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Review

Green technology in wastewater treatment technologies: Integration of membrane bioreactor with various wastewater treatment systems

Chin Hong Neoh [a], Zainura Zainon Noor [a,*], Noor Sabrina Ahmad Mutamim [b], Chi Kim Lim [c]

[a] *Centre for Environmental Sustainability & Water Security (IPASA), Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia*
[b] *Department of Chemical Engineering, Faculty of Chemical Engineering and Natural Resources, Universiti Malaysia Pahang, Leburaya Tun Razak, 26300 Gambang, Kuantan, Pahang, Malaysia*
[c] *Department of Construction Management, Faculty of Technology Management and Business, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia*

HIGHLIGHTS

- A consolidated review on the current state of the integrated MBR was made.
- Excellent efficiency in terms of pollutants removal by integrated MBR is reported.
- The studies show the possibility of valorization of wastewater for electric, biofuel and nutrients.
- Membrane fouling and reduction in energy demand are the key problem to solve.

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ABSTRACT

The increasing concerns of water resource are becoming an important issue as severe shortage of water has been seen throughout the world. Though membrane bioreactor (MBR) has made an enormous progress and has become a promising approach in wastewater treatment, there are still several limitations on conventional MBR and thus there emerged integrated MBR for wastewater treatment technology. This paper aims to provide a consolidated review on the current state of research for the integrated MBR system with other technologies for wastewater treatment and help to sustain the treatment process itself. The areas for potential applications of various types of MBR are discussed in this review article. It is expected to provide future prospects to implement integrated MBR as a promising wastewater treatment technology. The valorization of wastewater in integrated MBR would reduce pollution and more importantly open a new source of energy and nutrients. Moreover the integrated MBR makes energy and nutrient recovery to be environmentally and economically feasible.

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* Corresponding author. Tel.: +60 7 5535485; fax: +60 7 5581463.
E-mail address: zainurazn@utm.my (Z.Z. Noor).

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1. Introduction

A remarkable progress has been achieved on the application of MBR process to wastewater treatment and reclamation. Rapid expansion of the population in developing countries caused the existing conventional wastewater treatments plants overloaded and there will be no space available for expansion of the existing treatment plant [1]. In view of this, MBR has attracted growing interests as it has some distinct advantages of smaller footprint, less sludge production, higher separation efficiency and highly improved effluent quality as compared to conventional activated sludge treatment [2,3]. MBR is also able to retain small molecular weight organic micropollutants compared to conventional activated sludge process. MBR with ultrafiltration membrane is also able to retain some types of viruses [4].

Legislation, increasing level of water stress and growing confidence in the performance of MBR are the key market drivers as well as contribute to the expansion of MBR market. According to the Market Research Report, Asia–Pacific market share is 38% in the global MBR revenue market, followed by Europe (17%). The global MBR market is rising at a compound annual growth rate of 13.2% and is expected to reach $627 million by 2015. The MBR market is growing faster and has contributed to the larger market for wastewater treatment equipments including physical treatments, chemical treatment, biological treatment and membrane filtration. Meanwhile, MBR is also the largest market for other membrane systems treating wastewater such as microfiltration, ultrafiltration, nanofiltration, and reverse osmosis (RO) [5,6]. Even though some of the wastewater treatment system may be capable for treating industrial wastewater to meet current disposal requirement and producing water for basic uses in the industry, the treated effluent would need to be further polished by using integrated MBR for applications that need high grade water.

Extensive review papers are available for MBR in wastewater treatment technology. Fletcher et al. [7] studied the status of MBR technology as a trend in biotechnology. The authors focused on the fundamental facets of MBR process, membrane and configuration process. Ylitervo et al. [8] studied the potential of MBR which is not focused in wastewater treatment technology but for ethanol and biogas production in fermentation technology. Besides, applications and limitations of MBR in the treatment of high strength industrial wastewater have also been studied [2,9]. Wang et al. [10] studied a critical review on physical, chemical and biological cleaning in MBR and proposed the procedures of determining proper cleaning protocols. Goh et al. [11] studied the potential applications and possible configurations for membrane distillation bioreactor (MDBR) while Wang and Chung [12] studied the development, configuration design and application of MDBR. In contrast, Tijing et al. [13] studied the fouling and its control in membrane distillation bioreactor. Pellegrin et al. [14] studied the membrane processes for municipal and industrial applications which cover the pretreatment, MBR configuration, membrane fouling, fixed film and anaerobic MBR, membrane technology advances and modeling. Most review articles that related to integrated MBR are anaerobic MBR (AnMBR) which has the advantage of reducing organic matter and producing energy under anaerobic processes. For example, Ozgun et al. [15] studied the integration, limitations and expectations of AnMBR for municipal wastewater treatment. Another study on AnMBR was conducted by Phattaranawik et al. [16] with special emphasis on performance and bottlenecks in terms of its application at industrial scale. Skouteris et al. [17] studied the performance of AnMBR which focus on the comparison with other wastewater treatment technologies, energy recovery and membrane fouling issues. Nevertheless, there are few other studies were conducted for the overview of the various types of integrated MBR upon wastewater treatment and valorization. This paper aims to provide a review on the current research for the integrated MBR system for wastewater reclamation. It is the first study ever in the integration of MBR with other treatment technologies such as advanced oxidation processes (AOPs), granulation technology, reverse and forward osmosis (FO), MDBR and hybrid moving bed biofilm reactor-membrane bioreactor (Hybrid MBBR-MBR) in order to enhance the treatment efficiency of the wastewater. While the other important parts of the paper were focused on the sustainable development of MBR for the production of biofuel, generation of electricity and recovery of nutrients in which to make money and also contribute to environment.

2. Integration of MBR with other technologies

Integration of MBR with other technologies can be considered as a safer ‘multiple barrier approach’ for wastewater treatment. The purposes of the integrated MBR are to improve qualities of permeates, mitigate membrane fouling and enhance the stability of the treatment process. Table 2.1 shows the advantages and disadvantages of various integrated MBR in wastewater treatment technology.

2.1. Advanced oxidation processes (AOPs) and electrocoagulation processes

AOPs in general are being well known for their capacity in removing many organic contaminants. AOPs are able to convert recalcitrant pollutants into biodegradable intermediates that can be degraded in a biological process. However, it is negatively affected by suspended solids that act as scavengers toward hydroxyl radicals which are formed by ozone decomposition in water. In this view, MBR offers unique opportunities in terms of suspended solid-free effluent and thus enhance the efficiency of ozonation. AOPs can be used as pre- or post-biological treatment of wastewater. Pre-treatments have been proven useful in the case of wastewater which containing small amounts of biodegradable organics and large amount of recalcitrant compounds. In contrast, post-treatment results are preferable when biodegradable compounds are greater than that of recalcitrant compounds [18].

Mascolo et al. [19] studied the effective organic degradation from pharmaceutical wastewater by an integrated process of MBR and ozonation. The reactor was set up by placing the ozonation reactor in the recirculation stream of the MBR effluent. The organic compound (acyclovir) in the effluent was removed up to 99% from the MBR step and ozonation allowed to further remove 99% of the MBR effluent. For several organics identified in the

Table 2.1
Advantages and disadvantages of various integrated MBR in wastewater treatment technology.

Integrated technology of MBR	Advantages	Disadvantages and limitations
Advanced oxidation processes/ electrocoagulation-MBR	Effective in removal of recalcitrant contaminants (pharmaceuticals wastewater) Effective in removing colors Reduces the production of excess sludge Easy to operate Reduce membrane fouling	High capital and operational costs Not effective in treatment of wastewater with high TSS
FO-MBR	Produce good effluent quality Phosphorus recovery Low energy consumption as compared to conventional MBR Low fouling tendency compared to RO Effective in removal of trace organic contaminants Fouling is largely reversible Effective in treatment of wastewater with high TSS as compared to RO	Uncertainty of stability of membrane Increasing salinity/salt accumulation might decrease the microbial kinetics and water flux
RO-MBR	Low fouling tendency Cost of RO membrane is cheaper than FO membrane Low energy consumption as compared to conventional MBR	Not effective in treatment of high salinity wastewater compared to FO
Membrane distillation	Enhances biodegradation of recalcitrant compounds Low sludge yield Higher effluent quality Excellent process stability Cost effective compared to RO process Smaller footprint	Low removal of COD
Biofilm/bio-entrapped MBR	Reduces the concentration of suspended solids Reduce membrane fouling Improve nitrification and denitrification processes	Membrane fouling might be severe at the later stage of treatment
Granular MBR	Improve nitrification and denitrification processes High shock resistance capacity Reduce membrane fouling Smaller footprint	Membrane fouling might be severe at the later stage of treatment Long start-up period of granule formation

wastewater, the efficiency of the MBR treatment improved from 20% to 60% when the ozonation was placed in the recirculation system. This study found out that MBR-ozonation system gave results comparable to those obtained by the two separated treatment systems. In contrast, López et al. [20] studied the integration of solar photo catalysis followed by MBR for pesticide degradation. The permeate obtained in the coupled system was ready-to-use high quality water, with the absence of pesticides, absence of solids, and turbidity values (NTU) below 0.5. The results demonstrated that this system is able to treat the pesticide mixture without adding carbon source. Laera et al. [18] investigated integration of MBR with either ozonation or UV/H_2O_2 process by placing chemical oxidation in the recirculation stream of the MBR. The study reported the removal of synthetic wastewater contained nalidixic acid which was used in treating urinary tract infections. MBR alone is not efficient in removing the degradation products of the nalidixic acid as those compounds would pass through the MBR. However, integration of ozonation completely removed the degradation products in the step of chemical oxidation. An integrated thermophilic submerged aerobic membrane bioreactor (TSAMBR) and electrochemical oxidation technology using Ti/SnO_2–Sb_2O_5–IrO_2 electrode was developed for treatment of pulp and paper effluent [21]. The integrated oxidation processes completely decolorize the effluent and further enhance the removal of COD. The high quality effluent can be produced through the integrated process and has the potential for the direct reuse in the mill. Giacobbo et al. [22] investigated the integrated MBR-photoelectrooxidation (MBR–PEO) for tannery wastewater treatment. The MBR is responsible for the remaining biochemical oxygen demand (BOD) removal, while the refractory matter (contributed to COD) is removed by PEO. The treated wastewater could be recycled for the tanning and re-tanning steps. Fouling does not penetrate in the membrane pores and can perform well after 360 h of work without membrane cleaning. Lamsal [23] examined the fouling in nanofiltration membrane and explored various pre-treatment strategy to reduce the fouling process. The author found out that AOP pre-treatments with NF membrane resulted in an improved permeate flux but not permeate quality of the NF membrane. Merayo et al. [24] stated that higher COD removal was achieved treating the pulp mill effluent from the recycled MBR followed by AOPs. The remaining recalcitrant compounds could be more efficiently ozonized when the effluent was treated with MBR.

Electrocoagulation (Fig. 1(a)) is a technique that generates the coagulants *in situ* by dissolving electrically through either aluminum or iron ions from electrodes. The metal ions are generated at the anode while hydrogen gas is generated at the cathode. The released hydrogen gas will assist in floating the flocculated particles to the surface [25]. Keerthi et al. [26] investigated three different combinations of treatment technology (electrocoagulation combined with microfiltration, MBR, electrocoagulation integrated with MBR). The electrocoagulation integrated with MBR showed the best performance in fouling reduction, removal of COD and metal in tannery wastewater. This kind of integrated MBR is suitable for the treatment of wastewater similar to tannery wastewater aiming at zero discharge. Another study by Vijayakumar et al. [27] reported that integrating electrocoagulation using aluminum as anode and stainless steel as cathode with MBR is very effective in removal of metal compared to conventional MBR (without any integrated system). The integrated MBR was found to be efficient in removal of Cr, Cu, and Zn with an average removal efficiency of more than 90% (initial concentration was 25 mg/L). This system also enhanced permeation flux and improved membrane life. Alizadeh Fard et al. [28] focused on the application of electrocoagulation, electrofenton and electron-Fenton processes for excess sludge treatment in MBR. Technical and economical investigations which conducted in this study have shown that electrofenton-Fenton system was the best one. In the control of MBR, the constant sludge yield was approximately 0.1 g when

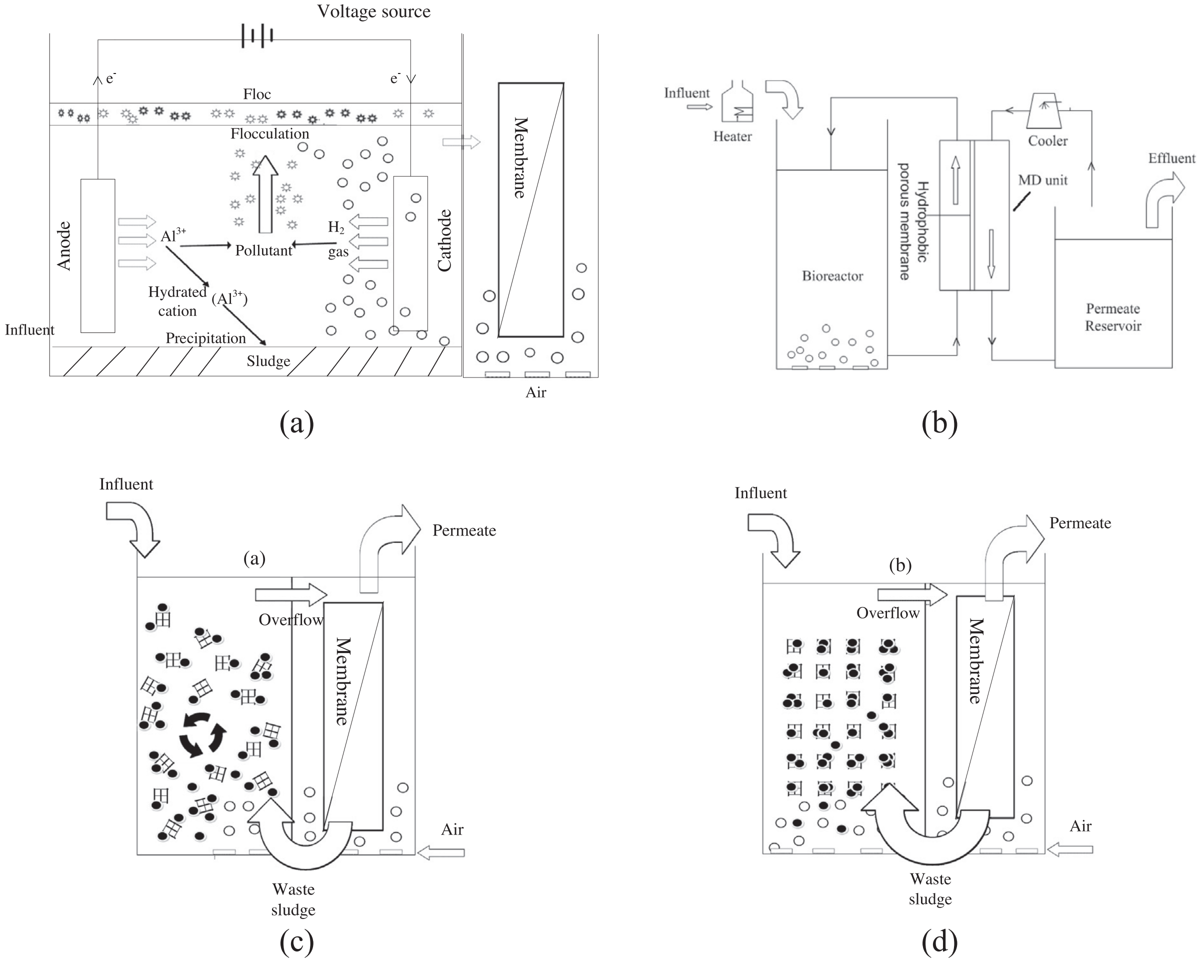

Fig. 1. Schematic diagram of the (a) integrated electrocoagulation-MBR with an external side stream membrane [98]. (b) Schematic diagram of the MDBR with an external side stream membrane [11,48]. (c) Biofilm-Membrane Bioreactor (BF-MBR), biofilm was formed on carriers with addition of fresh medium and withdraw of culture for a week and (d) Bio-entrapped-Membrane Bioreactor (BE-MBR), carriers were aerated for 6 h to entrap the cells in the pores of polyurethane foams [57].

mixed with suspended solid liquor (MLSS)/g of chemical oxygen demand (COD), however, when MBR is combined with the sludge oxidation process, the excess sludge production was almost zero. The oxidation process was found effectively to reduce membrane fouling and prolong the membrane chemical cleaning cycle. Still, the effect of sludge oxidation and total phosphorus removal was insignificant for both control and MBR-electrofenton process.

In summary, integrating MBR with AOPs and electrocoagulation were found to be effective in mitigation of membrane fouling, removal of recalcitrant compounds as well as colored compounds and metal. In other words, this system was effective in treatment of pharmaceuticals wastewater, and colored wastewater such as textile wastewater. Nevertheless, the excess sludge production, cost and optimization of parameters such as sludge retention time (SRT) and hydraulic retention time (HRT) needs to be further explored and investigated. APOs and electrocoagulation were found to be effective for wastewater treatment and reuse as they are able to produce high quality of effluent. However, more emphasis should be placed on the need of investigating the effect of AOPs and electrocoagulation on the urge to detect pathogens in the effluent.

2.2. Reverse osmosis (RO) and forward osmosis (FO) membrane

Osmotic membrane bioreactor (OMBR) has attracted growing interests due to the series of advantages such as good water quality production and low energy consumption. During MBR treatment, hydrophobic trace organic contaminants can adsorb the mixed liquor suspended solids (MLSS) and thus prolongs the retention time of the contaminants in the reactor. However, conventional MBR systems are not effective for the removal of some persistent hydrophilic trace organic contaminants [29]. Instead of MBR, OMBR is able to retain any micro pollutants with the stoked radius less than the molecular cutoff weight (MWCO) of the osmotic membrane thus significantly prolongs the biodegradation of recalcitrant compounds [3]. In OMBR, the pure water is obtained through water feed across a selectively permeable membrane under an osmotic driving force provided by a draw solution [30] and consequently minimizes the energy usage. In RO, the applied pressure to the seawater feed solution is the driving force for mass transport through the membrane (usually 2–17 bar (30–250 psi) for fresh and brackish water, and 40–82 bar (600–1200 psi) for seawater). While in FO, the osmotic pressure (27 bar (390 psi) for natural osmotic pressure) difference between the feed solution and the more concentrated draw solution is the driving force for mass transport [31,32].

Since RO process is operating at a very low hydraulic pressure; it has a low fouling tendency. Ogawa et al. [33] found that there was no significant difference in water qualities of permeates between nanofiltration and RO membrane in MBR used for municipal wastewater treatment. Nevertheless, membrane fouling was more significant in the nanofiltration membrane. Inorganic matter such as silica was the main foulant in the nanofiltration (NF) membrane while organic matter was mainly caused by the fouling of RO membrane. De Jager et al. [34] studied a pilot-scale dual stage MBR incorporating with ultra filtration (UF) membrane for treatment of textile effluent. This system reduced COD and turbidity of the effluent up to 75 and 94% to concentration of 190 mg/L for COD and 2.7 NTU for turbidity, but it only removed 29% of the color. The treated UF-permeate were further treated with NF and RO respectively;and both types of membrane are able to remove the color up to 96%. However, UF-permeate treated with RO successfully removed 92% of total dissolved solids compared to NF (29%). Farias et al. [35] reported increasing SRT resulted in RO fouling increment. Higher SRT led to improved removal of carbohydrates of the municipal wastewater, but the remaining carbohydrates may have had characteristics that resulted in greater RO fouling. De Jager et al. [36] investigated the color removal from textile wastewater using a pilot scale MBR and subsequent RO system. A consistent reduction in the color of the influent was achieved in the MBR. The residual color from the MBR was further reduced in the RO permeate (~12 ADMI (American Dye Manufacturing Index)) and a lower color unit was obtained compared to the potable water (~17 ADMI).

The advantages of FO using low or non-hydraulic pressure are low energy requirement, better rejection of contaminants and a lower membrane fouling tendency [37,38]. Tan et al. [3] studied the use of OMBR comprising cellulose triacetate FO membrane for synthetic municipal wastewater treatment and the effects of silver nanoparticles on system performance for 108 days. Significant salt accumulation was observed in the OMBR which led to a negative effect on ammonical nitrogen removal. Yet, the treatment efficiency recovered rapidly as the microorganisms acclimatized to the elevated saline environment. The nanoparticles caused a significant decrement in nitrifying efficiency and increased the production of extracellular polymeric substances (EPS) content. EPS was found to be an important factor governing membrane fouling [39]. Wang et al. [30] investigated SRT on sludge characteristics and membrane fouling in the OMBR. Lower water flux and salt accumulation in the OMBR system have been recognized as a major disadvantage to the FO membrane as it will lead to the reduction of water flux. SRT also had a strong effect of soluble microbial products (SMP) and microbial activity due to the variation of salinity. Lower SRT was helpful for alleviating the salt accumulation and flux decline. SRT had a negative impact on the removal of ammonical nitrogen and slightly affected the removal of total organic carbon (TOC) in the OMBR (keep constant at over 90% under SRT of 10 and 15 days). The difference in the TOC removal between system indicated that most dissolved TOC components probably microbial metabolic matters could be expelled by the FO membrane. Alturki et al. [40] reported the removal of the trace of organic contaminants (TrOCs, molecular weight higher than 266 g/mol) was above 80% and was possibly governed by physical separation of the FO membrane and depended mostly on biological degradation. In spite of that, there was evidence on continuous deterioration of biological activity in the OMBR, probably due to the increment of salinity in the reactor. A forward osmotic hollow fiber MBR (FOHFMB) was used for treatment of high strength saline phenolic wastewater using *Pseudomonas putida* [37]. Effluent from the chemostat was desalinated in the FOHFMB through FO process using magnesium chloride as the draw salutes. This study showed that biofouling of the membrane was reversible and membrane performance was recovered by osmotic backwashing. On the other hand, a combined system consisting of AnMBR and FO process was proposed and the FO membrane improved the removal of nitrogen and phosphorus in the AnMBR. The flux declining AnMBR combined with FO membrane was higher at temperature of 35 °C compared to 25 °C. AnMBR at 25 °C could maintain more microorganism growth and could effectively mineralize membrane foulants with small molecular size [41]. Cornelissen et al. [42] combined FO and RO processes in MBR for the reclamation of wastewater. The wastewater passes through the membranes in FO process and the RO process used to separate and recycle the draw solution, thus providing a dual barrier for trace organic contaminants. The study also made an assumption that RO membrane (20 €/m^2) is cheaper than FO membrane (30 €/m^2). A 5–25% cost saving was calculated for the reuse of wastewater with the OMBR with RO- post treatment compared to MBR-RO.

Water can no longer be pushed through the membrane to achieve recovery when RO system reaches its maximum hydraulic pressure. While FO system can treat water up to 150,000 ppm of total dissolved solids (four times the maximum RO systems) and concentrate it to over 280,000 ppm. In general, FO achieves higher recovery because it is not limited by an osmotic gradient. FO also operates at a lower pressure, which theoretically offers an energy saving compared to RO [43]. Energy consumption in FO typically up to 30% lower as compared to RO for desalination [44]. In contrast, McGovern and Lienhard V [45] investigated the theoretical and actual energy requirements of FO and RO desalination. The draw dilution step in FO desalination places the draw regeneration process a more energy consumption step compared to direct desalination using RO. FO is more energetic advantage when the salinities are higher than seawater and applications that do not require draw regeneration whereas RO cannot compete. Increasing level of academic interest in RO-MBR and FO-MBR will definitely emerge with significant findings to develop and exploit the technology for wastewater treatment.

The use of semi-permeable membrane in OMBR leads to salt accumulation within the reactor and resulting in saline environment that may affect the biological performance of the system. Bioaugmentation of salt-tolerant microorganisms or shorter SRT is suggested to enhance the treatment efficiency for a long period.

2.3. Membrane distillation bioreactor (MDBR)

MDBR combines a thermophilic bioprocess with the membrane distillation process. The water vapor across a thermal gradient through a hydrophobic and microporous membrane produces high quality water (Fig. 1 (b)). MDBR is able to capture the heat for electricity generation using a waste heat-to-power system. The generated heat can be used to drive the MBR process and reduces the reliance on electrical energy by fossil fuels [11]. Compared to MBR alone, MDBR is able to achieve high organic removal efficiency in municipal wastewater reclamation [46], produces less sludge yield [11], less sensitive to salt concentration and theoretically 100% salt rejection, low vulnerability to membrane fouling, low equipment cost and good performance under mild operating conditions [47]. The temperature difference between the feed and permeate is normally maintained at >30 °C. The feed temperature is preferably at >50 °C and thermophiles have to be used in the bioreactor. In the MDBR process, mixed liquor from bioreactor was continuously pumed to the MD unit and recirculated back to the bioreactor. This process transports water vapor through the pores of hydrophobic membrane to the permeate reservoir [11,48].

Wijekoon et al. [48] evaluated the performance of a MDBR process. The qualities of permeate with respect to the removal of TOC (>99%), total nitrogen (TN) (>96%) and TrOCs were high and were not significantly affected by the conditions of the bioreactor. TrOCs used in the studies that represent pharmaceuticals and personal care products were highly removed (>95%) by the system. The removal of TrOCs was contributed by biodegradation, sludge adsorption and rejection by membrane distillation. However, MBR alone has failed to remove recalcitrant TrOCs such as carbamazeipne and diclofenac. Goh et al. [11] pointed out some of the reasons for the lowered COD removal efficiency were due to the reduced colloidal COD removal as floc-forming species and protozoa which were absent at thermophilic condition. Futhermore, this may cause the decrement in biodiversity at thermophilic condition and hence, in its ability to degrade the large range of compounds as the mesophilic counterparts. The pH shift and lowered oxygen solubility with temperature increment are other potential factors which may affect COD removal. Phattaranawik et al. [49] used MDBR for treatment of organic wastewater and resulted in high quality water product with very low TOC and negligible salts. MDBR has the potential to be applied for wastewater reclamation in 'one step' and has more benefits (high quality effluent and low greenhouse gases emission) compared to the combined MBR and RO process. On the other hand, studies were conducted by Zhang et al. [50] to analyze the performances and microbial community composition on a lab-scale MDBR. The treatment of synthetic wastewater was conducted with and without adjusted of pH. TN removal efficiency was 87% on average without adjusting of pH and reached 99.8% with pH adjustment from the scale of 9–10 to 7–8. Taxonomy-dependent analysis revealed *Rubrobacter* and *Caldalkalibacillus* were the abundant members of the bacterial diversity. The two MDBR comprised of a low diversity bacterial community and a highly diverse eukaryotic community with no detection of archea.

Like osmotic system, MDBR can be as an efficient mean to achieve high removal of recalcitrant pollutants. Compared to osmotic system, MDBR is potentially applied in areas where hot wastewater and waste heat are produced in the industry since the heat is able to be captured for operation of MDBR. Availability of low grade waste heat and cooling agents are the important considerations for applications of MDBR.

2.4. Biofilm membrane bioreactor (BF-MBR) and bio-entrapped membrane bioreactor (BE-MBR)

BF-MBR is the addition of carriers inside the MBR that reduces the concentration of suspended solids and leads to mitigation of membrane fouling. This system is able to reduce the concentration of suspended solids without limiting the efficiency of the process [51]. It offers several advantages such as higher biomass activity and higher resistance to toxic substances [52]. Fig. 1(c) shows the schematic diagram of the BF-MBR where the biofilm was developed on the surfaces of the carriers.

Leyva-Díaz et al. [53] investigated a BF-MBR containing carriers in the anoxic and aerobic zones of the bioreactor and a BF-MBR which contained carriers only in the aerobic zone. Both the reactors showed better performances compared to MBR without carriers. The systems containing carriers had the greatest nitrifying activities because of the highest total concentration of nitrifying and denitrifying bacteria. The BF-MBR containing carriers only in the aerobic zone showed the best performance from the point of view of the kinetics of heterotrophic and nitrite-oxidizing bacteria. The absence of carriers in the anoxic zones reduced the growth of some aerobes while favored the growth of denitrifying bacteria. This system significantly mitigates the biofouling, improves both the nitrification and denitrification processes of MBR. Similar results have been reported by Subtil et al. [54]. The authors reported no significant difference observed between the BF-MBR and MBR for COD removal. However, BF-MBR showed better removal in ammonia and TN as well as lowered the fouling rate about 35% compared to MBR. In contrast, Yang et al. [55] compared the efficiency of BF-MBR and conventional MBR for the removal of TOC and TN in wastewater. BF-MBR demonstrated good performance on the removal of TN and ammonical nitrogen due to the efficiency of biomass in carrier that had performed well in nitrification of biofouling and denitrification. The specific oxygen utilization rate (SOUR) also proved that biofilm in BF-MBR has a better microbial activity than activated sludge in conventional MBR. However, membrane fouling behavior in BF-MBR was more severe and speculated caused by filamentous bacteria in the system. Rollings-Scattergood [56] designed BF-MBR incorporated hydrodynamic exterior carriers with highly porous interior packing. Again, the nitrogen compounds were superiorly removed in the BF-MBR when compared to MBR.; Whilst the fouling propensity was found to be increased by over four times in BF-MBR systems as compared to the conventional MBR.

Rafiei et al. [57] investigated the BF-MBR and BE-MBR in wastewater treatment and compared the removal fouling and removal efficiency of the reactors. Carriers in the BE-MBR were developed by immobilizing the cells using entrapment method. The cells will be entrapped in the pores of the carriers as shown in Fig. 1(d). The authors found out that fouling in BF-MBR was severe than the conventional MBR at the later stage of treatment resulting from the cell released of the carriers. BE-MBR demonstrated the best performances in terms of both removal efficiency of phenol and membrane fouling which was four times slower than the conventional MBR. Ng et al. [58] investigated a bio-entrapped membrane reactor (BEMR) and a salt marsh sediment membrane bioreactor (SMSMBR) for the treatment of pharmaceutical wastewater. In BEMR, activated sludge from the wastewater treatment plant was entrapped in bio-carriers.But somehow, it was not able to tolerate well with the hypersaline condition and resulted in lower COD SMSMBR were able to degrade recalcitrant compounds but nitrification activity removal compared to SMSMBR. On the other hand, marine microorganisms in was inhibited due to the saline effect. [59] compared the BE-MBR and conventional MBR for organic matter removal and membrane fouling reduction. The authors concluded that BE-MBR showed better performance in removal of COD and ammonical nitrogen at longer HRT and also continuous aeration. The BE-MBR was also less susceptible to fouling on account of slow growing microorganisms with long SRT.

BF-MBR and BE-MBR have a good performance in removing TOC and TN because of the better nitrifying process compared to MBR alone .Even so, there has been an argument in mitigation of membrane fouling for BF-MBR. The main reason contributed to the biofouling of membrane was caused by the position of membrane in BF-MBR. Fouling propensity might be lower in side-stream external membrane module followed by conventional MBR and finally submerged the membrane module in BF-MBR system. Furthermore, there is a lot of other factors that might contribute to biofouling. Study of metagenomic microbial communities in different types of wastewater are required to understand the relationship between bacteria on the surface of carriers and membrane. Immobilization of cells by entrapment method in BE-MBR showed better performances in removal efficiency and membrane fouling.

2.5. Granular MBR

Aerobic granular sludge systems were studied extensively for operating at high organic loading. Simultaneous nitrification and denitrification could be achieved inside the granules because of its spherical compact structure. In addition, granular sludge has a rich microbial morphology, and is capable to work efficiently compared to a single microorganism [60].

Vijayalayan et al. [61] studied the combination of sequencing batch airlift reactor (SBAR) and membrane airlift bioreactor (MABR) for treating synthetic wastewater. SBAR was used to cultivate aerobic granules and MABR for further treating the effluent from SBAR by polyethylene membrane filtration. Both aerobic and anoxic zones exist in MABR, while in SBAR, aerobic granules was cultivated through simultaneous nitrification (high aeration) and denitrification (low aeration). The membrane fouling in the system was reduced significantly by the granular sludge; however, the release of soluble extracellular polymeric substances (EPS) from granule disintegration after 20 days was accountable for membrane fouling. Hence, ratio of new and old granules should be maintained in reactor with a suitable solid retention time to enhance the granule stability. Zhao et al. [60] studied the aerobic granular sludge membrane bioreactor (GMBR) for treatment of pharmaceutical and personal care products. The results showed that the sludge granulation process in the system was rapid but unstable, and that the system exhibits a dissolution-reunion dynamic equilibrium. This system exerts a great removal of COD, ammonium nitrogen and total phosphorus.

Li et al. [62] studied the Anammox (anaerobic ammonia oxidation) granules formation and performance in a submerged anaerobic MBR with continuous feeding and completely mixing. Stable removal efficiency up to 88% of TN was accomplished by the formed granules. The operation cycle of the membrane was prolonged by 2 times with the increasing of the granule size. The authors concluded that the Anammox granules showed high activity, high shock resistance capacity, fast growth rate, mitigate fouling and potential in treating of high strength nitrogen wastewater.

3. MBR as a sustainable wastewater treatment option

Due to global environmental concerns and energy insecurity, there is emergent interest to find out sustainable and clean energy source with minimal use of fossil fuels. World Bank stated that the greatest challenge in the water and sanitation sector over the next two decades will be the implementation of low cost sewage treatment that will at the same time permit the selective reuse of treated effluents for agricultural and industrial purposes. It is highly beneficial to utilize wastewater as the low cost substrates for production of energy and value added products whilst simultaneously solving the environmental problems.

3.1. MBR utilization for biofuel production

Biogas is renewable fuel and can be used as an alternative to the fossil fuels. The production of biogas depends on the activity of methanogen. MBR for biofuel production is still a new concept whereby only a few industries employ anaerobic biological process for wastewater treatment [8]. Methanogen has a very slow growth rate and is easier to wash out from the conventional anaerobic treatment system. Anaerobic process is complex compared to aerobic processes. There are high chances of process failure due to the presence of inhibitory substances, such as heavy metals, chlorinated hydrocarbons, and cyanides that are present in feeding wastewater or sludge. The net biomass production must exceed the net biomass loss for biological treatments to function properly. However, in conventional anaerobic biological treatments, the net biomass lost to the effluent is higher due to the poor settling characteristics of the biomass. Besides that, conventional anaerobic biological treatments were also not effective in removing residual levels of soluble and colloidal contaminant with poorer gas capture, poorer odour control, limited ability to capture nutrients and expensive de-sludging processes [63,64]. In view of this, AnMBR has gained attention as it has potential for energy recovery and retains the biomass for an efficient treatment. The integration of membrane also results in a good quality effluent that has significantly lower amount of particles and pathogens [15]. Table 3.1 shows the types of AnMBR and membrane yield generated in each AnMBR

Sheldon et al. [65] studied the utilization of anaerobic expanded granular sludge bed (EGSB) for treatment of paper mill effluent followed by a post-treatment side stream MBR (ultra-filtration membrane). EGSB system had successfully removed 65–85% of COD and satisfactory improved results were obtained with an overall MBR reduction in COD of 96%. An upward trend of methane production was noticed when the HRT was decreased (from 10.3 to 7.7 h) and the OLR was increased (from 4.8 to 5.5 kg COD). Integrated anaerobic fluidized-bed membrane bioreactor (IAFMBR) with granular activated carbon (GAC) was developed to treat domestic wastewater with energy recovery. At HRT for 6 h, methane yield was 180 L; conversion of 53% of COD into methane in biogas. The reactor contained two parts; outer part performs as anaerobic fluidized bed reactor with GAC as carriers and the inner part serves as anaerobic MBR [66]. Wei et al. [67] studied the comprehensive effects of organic loading rates (OLR) on methane production as well as organic removal and biomass production to optimize AnMBR operation. A very steady and high COD removal was achieved over a broad range of volumetric organic loading rates (OLR). The AnMBR achieved high methane production of over 300 mL/g COD at a high sludge OLR of over 0.6 g COD/gMLVSS/d. The authors concluded that the integration of heat pump and FO into the mesophilic AnMBR process would be a promising way to net energy recovery from typical municipal wastewater, especially in a temperate area. Youngsukkasem et al. [68] studied the rapid bio-methanation of syngas in a reverse membrane bioreactor (RMBR) by using membrane-encased microorganisms. Recalcitrant compounds such as lignin and plastic wastes cannot be decomposed by the microorganisms in conventional anaerobic process. However, thermochemical processes have the potential to convert this kind of wastes and non-degradable residues into intermediate gas, called syngas. The digesting sludge encased in the PVDF membranes was able to convert syngas into methane and displayed a similar performance as the free cells in batch fermentation. At thermophilic conditions (55 °C), there was a higher conversion of pure syngas and co-digestion using the encased cells compared to mesophilic conditions. A submerged anaerobic MBR with FO

Table 3.1
Types of AnMBR and methane yield generated in each AnMBR.

Authors	Types of AnMBR	Wastewater	Methane yield	Membrane
Gao et al. [66]	Integrated anaerobic fluidized-bed MBR	Domestic wastewater	180 L methane per kg $COD_{REMOVED}$	Hollow fiber membrane
Wei et al. [67]	Mesophilic AnMBR	Synthetic municipal wastewater	300 mL/gCOD	Hollow fiber PVDF UF membrane
Youngsukkasem et al. [68]	Reverse MBR	Synthetic organic medium	0.9 mmol	PVDF membrane
Chen et al. [69]	FO submerged AnMBR	Synthetic wastewater	0.21 L/gCOD	Flat-sheet cellulose triacetate (CTA) membranes
Sheldon et al. [65]	Anaerobic/aerobic hybrid side-stream MBR	Paper mill effluent	28.6 L/day	Ultra-filtration membrane
Jensen [64]	AnMBR	Red meat processing wastewater	360 L methane per kg COD	Submerged hollow fiber membrane

membrane was studied by Chen et al. [69]. The AnMBR was operated at 25 °C using the synthetic wastewater as substrate. Due to the membrane fouling and the increasing salinity in the AnMBR, the water flux was reduced. However, the authors claimed that the level of salinity in the reactor was not a concern in terms of inhibition or toxic effects and an average value of 0.21 L CH_4/g COD was obtained. The removal rate for ammonical nitrogen and total phosphorus were up to 60% and 100% respectively, exhibiting the excellent interception of FO membrane. Jensen [64] studied the treatment of wastewater and nutrient recovery from red meat processing facilities using AnMBR pilot plant. The AnMBR removed over 90% of COD consistantly and produced approximately of 360 L methane per kg COD. Economic comparisons show that the payback of AnMBR is comparable to a conventional anaerobic lagoon due to increased gas capture resulting in improved energy recovery.

Jensen [64] estimated that in an AnMBR, 10% of the capital costs are in membranes and 50% in vessel. Biogas produced through AnMBR can lower the cost further by using the gas to feed a boiler, and/or a trigeneration system to produce heat, power and colling. Pretel et al. [70] investigated the operating cost of an AnMBR treating sulphate–rich wastewater. Operating at high ambient temperature and/or high SRT allows significant energy savings (minimum energy demand: 0.07 kW h/m^3). While low/moderate sludge productions were obtained (minimum value: 0.16 kg TSS/kg $COD_{REMOVED}$), which further enhanced the operating cost (minimum value: €0.01 per m^3). Each cubic metre of biogas contains the equivalent of 6 kW h or 21.6 MJ of energy and approximately 35% of the total energy is converted to electricity while others are converted into heat, some of which can be recovered for heating applications [71].

The limitation of biogas recovery is the lower biogas recovers in small capacity of treatment plant. Most of the methane produced in the treatment plant is lost through the effluent of the treatment plant. The methane concentration of about 16 mg/L (equivalent COD 64 mg/L) is expected in the effluent caused by the partially high pressure of methane gas inside the treatment plant [72]. This issue must be addressed for ideal application of AnMBR. Besides, continuous process optimization should be conducted as the payback period of an AnMBR remains comparatively high [64]. Last but not least, the competition between methanogen and sulphate in reducing bacteria for the available substrate is another issue facing in the AnMBR. The available COD for methanisation would reduce when there is significant sulphate content in the effluent [70].

3.2. Electricity production

One of the restrictions of wide application of MBR is the high energy consumption, estimated at 0.8–1.1 kWh/m^3 [73]. Thus, integration of microbial fuel cells (MFC) with MBR is recommended since energy consumption of MBR can be further lowered. MFC can convert the chemical energy in organic matters into electrical energy by the catalytic reaction of microorganisms. In other words, MFC can provide clean and safe energy, quiet performance, low emissions, and ease in operating, apart from treatment of wastewater. MFC is generally composed of two chambers as shown in Fig. 2; and anode chamber where the oxidation of organic compounds takes place under anaerobic condition and a cathode chamber where the oxygen or ferricyanide is reduced under aerobic condition [74]. However, MFC alone leads to low efficiency treatment and poor effluent quality due to limited biomass retention [75]. Effluent from MFC alone still contains a certain amount of suspended solids and the remaining contaminants need further treatment before being discharged. Combination of MBR-MFC system or known as electrochemical membrane bioreactor (EMBR) or membrane bioelectrochemical reactor (MBER) or bioelectrochemically-assisted membrane bioreactor (BEAMBR) offers a convincing option for wastewater treatment and energy recovery. The types of cathode, anode, membrane and power density generated in each MFC-MBR system were listed in Table 3.2.

Wang et al. [76] conducted a study related to MBR-MFC and stated that only 28% of COD was removed in the anode chamber while the majority of organic pollutants (total removal of COD was 85%) were removed in cathode chamber. Wang et al. [77] claimed that they developed a more practical MBR-MFC integrated process in which they were trying to reduce the investment and operating cost. The authors used aeration tank of MBR as a cathode chamber, low-cost nylon mesh was adopted as filter material, and low cost anode and cathode. Synthetic wastewater containing acetate was used as an influent for the system. Wang et al. [78] studied the use of MBR-MFC without aeration for energy recovery and

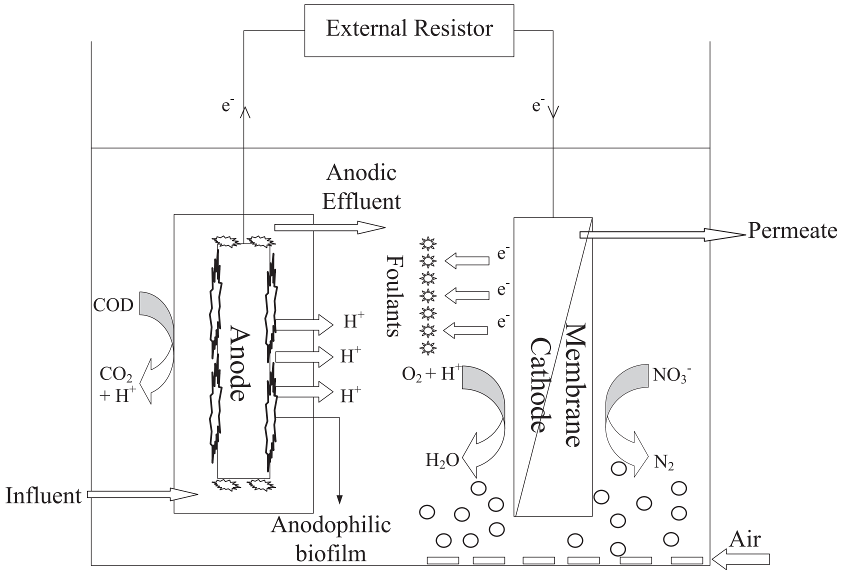

Fig. 2. Schematic diagram of MFC-MBR and mechanism of electric field on membrane fouling mitigation. Electrons generated in anode are transferred to membrane cathode and exerts and exerts additional repulsion force to membrane foulants [85].

Table 3.2
Types of cathode, anode, membrane and power density generated in each MFC-MBR system.

Authors	Anode	Cathode	Maximum power density (W/m^3)	Membrane
Wang et al. [86]	Graphite rod	Stainless steel mesh	4.35	Stainless steel mesh
Wang et al. [77]	Activated carbon fiber	Carbon felt	6	Nylon mesh with pore size of 74 μm
Wang et al. [78]	Graphite felt	Graphite felt	7.6	Non-woven cloth
Wang et al. [76]	Graphite felt	Graphite rod & stainless steel membrane	8.62	Flat-sheet membrane made of stainless steel mesh
Wang et al. [84]	Graphite rod	Stainless steel mesh	1.43	Stainless steel mesh
Ge et al. [79]	Carbon brush	Carbon cloth coated with 10% Platinum (Pt)	2 (wastewater)	PVDF Hollow-fiber membrane
Li et al. [73]	Carbon cloth	Carbon cloth coated with 10% Pt	0.15	PVDF Hollow-fiber membrane
Huang et al. [81]	Graphite rod	Flat-sheet membrane made of stainless steel mesh	8.6	Flat-sheet membrane made of stainless steel mesh
Wang et al. [82]	Carbon felt	Carbon felt	0.76 mA	Tubular ultrafiltration membrane
Liu et al. [85]	Graphite granules	Stainless steel mesh	0.15	Stainless steel membrane
Li et al. [83]	Graphite granules	Polyester filter cloth, modified by *in situ* formed PANi (polyaniline)-phytic acid (PA)	0.78	Polyester filter cloth, modified by *in situ* formed PANi (polyaniline)-phytic acid (PA)

wastewater treatment. The anodic chamber was inoculated with synthetic wastewater containing acetate. The graphite cloth cathode was immerged in a laboratory scale MBR for 5 min to inoculate nitrifiers and dinitrifiers as to enhance the operation process. Effluent from anodic chamber penetrated through non-woven cloth (as separator and membrane) and air cathode, and was finally discharged from the system. Despite air cathode was easier for construction and significantly improved the power density, the drawbacks of air cathode included membrane pH gradient, water leaking through cathode and accumulation of inorganic salt deposits. The authors claimed that those problems were improved through the unique configuration of their EMBR. Another study was conducted by Wang et al. [76] where a new MBR-MFC process was developed using an up-flow reactor design. The lower part was the anode chamber of the MFC while the upper part was a MBR installed with a stainless steel membrane. The authors used the stainless steel membrane as solid liquid separator and as a cathode for the MFC. Graphite rods were fastened on the membrane and connected to the external resistor by copper wire. The authors claimed that this type of MBR-MFC is easier for operation and maintenance. Again, the synthetic wastewater containing acetate as influent was used by the authors. Ge et al. [79] investigated the use of hollow-fiber membrane bioeletrochemical reactor for domestic wastewater treatment. The MBR-MFC was constructed with a tube made of cation exchange membrane (CEM). The CEM tube formed an anode compartment and the cathode was directly exposed in the air to avoid active aeration. The MBR-MFC was first operated with synthetic wastewater containing acetate, producing maximum electricity at 0.038 kWh/m^3. The MBR-MFC was preceded to domestic wastewater and produced the maximum electricity at 0.025 kWh/m^3. The wastewater gave lower electricity as the COD is 1/3 lower than the synthetic wastewater. Although this kind of MFC-MBR gave a lower energy consumption (no aeration require), this kind of reactor has a limited nitrogen removal and requires post-processes to remove or recover nutrients like other anaerobic treatments [80]. Li et al. [73] studied the advancing MBR-MFC with hollow-fiber membranes installed in the cathode compartment. The cathode compartment was aerated with air. The energy production in the MBR-MFC was 0.011–0.039 kWh/m^3 from the synthetic wastewater containing acetate and 0.032–0.064 kWh/m^3 from the cheese wastewater. Compared to MBR and AnMBR fed with the cheese wastewater, MBR-MFC used by Li et al. [73] achieved a better removal of COD and TN. Huang et al. [81] studied two MBR-MFC operated under closed-circuit and open-circuit modes. Maximum power density of the MBR under closed circuit operation was as high as 8.6 W/m^3, indicating that the biochemical MBR did not only achieve efficient wastewater treatment but also power production. To the best of our knowledge, this is the only study on identification of microbial communities on MBR-MFC by high-throughput 454 pyrosequencing. Under closed circuit condition, *Bacteroidetes* was the dominant phyla in the anode samples while *Protebacteria* was the most dominant phyla in the cathode samples. Wang et al. [82] studied a MFC-tubular MBR system where the bio-cathode MFC was developed as a biosensor for COD real-time monitoring and the performance was analyzed in terms of its current variation caused by operation parameters. This sensor output had a linear relationship with COD and mixed liquor suspended solids (MLSS) concentration. The authors concluded that this system provided an opportunity to widen the application of MFC-base biosensor. Li et al. [83] studied a simple and low cost MBR-MFC system without using any noble metal. The authors claimed that they are the first to utilize a low cost and conductive polyester filter cloth, modified by *in situ* formed PANi (polyaniline)-phytic acid (PA) as cathode. Potential anode cell was not affected by the anode types as it was regulated by the respiration of inoculated *Shewanella oneidensis*. This MBR-MFC system was able to remove COD of the synthetic wastewater up to 95% with the modified membrane as cathode. However, the electricity was indeed low and further studies are needed to improve the electricity generation.

Wang et al. [84] studied the utilization of MFV in MBR to mitigate membrane fouling. The results showed that the formed electric field reduced the deposition of sludge on membrane surface by enhancing the electrostatic repulsive force between them. The other reason that contributed to membrane fouling is the H_2O_2 produced at the cathode which is able to remove the membrane foulants. This system exhibited a good performance where the COD removal was 94%, 97% for ammonical nitrogen removal as well as a low effluent turbidity below 2 NTU. Liu et al. [85] studied the integration of MBR-MFC for electricity generation, fouling mitigation and artificial wastewater treatment. The authors identified that the sludge properties and aeration in cathodic chamber were the main affecting factors on electricity generation. They found that MFC was a successfully alleviated membrane fouling under closed circuit condition. Electrons generated in anaerobic chamber can be transferred to cathode membranes via an external circuit and the protons generated in anode zones would cross the separator to cathode chambers (Fig. 2). This exerts an additional repulsion force to membrane foulants such as negatively charged sludge, organic matters and mitigates membrane fouling. This system was successful in the removal of offensive smell, total nitrogen, COD and turbidity after aerobic treatment and filtration from the synthetic wastewater, and similar to the sequential anaerobic–aerobic system.

In summary, MBR-MFC achieved a better performance with potential advantages in energy consumption and recovery as well as minimization of membrane fouling. It also can be turned into a simple and rapid COD biosensor. Compared to conventional COD sensors, the bio-cathode MDC-based biosensor does not need external power sources. It makes an intelligent use of the electrical energy [82]. Some researchers utilized the membrane as cathode and filtration membrane. The others utilized the aeration in cathode chamber to enhance the reducing of electron and mitigation of membrane fouling. Whatever the design and material of MFC-MBR are, the goal was to target a low cost sustainable development of MBR technology. Further development would address the challenges as in scaling up system, capital cost and operation cost.

3.3. Nutrients and metals recovery

Phosphorus is an important non-renewable resource. Most phosphorus tend to be lost from terrestrial environment and end up in deep-sea sediments where only tectonic movements in geologic times can bring them back to the land [87]. Mineral fertilizers (especially nitrogen and phosphorus) led to a substantial increment in agricultural yields. There is no substitute for phosphorus in crop growth and it cannot be synthetically manufactured. Approximately 90% of all phosphate demand is for food production, primarily for the production of fertilizer (82%) and animal feed additions (7%) [88]. Recovering phosphorus from wastewater is a desirable alternative to provide sustainable phosphorus supplies. Qiu and Ting [87] studied the direct phosphorus recovery from municipal wastewater via OMBR for wastewater treatment. PO_4^{3-}, Ca^{2+}, Mg^{2+} and unconverted NH_4^+ were rejected by the membrane and accumulated within the bioreactor. The rich phosphorus supernatant was then recovered via precipitation by adjusting the pH to 8–9.5. Apart from being utilized by microorganisms, this kind of reactor can recover almost all the phosphorus. In contrast, Johir et al. [89] investigated the MBR-ion-exchange hybrid system for recovery of phosphorus and nitrogen from MBR effluent. The MBR was operated at HRT of 4 h and able to remove DOC up to 90% while over 98% of phosphate and nitrate were obtained during degeneration of columns. Besides studied the treatment and production of methane from red meat processing wastewater which have been discussed in Section 3.1, Jensen [64] also studied on the nutrient recovery in using AnMBR. The nutrient recovery accounted for 90% of nitrogen (NH_3) and 74% of phosphorus (PO_4) and suggested that the AnMBR is not optimized for nutrient recovery. Jensen [64] suggested that optimization should focus on maximizing the release of nutrient in the anaerobic step to facilitate recovery in a cyrstalliser and depressed pH is a potential strategy to prevent loss of nutrients.

Biological production of H_2S is a conventional method of precipitating metals from wastewater. The sulfate reducing bacteria is grown in the wastewater and the production of H_2S leads to metal precipitation. These metal sulphides are insoluble and can thus be easily separated. Nevertheless, this application is limited due to the biologically hostile characteristics of the wastewater that leads to the inhibition of microbial activity. An extractive membrane bioreactor: sulphate-reducing bacterial (EMBR-SRB) system can be used to solve these limitations [90]. Tabak and Govind [91] pointed out the advantages of using EMBR-SRB: large microporous membrane surface to the liquid phase, formation of H_2S outside the membrane and preventing the mixing with the pressurized hydrogen gas inside the membrane. The authors suggested this system significantly improves the process operability for metal recovery and the cost for the treatment of acid mine drainage.

4. Future trend of MBR technology

The main contributors to energy costs in MBR are sludge transfer, permeate production and aeration which is often exceeding 50% of total energy consumption. Energy consumption of membrane related modules was in the range of 0.5–0.7 kWh m^{-3} and specific energy consumption for membrane aeration in flat sheet was 33–37% which was higher than in a hollow fiber system. While submerged membranes in MBR reduces the pumping energy requirement to 0.007 kWh m^{-3} of permeate compared with side-stream membrane (3.0 kWh m^{-3}) [92]. Future trend of MBR might be focused on two aspects which are reduction of energy demand and membrane fouling.

4.1. Reduction of energy demand

There are two ways to reduce the demand of energy in MBR. The first one is the production of electric through the treatment process and supplies it to the system such as aeration system which contributed to most of the energy consumption on MBR. This can only be done using MFC where the microorganisms will oxidize the organic compounds and produce electric simultaneously. Yet, the major drawbacks of MFC is the poor permeates' quality. Another polishing system might be needed in MFC-MBR for further polishing the effluent or optimizing the treatment process such as bioaugmented of known bacteria. In future, research and development on powering up the MFC to produce electric with no harmful emissions might increasingly become important.

The second type of integrated MBR that able to produce energy is the integrated anaerobic MBR. However, commercialization of AnMBR at industrial scale is still pending due to membrane fouling and membranes sensitivity to toxicity [17]. AnMBR is in most efficient when treating of low/non sulphate wastewater in warm/hot climates whereby theoretical optimum energy productions of 0.11 kW hm^{-3} could be achieved [70]. In summary, the electric and energy produced in the integrated MBR is expected to cover the energy required for wastewater treatment and the excess energy could be further used.

The second idea of reduction of energy demand in MBR is to use system with low or non-hydraulic pressure and/or a lower membrane fouling tendency. RO and FO are low in energy consumption and have low fouling tendency. However, this system resulted in salt accumulation within the reactor and affects the biological performance of the system. Membrane improvements and control of microbiological activity are extremely important to aide in the long-term reliability of RO-MBR and FO-MBR. Bioaugmented of certain bacteria that is able to resist the saline environment and oxidizes the organic compounds in the reactor might be one of the solutions to maintain the biological performance of the system.

4.2. Reduction of membrane fouling

Membrane fouling and energy consumption (aeration) are interconnected and considered as a major drawback in application of MBR [93]. Air scouring for the membrane and aeration of activated sludge are accounted for 60–80% of the energy consumption in MBR [94] .There are several methods to reduce the membrane fouling of MBR such as optimization of HRT and SRT which were discussed in some review papers [2,9,13,15]. However, this study is focusing on the integrated system with MBR that able to reduce membrane fouling. Various integrated system such as AOPs, RO-MBR, FO-MBR, MDBR, MBR-MFC, AnMBR that were discussed in this review paper show the ability to mitigate membrane fouling. However, there has been an argument in mitigation of membrane fouling in BF-MBR and granular MBR. Besides, increasing the SRT led to a decrease in the fouling of the MBR membranes. In contrast, increasing the SRT of the MBR resulted in increased fouling of the RO membranes. These indicate that the constituents of foul MBR membranes are not the same as those of foul RO membranes [35].Hence, further research should be focused on SRT and/or HRT of the integrated MBR to mitigate the membrane fouling.

(1) Important applications of enzymatic membrane reactors have been developed in the field of food industries and fine chemical synthesis to produce and transform raw materials [95]. However, there has been increment in interests of enzymatic membrane reactors for environmental purposes. Lloret et al. [96] studied the removal of estrogenic compounds from filtered secondary wastewater effluent while Ba et al. [97] studied the removal of aromatic pharmaceuticals in wastewater. The enzymes were trapped in the membrane either using smaller pore size of membrane and/or insolubilized enzyme which aggregated sizes are larger than the pores of the membrane. Integration of the enzymes in the MBRs might be useful in degradation of micropollutants that cannot be degraded by the bacteria in the MBR system.

5. Conclusion

The many advantages associated with the MBR technology make it a reliable and valuable option, more favorable over other waste management techniques. In this review, integration of MBR with other treatment systems have been introduced and discussed. Future research in MBR is likely to focus on reduction in energy demand and membrane fouling during the operation. More and more new structure of MBR had been proposed for practical application regarding revolutionary in environmental engineering. MBR showed a good performance in terms of high organic removal and it would be an attractive alternative for water reuse and recycle in near future. The other development of the integrated MBR is required to address design issues for simultaneous treatment and valorization of wastewater. There are several options one can choose in order to find the most appropriate MBR technology for a particular region. The attractive advantages and interesting engineering characteristics of integrated MBR have great potential to play an important role in wastewater treatment for sustainable development. The continuous effort in academia and industry will contribute to emerge integrated MBR in treatment and valorization of wastewater.

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