. In addition, other authors [115, 116] observed a reduced fouling rate and enhanced critical flux during vibration enhanced filtration. In addition, Li et al. [116] reported that 1-2% loosening of fibers can further increase the permeate flux. Bilad et al. [114] demonstrated that MMV-MBR achieved higher flux and lower degree of fouling compared to aerated systems. In the HFPV-MBR periodic high frequency vibrations up to 223 Hz were implemented during the relaxation of hollow fibre membranes, without interrupting the operation of the submerged MBR system [117]. Subsequently, membrane performance in respect to TMP and flux were recovered to conditions of a nearly clean membrane [118]. Although various VMBRs seem very promising it is important to note that many of the vibration systems were investigated at small scale and at low MLSS concentrations of 4-5 g/L. Additional information on the vibration/rotation MBRs have been provided in a recent review by Wang et al. [136]. The **reciprocation MBR (rMBR)** utilizes inertial force on the membrane fibres by the horizontal reciprocating motion of the membrane cassette to reduce membrane fouling in the absence of air scouring [119, 120]. The rMBR eliminates a need for air scouring system and elevated DO concentration in the return activated sludge stream to the anoxic tank reducing denitrification efficiency.

The newly developed **helical membrane** modules strengthen scouring, reduce membrane fouling and increase permeate flux due to vortex mixing and associated intensified turbulence at the membrane surface [137, 138]. In the early systems, the module was positioned vertically with a lower part loose, whereas in a more recent version the module rotated counter clockwise to further increase permeate flux by 27% [130]. 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[7]. In **baffled MBR** (BMBR), inserted baffles divide the bioreactor into two zones, to alternatively create anoxic/aerobic conditions in the tank as long as wastewater is fed in appropriate way [139]. These conditions are expected to stimulate simultaneous nitrification and denitrification, resulting in efficient nitrogen removal [140]. During pilot-scale experiments, the average removal efficiencies of TOC, TP and TN were 85%, 97% and 77%, respectively [140]. Furthermore, due to difference in gas hold-up and fluid density in different zones, during aeration a cross flow over membrane surface is created providing additional membrane cleaning [113]. For example, Shariati et al. [141] developed an **airlift oxidation ditch membrane bioreactor (AOXMBR)** consisting of submerged flat-sheet membrane and air injection system placed between two baffles providing aeration for biological purposes, membrane scouring and activated sludge circulation. Recently, the use of baffles, inserted in the membrane compartment of a submerged MBRs, was investigated to optimize hydraulic conditions in the reactor in order to improve aeration efficiency [113] and to enhance the efficiency of mechanical cleaning with granules [112]. Table 4 provides an overview of novel MBR configurations for improved membrane fouling control.

Table 4. Overview of novel MBR configurations for improved membrane fouling control

MBR type	Membrane type	Main findings in terms of fouling	Reference
Rotating MBR	Flat sheet	Flux increased from 42 $L/m^2 \cdot h$ to 47 $L/m^2 \cdot h$ when rotational speed increased from 15 to 25 r/min	[125]
Rotating MBR	Flat sheet	Membrane fouling rate is much lower in rotating MBR compared to conventional MBR for the same energy consumption	[128]
Rotating MBR	Tubular	The fouling rate decreased as the rotational speed of the module increased	[129]
Rotating MBR	Hollow fibre	At the tested rotational frequencies, high dispersive conditions were present and significantly larger then those observed during static operation	[130]
Reciprocal MBR	Hollow fibre	Low and stable transmembrane pressure was achieved at 40 $L/m^2 \cdot h$ by use of repetitive membrane reciprocation	[132]
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	[131]
Baffled MBR	Flat sheet	10–30% increase in membrane surface shear compared with the no-baffle configuration at the same aeration intensity	[114]

5.2. Energy demand reduction

In another approach, Akamatsu et al. [122] proposed the application of intermittent **electric field** for fouling mitigation as an energy-saving alternative to energy intensive air scouring. Mechanisms of fouling reduction via electric field may include electro-coagulation (increase sludge size and reduce Zeta potential), electrophoresis and electrostatic repulsion/rejection against electronegative colloids or particles [142]. To reduce the energy demand associated with electric field generation new configuration of electrodes and membrane, **electrochemical MBR (EMBR)**, coupled with low voltage and low intensity electric field was developed [142]. Copper wire cathodes inside the membrane module and stainless steel mesh anodes outside the module were used. The application of a minute electric field, through electrostatic repulsion and electrophoresis mechanisms, contributed to 20 times lower fouling rate, 20-25% higher flux and slightly enhanced removal of COD, phosphorous and ammonia. In submerged **membrane electro-bioreactor (MEBR)** electrocoagulation was incorporated inside of the MBR and intermittent direct current field was applied [143, 144]. Under the 15 min on and 45 min off operational mode, the fouling rate was reduced by up to 16% [143]. The removal efficiency of COD increased from 75-90% to 85-95%, and phosphorous removal from 75-96% to 98% on average. However, the nitrification process was less efficient when a direct current was applied as the maximum removal efficiency of ammonia reduced from 97% to 82% [144]. Current should be applied intermittently and at density below 25 A/m^2 to maintain high microbial activity [145, 146]. Ibeid et al. [147] studied electrokinetic processes leading to 3 times lower fouling rate in a pilot-scale MEBR. The electrokinetically conditioned activated sludge was found to have less fouling potential due to: i) removal of soluble microbial products (SMP) and colloidal organic materials; ii) changes in the structure and morphology of

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[7]http://xflow.pentair.com/en/products/compact-helix

suspended solids, and thus also activated sludge flocs. During further pilot-scale experiments with hollow fibre membranes, improvement in sludge filterability, no significant TMP increase and enhanced treatment performance were observed [148]. During steady state operation, the removal efficiencies of COD, NH_3-N and PO_4-P, were 92%, 99% and 99% respectively. The specific energy demand of the system was in the range of 1.1–1.6 kWh/m^3. Zhang et al. [149] studied two **electro-MBRs (e-MBRs)**, one with stainless steel anodes (Fe-MBR) and the other one with titanium anodes (Ti-MBR), with intermittent application of low-voltage electric-field to suppress fouling. In the Fe-MBR, 30% reduction of TMP was achieved, while 0.052 kWh/m^3 more electricity was consumed. Hosseinzadeh et al. [150] operated flat-sheet electro-MBR in parallel to conventional MBR pilot-plant. They demonstrated reduced fouling rate leading to less frequent membrane cleanings and improved COD removal from 80% to 85%. Furthermore, the maximum current density which does not disturb the biological activity of microorganisms was reported to be 10 A/m^2. Similar current density was also reported by Tafti et al., [151] who under the optimum conditions with a current density of 12.5 A/m^2 and an exposure mode of 185 sec on − 415 sec off, achieved improved sludge characteristics, reduced fouling rate and enhanced removal performance. The removal efficiencies for COD and phosphate removal were respectively 4% and 43% better compared to an unmodified MBR system. However, the aforementioned methods require the application of an external electric field, which increases energy demand, but also adds up to system complexity [152]. Therefore, owing to H_2O_2 production at the cathode, the in-situ generated electricity was utilized to achieve good antifouling performance and high COD and ammonia removal efficiencies [152].

In a similar approach, a system combining conventional MBR and microbial fuel cells (MFC) into a novel **bioelectrochemical membrane reactor (BEMR)** was proposed [153]. In the proposed concept, bacteria act as catalyst to oxidize various substrates and produce electricity partially offsetting the energy consumption of the MBR process, while MBR improves biomass retention and treated effluent quality, which are known drawbacks of MFC systems [154]. In an early attempt, Wang et al. [153] replaced a regular membrane with a stainless steel mesh, with the biofilm that formed on it serving as the filtration material and the cathode to demonstrate electricity generation potential and high removal of COD (82-94%) and ammonia (93-99%). In the following years, the studies which were developed integrated MFC and MBR systems with the use of different membranes: nylon mesh [154], non-woven cloth [155], electrically conductive [156], PVDF hollow-fibre [157], modified polyester filter with polyaniline [158], cation exchange hollow-fibre [159] and flat-sheet [160]. Despite different systems they were able to demonstrate that, under the optimized operating conditions, it is possible to produce high-quality treated effluent and recover energy from wastewater [153-160], highlighting the potential of the technology. However, process complexity of the integrated systems, power production during operation at low temperatures and removal of oxidized pollutants (e.g., nitrate and nitrite), remains the challenge.

Marbelia et al. [161] integrated microalgae cultivation and nutrient removal in a **membrane photobioreactor (MPBR)** system with the organic carbon removal achieved in the MBR and nutrient removal in the photobioreactor. The system has a potential to reduce nutrient removal costs in MBR in parallel to the reduction in nutrient and primary harvesting costs in the microalgae processing. Other authors [162-165] have also looked at the potential integration of microalgae and membranes.

5.3. Enhanced nutrient and/or refractory compound removal

In cases where nutrient removal is required, anoxic–oxic (AO or A/O), anaerobic–anoxic–oxic (A^2O) or modified Ludzacke Ettinger (MLE) configurations are applied [166].

Sun et al. [167, 168] demonstrated removal efficiencies of **A/O MBR** with regard to COD, phosphorous, ammonia and nitrogen to be of 80-95%, 60-80%, 95% and 50-70%, respectively. Gao et al. [169] achieved removal efficiencies of COD, ammonia and nitrogen of 95%, 98% and 74%, respectively. At SRTs above 30 days the A/O-MBR process was also suitable for antibiotics removal [170]. Thermochemical sludge disintegration incorporated in return sludge stream of A/O-MBR reduced sludge by 33% and introduced external carbon source coming from disintegrated sludge. This in turn, helped denitrification which, subsequently, improved nitrogen removal [171]. Studies of microbial community involved in fouling revealed that high evenness of microbial community lead to more severe membrane fouling [169]. Khan et al. [172] observed 25% reduction of the soluble EPS and a 37% reduction of the bound EPS concentrations in A/O-MBR compared to conventional MBR, subsequently, leading to reduced fouling and enhanced filtration performance. The filtration cycles were 12, 14 and 20 days for conventional MBR, moving bed MBR and A/O MBR, respectively. In addition, A/O-MBR showed the highest removal efficiencies for nitrogen and phosphorus of 83% and 70%, respectively. **Vertical MBR** (VMBR or VSMBR or

IVMBR) compose of two zones, lower anoxic and upper oxic, in one reactor [173]. VMBR, developed to increase organics and nutrient removal, mitigate membrane fouling and to reduce sludge production [174], was commercialized in 2009 when Daewoo introduced DMBRTM. Under optimum conditions (i.e., anoxic zone/oxic zone ratio = 0.6, HRT = 8 h, and internal recycle rate = 400%), the average removal efficiencies of TN and TP reached 75% and 71%, respectively [2, 173]. In order to increase MLSS in the upper zone and to prevent high sludge loading in oxic zone Ding et al. [175] introduced a three-phase separator in a lab-scale IVMBR to separate anoxic and oxic zones and create favourable conditions for the nitrifying and the denitrifying processes. The removal efficiencies for COD, NH_4-N, TN and TP were 95% (down to 12 mg/L), 98% (to 0.9 mg/L), 74% (to 13 mg/L) and 22% (to 3.6 mg/L), respectively. Chae et al. [176] reported the removal performance of a full-scale VMBR to be 79% and below 50% for TN and TP, respectively. Introduction of $FeCl_3$ dosing for enhanced phosphorus removal improved total phosphorus removal to 90%. Average specific energy consumption of the full-scale DMBRTM systems was 0.94 kWh/m^3 [176]. In **A^2O-MBR**, the anaerobic process partially converts refractory organics to more readily degradable, whereas anoxic-aerobic process provides enhanced nitrogen removal via pre-denitrification and aerobic nitrification [24]. Furthermore, elimination of potential membrane foulants, especially soluble EPS, observed in A^2O is expected to benefit the downstream MBR process [177]. Therefore, the A^2O-MBR system is an attractive alternative for the treatment of chemical-intensive industrial wastewater, such as coke [178, 179] or textile [24] effluents. The combined system provides efficient and cost-effective removal of nitrogen and refractory pollutants, especially at high and varying loading rates [178]. However, some of the refractory compounds are not removed [24]. Improved removal of nitrogen and phosphorus may be achieved through reduced recirculation of DO from the aerobic to the anoxic tank [180, 181]. In addition, high phosphorus removal can be achieved under optimized discharge of excess sludge [182]. Besides, organic carbon source derived from sludge treatment can be used as an internal carbon source in A^2O-MBR to enhance removal of TN and TP by 11% and 28%, respectively, without leading to severe membrane fouling [177].

Other configurations were also developed, primarily to increase, removal of organics or refractory compounds such as pharmaceuticals. Baek and Kim [183] demonstrated that operation under oxygen-limited conditions does not compromise nitrification, thus, enabling reduction of the MBR aeration related costs. Under alternating hypoxic/oxic condition, i.e., periodic low DO, simultaneous nitrification and denitrification was observed in a lab-scale **hypoxic/oxic MBR (HO MBR)** [184]. **Anoxic MBR**, with membranes submerged in anoxic and not in aerobic tank, allowed to lower nitrogen concentration in permeate from 7.1 to 5.2 mg/L, however, at the expense of 20% lower permeability, 25% lower sludge settleability and increase in permeate phosphorous concentration from 0.5 to 0.9 mg/L [185]. Sun et al. [186] study the performance of **MBR with integrated sludge settler** acting as a post-denitrification process for improved organics degradation and nutrient removal. The lab-scale system achieved TOC, TN, and TP removal efficiencies of about 94%, 85%, and 87%, with treated effluent concentrations of less than 5, 6, and 1 mg/L, respectively. **Pure oxygen** was used instead of air to provide higher oxygen transfer efficiency in order to improve nitrogen removal [187] and to treat wastewater with high COD loading of 2-10 kg$_{COD}$/m^3.day [188]. Mascolo et al. [189] integrated the ozonation process in the recirculation stream of MBR treated effluent, returned to the inlet with a ratio of 3:1, to threat pharmaceutical wastewater. The integrated **MBR-ozonation process** enhanced removal of COD and ozonation biodegradable products, and required lower ozone doses compared to separate MBR and ozonation systems [190]. The introduction of the ozonation step did not affect filtration and biological processes of the MBR. The combined MBR and UV/TiO_2 photocatalysis process, an **MBR-TiO_2**, removed up to 95% of carbamazepine from synthetic wastewater under 4:1 recycling ratio [191]. **Fungi MBR** utilize fungi which have a high resistance to inhibitory compounds to eliminate toxic organic compounds which can serve as a substrate for fungi [2]. Yang et al. [192] achieved 80-90% removal of bisphenol A and about 55% removal of diclofenac in a continuous flow fungal MBR.

Osmotic MBRs (known as OMBR or FO-MBR) have attracted the attention of the research community in the recent years [193-197]. In an OMBR, microfiltration or ultrafiltration membrane is replaced by FO membrane to extract water from activated sludge into draw solution concentrated with salts (e.g., $MgCl_2$, NaCl, KCl) that generates driving force, i.e., osmotic pressure [2, 198]. Through osmosis, water permeates through FO membrane into a high osmotic pressure draw solution [199]. In the process draw solution is gradually diluted by treated water and requires re-concentration. Therefore, the diluted draw solution is treated by reverse osmosis, producing high-quality water and re-concentrated draw solution that may be reused in the FO process [200]. OMBR can be operated in a submerged or side-stream configuration. Advantages of OMBR often reported in the literature include excellent

removal of contaminants including trace organics and low membrane fouling propensity [2, 201]. The most important constraint is the gradual reduction in the removal efficiency due to decreasing driving force caused by dilution of draw solution and accumulation of organics and salts in the bioreactor that may affect nutrient removal [202]. In addition, flux of FO membranes tends to be low likely due to internal and external concentration polarization, and re-concentration of draw solution ads to the operational costs [203]. According to a recent review [199], the development of high performance and robust FO membrane, selection of cost-effective draw solution, and effects of salts accumulation in the bioreactor are the key challenges of the OMBR. In the latest review, Wang et al. [11] pointed out the salt accumulation in the mixed liquor, organics contamination of the draw solution and membrane fouling as the key operational challenges resulting in a relatively low water fluxes. Bowden et al. [204] addressed some of these challenges by studying the use of organic, ionic salts such as the draw solution because of their potential to biodegrade and not accumulate in the bioreactor. Nawaz et al. [205] identified draw solutes which are and which are not suitable for the use in OMBRs and Qiu et al. [206] used seawater brine from SWRO as draw solution. Wang et al. [207], Luo et al. [208] and Holloway et al. [202, 209] studied the use of MF and UF membranes, respectively, operated in parallel to FO membrane to mitigate salts accumulation in the bioreactor. Moreover, by combining MF or UF membrane with an OMBR, phosphorous can be directly recovered [206]. Since OMBR results in the accumulation of phosphates and ammonia or nitrate in the mixed liquor, the potential recovery of nutrients is facilitated.

However, since reverse osmosis produces excellent quality water the OMBR may be more applicable for water reuse rather than for wastewater treatment.

Over the years, several additives have been tested to control membrane fouling in MBRs: organic polymers, inorganic flocculants, carriers and particles. The particles like powdered activated carbon (PAC), granular activated carbon (GAC) and zeolite have been applied to combine synergetic effects of adsorption, biodegradation and membrane filtration [7, 210]. Traditionally, **activated carbon** has been added mainly to reduce fouling [210, 211]. However, synergetic effects of activated carbon adsorption, biodegradation and membrane filtration leads to better permeate quality with regard to recalcistrant pollutants [7]. Therefore, in more recent studies, addition of activated carbon has been studied for the removal of pharmaceuticals [212-214] and water reuse [215]. At high dosage of 1 g/L of PAC, the removal efficiencies of sulfamethoxazole and carbamazepine increased from 64% to 82% and from below 20% to 92%, respectively [212]. With the addition of PAC, the biological activated carbon is formed providing uptake and/or entrapment of soluble organics and colloids [216]. In other studies, the addition of GAC has successfully removed trace organic contaminants from MBR permeate, however, a compound-specific gradual deterioration of the removal has been observed urging for strict monitoring [213, 214]. The complete saturation of GAC column by different compounds occurred in the following order: TN > TOC > persistent trace organic contaminants. Furthermore, since some PAC is lost with sludge discharge regular addition of PAC is needed to maintain fouling mitigation and membrane filtration performance [211, 217]. Hai et al. [218] developed the **bioaugmanted MBR** with GAC-packed anaerobic zone beneath the aerobic zone with the membrane module to remove colour and TOC from textile wastewater. Stable de-coloration along with significant TOC removal over a long-term operation under high dye-loadings was demonstrated. Application of activated carbon in MBRs have been discussed in detail in a recent review [7].

5.4. Synergistic effects utilization

Implementation of biofilm processes in MBR can be done by the addition of media (e.g. biofilm carriers) in moving or fixed bed configurations, or aerated membranes in the bioreactor as a support for biofilm growth [219]. Recent studies on **hybrid growth membrane bioreactors**, in which biomass is in suspension and attached to packing media, were mainly devoted to fouling and testing of different configurations [220-225]. Yang et al. [223] evaluated four types of hybrid growth MBRs and concluded that the system containing carriers but without a draft tube, was the preferred option to reduce membrane fouling without affecting the removal efficiency. Airlift HG-MBR equipped with a draft tube and carriers was the second preferred option, but the proposed design had limited carrier packing ratio, limiting biofilm fraction for the reduction of MLSS. The **attached-growth** media have a positive role in controlling membrane fouling in MBR systems and allow operation at 30% higher critical flux, however more excess biomass is produced [221]. Hu et al. [222] demonstrated reduced membrane fouling rates in two attached-growth MBRs: one with carriers and one with carriers and baffles. The operation times were, respectively, 4.2 and 3.5 times longer compared to a suspended-growth MBR. The optimum media volume fraction for membrane

performance was 30% above which decrease in membrane performance was observed. Introduction of **biofilm carriers** into a conventional MBR enhanced organic, nitrogen and phosphorous removal by 4, 5 and 13%, respectively [226]. In addition, the period between membrane cleanings was prolonged from 60 to 140 days [227]. Ng et al. [228] developed the **bio-entrapped membrane reactor (BEMR)** packed with bio-ball carriers and operated nearly 4 times longer than conventional MBR before reaching critical TMP, thus, contributing to reduced chemical cleaning frequency [229]. Rafiei et al. [224] demonstrated that a bio-entrapped MBR with cells entrapped in polyurethane foam provided better results with regard to membrane fouling and removal efficiencies of COD, ammonium and phenol, when compared to biofilm and conventional MBRs. Cuevas-Rodriguez et al. [225] compared conventional, moving bed and fixed bed MBRs and concluded that **moving bed MBR (MBMR)** provides better membrane filtration performance (i.e., flux, permeability, cleaning frequency), but lower nitrogen removal. The coexistence of biofilm and suspended biomass in the **fixed-bed MBR** with biofilm support media fixed in the column, resulted in 43% lower membrane fouling rate, 4% better COD removal, nitrogen removal in the range of 75%, and improved dewatering and settleability of the sludge compared to conventional column-shaped MBR [230]. However, fouling tendency was similar in both tested configurations. Formation or cultivation of aerobic granules in an MBR can mitigate membrane fouling, increase permeate flux, and reduce energy consumption. Besides, in granular MBR, simultaneous nitrogen removal can be realized in the multiple microenvironments of aerobic granules [231]. Simultaneous organic/nitrogen removal and membrane fouling control was successfully explored in a **batch granulation MBR** (BG-MBR), consisting of a sequencing batch airlift reactor (SBAR), settler and submerged MBR [232].

Commercial developments focused on synergistic effects of two different membranes configurations. In 2008, Microdyn-Nadir introduced BIO-CEL membrane which combines the advantages of hollow-fibre and flat-sheet membrane. The BIO-CEL self-supporting membrane is made of two flat sheet membrane sheets laminated on the spacer to provide support and enable backwashing [233]. In 2014, new and larger module, BIO-CEL XL, have been developed [234]. According to the company, membrane has also a self-healing potential (based on turbidity). Furthermore, a continuous mechanical cleaning process with granulates, has been developed by MICRODYN-NADIR GmbH under the Bio-Cell®-Mechanical Cleaning Process (Bio-Cell®-MCP) name. Recently, Fibracast, part of Anaergia group, developed FibrePlate™ membrane, which also combines the strengths of hollow-fibre and flat-sheet membrane into one UF hybrid membrane [235]. According to the producer, the membrane couple high packing density and a back-wash capability, with low TMP and ease of operation, while reduced capital and operating costs [236]. In addition, in 2014, GE WPT introduced MBR with carriers, MACarrier, to tackle, among others, refractory COD, toxicity, phenols during treatment of difficult wastewater streams [237, 238]. In 2015, Pentair presented a new flux enhancement technology for tubular membranes, Helix.

6. Overall Life Cycle of MBRs

Although MBRs have been widely applied for wastewater treatment with various configurations and combinations, a holistic evaluation over their environmental performance is required with the view to ensure their effectiveness from both a technological and an environmental point of view [239].

Over the last decade, MBRs have been applied within the wastewater sector, since they combine a design economic of space, a sufficient biomass control along with a high-quality treated effluent as well as an efficient retention of microorganisms and viruses [239-242]. Additional advantages regarding the MBR's implementation include more efficient protection of biodiversity via a reliable operation and efficient removal of trace organics and emerging pollutants in addition to the preservation of the local natural heritage through an optimized energy and local water resources use [243]. However, MBRs exhibit higher energy demands compared to the CAS process; i.e. MBR require around 0.4-1.6 kWh/m^3, instead of 0.3-0.6 kWh/m^3 for the CAS [239, 244-248]. The total energy consumption for full-scale MBRs can be as high as 6-8 kWh/m^3 in the case of high-strength wastewater (e.g. industrial streams and landfill leachate) [242, 244, 249]. Previous pilot-scale studies have concluded unequal energy ratios, such as 0.14 kWh/m^3 for conventional wastewater treatment [242, 250] and 4.0 kWh/m^3 for grey and black water [242, 251]. MBRs and membrane polishing stages for advanced treatment can increase the energy consumption by 50-70% compared to the CAS process; the MBR systems, in particular, typicaly require energy within the range of 0.4 to 1.6 kWh/m³ [27, 243, 252], which is 20-50% higher than the energy required in the CAS process [243, 253, 254]. The environmental impact analysis of five treatment processes performed by Hoibye et al.

[246] showed that the application of advanced technologies for the improvement of treated effluent quality is often accompanied by environmental damages incurred from achieving this improvement. Sand filters exhibited the highest environmental performance, while ozone and membrane processes were least favourable in terms of their environmental profile. Even when comparing an MBR with a CAS system providing similar treated effluent quality (e.g. CAS followed by UF and UV), the MBR would still be more energy consuming [255]. The MBR's higher operational cost is linked to the aeration requirements, the membrane fouling as well as the more enhanced pretreatment needed to reduce the fouling [1, 22, 239, 242].The nexus between wastewater and energy must be addressed for sustainable wastewater management.

Life cycle assessment (LCA) is applied for the assessment of the environmental impact associated with a whole process/product/service by considering the environmental load of every single stage during the life cycle of the process/product/service under investigation [239, 256, 257]. LCA has been widely applied in wastewater treatment [239, 258, 259], while it is an important tool in order to understand environmental impacts of alternative schemes and gain information which can be useful at a policy level. However, the LCA of MBRs is limited to few studies [239], while Fenu et al. [255] highlighted the fact that the scientific literature on the energy requirements of full-scale MBRs is rare. Furthermore, the authors question the reliability of the calculations regarding the energy demands of pilot-scale MBRs, since the limited scale of the study negatively affects the energy performance [255]. In addition, the LCA of an MBR should be implemented for various operating conditions when the final target is the environmental assessment and optimization of the process [260].

Ortiz et al. [261] performed the LCA of several treatment schemes including a CAS system, a CAS with tertiary treatment, an immersed MBR and an external MBR. The LCA results showed that the CAS with tertiary treatment produced the highest environmental load; nevertheless, both the external and the submerged MBRs also resulted in comparable environmental impacts. The external MBR exhibited higher environmental load compared to the immersed MBR due to its higher electricity demands [261]. However, the MBRs can satisfy the strictest discharge standards; the latter is particularly important in cases where the quality of the treated effluents is a priority [261, 262]. Moreover, Memon et al. [263] investigated the potential environmental impacts of an MBR against three alternative processes (i.e. reed beds, membrane chemical reactors and an innovative green roof water recycling system - GROW) for the treatment of greywater generated in households. The authors concluded that the processes based on natural treatment (i.e. the reed beds and the GROW) were characterized by the lowest environmental impact. Høibye et al. [246] performed LCA for three advanced treatment processes (i.e. sand filtration, ozone treatment and MBR) for urban wastewater treatment. Relatively higher energy consumption was observed in the MBR system generating, subsequently, higher environmental impacts and costs compared to the alternatives of ozone treatment and sand filtration [246]. Hospido et al. [239] applied the LCA for the evaluation of four MBRs of increasing complexity. The energy use was the most important factor for the estimation of the environmental load of the systems under investigation, while there is an inverse relationship between the environmental cost of a treatment and its technological complexity [239].

Hospido et al. [239] point out that the LCA studies should not exclusively include the environmental dimension, but they should also be coupled with technical and economic aspects (constraints and benefits) in order to holistically evaluate the sustainability of a treatment process. Furthermore, the selection of representative environmental indicators plays an important role for the LCA [243]. For instance, if the main goal is wastewater treatment the fact that the MBR systems promote the reduction of aquatic toxicity and eutrophication can prevail over the disadvantage of high energy requirements [243]. Finally, Høibye et al. [246] discussed the peer-reviewed literature gap on full-scale data concerning the application of advanced wastewater treatment processes and the effect of the operational conditions (e.g. energy and resource requirements). The acquisition of knowledge on the latest technical developments concerning the advanced treatment techniques as well as the inclusion of additional vectors in an LCA (e.g. more hazardous substances, more emission sources, new toxicological data etc.) will lead to more complete assessments [246]. The assessment of the impact of a target technology requires a holistic approach. The quantification of the environmental benefits which are derived from wastewater treatment in economic terms is crucial for supporting the decision process. Thus, the use of economic feasibility indicators for the target process, including internal and external costs and benefits associated with the environmental damage avoided can provide useful information for decision making [264]. Molinos-Senante et al. [264] demonstrated that, when the feasibility study considers externalities, the greatest environmental benefits of advanced processes (e.g. MBRs) allow to offset

their higher cost. The MBRs exhibited the second higher total annualized equivalent cost; however, there were capable to produce suitable treated effluent independently of the influent load.

As the standard MBRs are criticized as an energy intensive option, several of the innovative membrane processes for wastewater treatment aim to reduce the environmental load. Table 5 compares the performance of standard MBR, AnMBR, BF-MBR, MABR and FO-MBR against energy demand and their impact on climate change, fresh water and marine eutrophication. The comparison is qualitative and is based on the authors' interpretation of the different processes. At the moment, there is no LCA study comparing these technologies in a systhematic way since some of these processes have limited or no full scale applications. The MBR has a high energy and carbon footprint due to the requirement for membrane cleaning (air scouring, chemical cleaning, etc.), while it can achieve very high treated effluent quality with low nutrient concentration and thus a very low impact to marine and fresh water eutrophication. The AnMBR is very attractive in terms of energy efficiency with energy recovered from sewage and no aeration requirements. However, the escape of dissolved methane in the permeate increases significantly the carbon footprint of the process. In municipal wastewater treatment the application of high rate anaerobic treatment processes has shown that the loss of methane can be up to 30-40% of the produced methane. The BF-MBR process requires high DO concentrations in the bioreactor for the nitrification process and is thus considered energy and carbon footprint intensive. In the FO-MBR there is no external pressure applied, fact which results in decreased energy requirements. The process results in very high phosphate and ammonia rejection, but nitrate rejection from the FO membrane is not as high.

Table 5. Comparison of the performance of MBR, AnMBR, BF-MBR, MABR and FO-MBR against energy demand and their impact on climate change, fresh water and marine eutrophication

Process type	Energy related emissions	Climate change impact	Fresh water eutrophication	Marine eutrophication
MBR	High	High	Low	Low
AnMBR	Low	High	High	High
BF-MBR	High/ medium	High/ medium	Medium	Low
MABR	Medium/Low	Medium/Low	High	Low
FO-MBR	Medium	Medium	Low	Low/Medium

7. Markets for MBRs & AnMBRs

The MBR market has seen growth albeit at a slower rate than projected around 2010. Up until this time the MBR process of wastewater treatment was seen as being the best new technology with two of the main selling points being their smaller footprint (less than 25% of the footprint of a traditional system according to Ovivo[8]) and less labour (50% less according to Ovivo[9]). Other benefits such as less concrete used in construction, simpler operation due to fewer moving parts, and better nitrogen and phosphorous removal than traditional methods added to the list of advantages. However, even with all of these advantages MBR's have failed to capture the acceptance rate originally expected.

The main reason cited by many in the industry has been due to high energy consumption used mainly by the aeration process for membrane fouling mitigation. Although anaerobic systems offer the ability to overcome the energy hurdle, so far the market for AnMBR's has remained at roughly 1% of the total MBR market with the total MBR space remaining a niche market itself. Another reason for slow acceptance has been the reliance on municipal applications. With municipal applications dependent on many factors including funding, regulation, enforcement, the state of current systems, and population growth; events such as the financial crisis have continued to stunt growth. However, the market for MBR systems does have the potential for more acceptance as systems become more efficient and components become cheaper.

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[8]http://www.etec-sales.com/pdf/OVIVO%20-%20Enviroquip%20-%20MBR.pdf

[9]http://www.ovivowater.com/product/municipal/municipal-wastewater/aerobic-treatment-nutrient-removal/mbr/ovivo-mbr/

Other factors that should not be disregarded are the makeup of the MBR industry, application, and geographic demand. As MBR or AnMBR systems can be bolted together from a variety of manufacturers and contractors or come from turn-key system integrators and as MBR's can range in size from shipping containers to massive plants; judging 'growth' can be problematic. Demand will also vary as geographic areas or applications have varied situations. In other words, defining the 'market' will depend on what components are being gauged (membranes, tanks, complete systems), what applications are experiencing growth or decline (municipal, industrial, shipping, etc.), and the state of various geographic areas (environmental enforcement, population, age and capacity of current systems).

7.1. Industry & Application Makeup

The MBR manufacturing industry is made up of several tiers of manufactures based on product and service offerings. From global companies that offer full service to smaller sized component manufacturers, the industry can be roughly divided into the following:

- System Integrators – these are companies that offer turn-key solutions. They offer membranes, membrane modules, plumbing, pumps, tanks, etc. Most notably are GE, Veolia, Suez Environnemont, and Evoqua
- Component Manufacturers – mainly membrane manufacturers, these are significant companies nonetheless and include companies such as Kubota, Mann+Hummel, Nitto's Hydraunautics, Koch, or Mitsubishi
- MBR Systems – companies such as Ovivo will fall into this category in which the MBR system is built but membranes and their modules will be bought from membrane manufacturers
- Application Specific Manufacturers – these sets of companies will concentrate on specific areas such as shipboard systems, petroleum, mobile units, or even small village scale units. Companies in this category include A3, Orelis Environnement, or Huber. Notable in the shipping category is Wärtsilä Hamworthy.

Although both MBR and AnMBR systems are made up of many components, the area that continuously attracts the most attention is the membrane. Most likely because leading membrane companies such as GE have championed the system; volume, market size, and numbers of applications are most often associated with membrane and membrane modules. However, this creates an additional problem. As membranes have a life expectancy of anywhere between 5 to over 10 years, as new low cost entrants enter the market such as Chinese based Origin Water, and as membrane prices continue to fall overall [265]; membrane profit margins will continue to fall for producers. Additionally, as with any other business deal, the more volume sold the greater the discount. This will mean that by square unit of measurement the price of a large scale municipal plant will be much lower than those in smaller applications. These reasons are undoubtedly why Siemens divested its Water Technologies division, including MEMCOR membranes, creating the company Evoqua.

As profit margins for membranes are lowered but as the overall MBR market itself grows, it is expected that many more mergers, acquisitions, and divestitures will take place. For example, Ovivo which had traditionally used Kubota membranes signed an agreement with Microdyn Nadir for their membrane technology in October 2015. Mann+Hummel in May 2014 had bought a 50% stake in Microdyn Nadir. Thus with Ovivo being one of the largest municipal MBR systems suppliers in the US coupled with the fact that Microdyn Nadir technology is based on flat sheet membranes similar to Kubota; Mann+Hummel could threaten Kubota's market share over time. As Kubota has been known in the industry to be number two, the loss of new units in the US could threaten this position.

Overall, what seems to have not changed is GE's market dominance. A result of the 2006 $656 million acquisition of Canadian based Zenon, GE gained ultra-filtration hollow fiber technology. GE furthered its commitment to this area by establishing membrane manufacture in Oroszlány, Hungary in which it expanded in 2012 to a size of 80,000 m^2 and a capacity of 250 ZeeWeed MBR systems per year. No other manufacturer has come close to achieving the amount of volume that GE produces. With its 2014 acquisition of UK based Monsal GE now offers anaerobic systems, signalling more industry acceptance for this method and hedging GE for future market acceptance of this technology. So far the most notable company in this space has been ADI Systems however, the number of installed units remains low.

7.2. Geographic & Application Makeup
7.2.1 Small Scale Applications

Although MBR systems are known to lend themselves well to large scale municipal plants many smaller applications are prevalent. Such applications are in buildings, industrial applications, landfill leachate, and shipping. Such units will largely go unnoticed due to being small scale applications however, due to increased environmental regulation and enforcement they will be critical for compliance and operation. These systems will also save facilities money by using less labor, taking up less real estate, and in the case of many industries creating the ability to recycle water. Examples include:

- Food and Beverage – champagne, wine, beer, potato processing are all examples of water intensive, high solid biological applications. The use of an MBR allows for water reuse and environmental compliance. AnMBR's have also been employed in such areas as Mars chocolate in Veghel, the Netherlands (Veolia's Memthane using Pentair X-Flow membranes)
- Pulp and Paper – MBR's can process sludge prior to desalination. Siemens piloted the use of an MBR before the RO stage at Albert Köhler GmbH & Co. KG, based in Gengenbach, BadenWürttemberg, Germany in 2008
- Oil and Gas – a sign of this application having higher margins, Siemens kept these applications in their portfolio after the divestiture of their water business. Siemens' EcoRight™ and Petro™ systems are examples of where oil sludge can be processed prior to desalination for water reuse
- Shipping – the IMO's (International Maritime Organization) MARPOL (The International Convention for the Prevention of Pollution from Ships) regulates sewage under AnnexIV requiring that ships cannot dispose of sewage in or near shore. For cruise ships and warships especially due to high on-board populations, MBR's are the best method as conventional black water holding tanks will produce effluent gas, the cost of using port facilities is time consuming as well as expensive, space is limited, while power is readily available
- Slop Waste and Port Reception Facilities – also regulated by MARPOL, these facilities process oily bilge and ballast water as well as oil and chemical residue from holding and shipping tanks where the tanks must be cleaned when changing payloads. Nature Group is a prime example of a port reception facility incorporating MBR's within its system. Although a niche application due to most oils being incinerated, where large amounts are present, such as petroleum ports or even train depots, MBR's can be incorporated
- Landfill Leachate – this application is still very niche and mostly used in Europe
- Livestock – similar to food and beverage where water use and biological solids are high but with even higher rates of ammonia, nitrogen and phosphorous, the use of MBR's has been proven in abattoirs. Additionally AnMBR's are being marketed for use in dairy farm applications to produce biogas from cattle manure to reuse water

7.2.2 Municipal Applications

Municipal applications get the most exposure due to their high volume and investment cost. However, these applications will also have the greatest price pressures, be the most competitive, have the highest risk due to the possibility of warranty issues, and will have lower comparative margins to niche applications. As mentioned earlier, municipal applications will also be subject to population density, the state of current systems, if environmental regulations are in place and enforced, and of course the economy. In other words, municipal applications can experience growth and decline in different geographies.

In North America, many new facilities have come online. Indeed, this market has continued to show overall growth which could be contributed to lower energy costs. In comparison, Europe has seen the introduction of a few large scale facilities but most likely due to higher energy costs has not seen large scale acceptance. Looking at comparative electricity costs in the EU in comparison to the US shows how an energy intensive system would be exponentially more expensive to operate in the EU[10]. In China, many applications will be new systems due to the construction of new facilities and tightening environmental policy. The same will be true in North America. Both areas have growing populations and will have the need to build entirely new systems rather than simply repair old ones. In China over 1,604,000 m^3 of capacity was installed from 2012 to 2016[11] alone.

7.3. Patent & intellectual property trends

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[10] Source: U.S. Energy Information Administration and Eurostat https://www.eia.gov/todayinenergy/detail.cfm?id=18851

[11] The MBR Site http://www.thembrsite.com/about-mbrs/largest-mbr-plants/

7.3.1   Methodology

Using patent data from the European Patent office (EPO)[12] which covers patents globally, a search was conducted using the search terms "MBR OR membrane bioreactor" in the title from 1 January 2006 to 31 December 2015. From the total amount found those that mention "anaerobic" in the title were isolated.

7.3.2 Findings

Overall publications of MBR and AnMBR patents grew with a spike in 2013 but with a recovery almost reaching 2013 levels in 2015 (Figure 3 and Table 6). Noting that this represents 'publication date' not 'application date' will mean an adjustment in the time frame back, as many will have taken years to have reached publication. However, growth in IP research can be shown.

The top country for patents is by far China with Harbin Institute of Technology taking the bulk of these (Table 7). Harbin is listed as the first applicant over 22 times. Origin Water, also from China, has over 16 patents. In comparison Siemens had 16 patents, GE had 10, and Veolia had 9 during the same period.
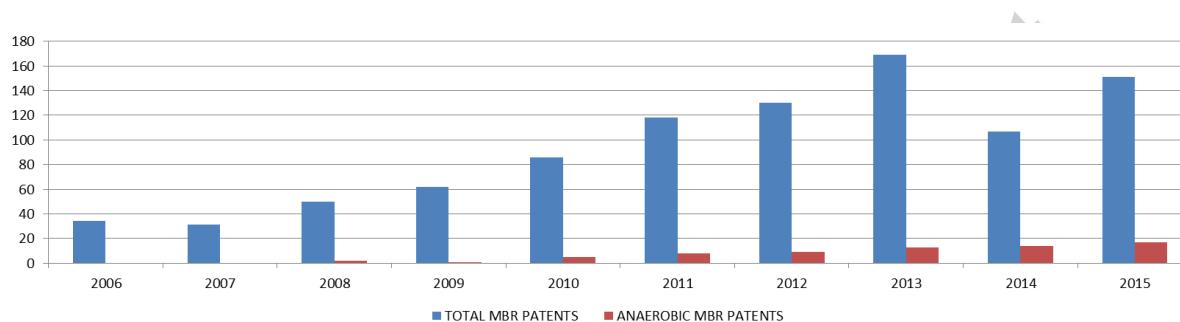
Figure 3. Number of aerobic and anaerobic MBR related patent publications in 2006-2016 period.

7.3.3 AnMBR Patents

Anaerobic systems comprised a small portion of the total with 2015 being the highest number (17 out of 151 total MBR systems). However, there is constant growth seen in this space. Again, Harbin Institute of Technology is one of the leading patent applicants with 7 patents in the anaerobic area. The University of Shandong has 6 patents. Veolia has 4 patents in comparison. Although GE or Monsal aren't listed, further research did show 4 patents from Monsal although only one fell into the time frame and was related to general solid liquid separation not specific to AnMBR's.

Table 6. Total number of aerobic and anaerobic MBR related patents in 2006-2016 period

Year	Total patents (MBR & AnMBR)	Anaerobic MBR patents
2006	34	
2007	31	
2008	50	2
2009	62	1
2010	86	5
2011	118	8
2012	130	9
2013	169	13
2014	107	14
2015	151	17
Total	**938**	**69**

Table 7. Number of MBR related patents in 2006-2016 period per country of patent submission

Country	Number of patents
China	736

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[12]https://www.epo.org

Korea (South)	47
United States of America	38
WIPO	25
Japan	13
European Patent Office	12
Taiwan	11
Canada	11
Australia	8
Singapore	6
Russian Federation	5
Germany	4
New Zealand	4
Netherlands	3
Mexico	3
India	2
Israel	2
Poland	2
Ukraine	1
Slovenia	1
Czech Republic	1
Hong Kong (S.A.R.)	1
South Africa	1
Switzerland	1
Total	**938**

8. Conclusions

In this paper, recent developments with regard to energy reduction, membrane fouling control and novel configurations in MBRs were reviewed. In addition, LCA and market prospects for MBR technology were discussed.

MBR fouling and energy issues have attracted the attention of researchers, practitioners and MBR suppliers, and have led to a number of fouling-mitigation and energy-saving solutions, optimization strategies and new commercial products. These advances concentrated on the module configuration, aeration strategies, control systems, surface modifications, low-energy membrane cleaning methods or novel fouling mitigation methods, for example, mechanical cleaning with granular medium, membrane vibration or electric field. Among other approaches to reduce energy demand and/or improve energy efficiency the following were most frequently applied: operation closer to optimal flow conditions to maximize hydraulic utilization of the membranes, flow equalization, adjustment of operational settings (e.g., filtration protocol, MLSS concentration), implementation of new and/or optimization of current aeration strategies, introduction of aeration control systems, installation of variable speed drivers on blowers/pumps, primary clarification ahead of MBR or modular design providing multiple treatment lines enabling gradual adjustment to the inflow. A number of novel MBR configurations have been proposed in order to provide improved membrane fouling control, reduced energy demand, enhanced nutrient removal or improved removal of refractory compounds. Among these developments, hybrid systems, combining MBR with other processes, utilizing prospects of the different processes in order to overcome typical constraints of the MBRs were predominant.

Despite continuous improvements and developments, key challenges that still need to be overcome in order to facilitate the market penetration of the MBR technology are fouling control aspects and economics of membrane use aspects. Among the fouling control aspects, the development of innovative antifouling membranes, stable flux production for long term operation, effective and/or low-energy membrane cleaning procedures and identification of tailored pre-treatment protocols for mitigating the fouling problem are still needed. In respect of economics of membrane use the required advances should focus on cost effective membrane materials production, durability against washing chemicals, life expectancy, energy efficiency and competitive cost per m^3 wastewater treated and

down-scaling issues in small and decentralized systems. Finally, development of a holistic approach for the environmental impact assessment of full-scale MBRs integrating LCA, model analysis, water quality indicators and impact categories is required. Based on the amount of published literature in the recent years, interest from the MBR practitioners and already close relation to the practice, significant progress is anticipated in the area of novel fouling mitigation measures, particularly in effective and/or low-energy membrane cleaning. The likelihood of being transferred into practice is also significant for the cost effective membrane materials production. It is expected that recent advances in material science will also contribute towards the development of antifouling membranes.

9. Acknowledgments

10. References

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Highlights

- Recent developments in membrane bioreactor technology are reviewed.
- Novel MBR configurations have been revised.
- Available energy reduction and fouling control measures are highlighted.
- Life Cycle Assessment (LCA) and market prospects are discussed.
- Challenges that needs to be addressed and perspective of MBR are discussed.