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Development of membrane separation technology and membrane-based bioreactor in wastewater treatment: conventional membrane and dynamic membrane

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ABSTRACT

Nowadays, membrane has played an important role in wastewater treatment. However, high membrane cost and membrane fouling has hindered the developing of conventional membrane separation technology. With low-cost supporting membrane and easy operation, dynamic membrane (DM) technology presents a new route for pollutants separation in wastewater treatment. Similar pollutants removal and high separation efficiency made it more suitable for application in wastewater pretreatment and sludge separation. To have a full understanding of recent development of membrane separation technology, microfiltration, ultrafiltration, nanofiltration, and dynamic membrane filtration were briefly introduced and compared in this study. The filtration and pollutants removal performance in membrane bioreactor and dynamic membrane bioreactor were also evaluated. Besides, future perspectives of membrane separation technology with membrane fouling control, membrane cost and maintenance were presented for better application of membrane technology. Overall, DM technology indicates one potential developing direction of membrane separation technology in wastewater treatment.

Keywords: Membrane separation; Wastewater treatment; Dynamic membrane; Membrane bioreactor

1. Introduction

Membrane separation technology mainly refers to the separation process with selective membrane as separation medium to separate, concentrate and purify. The first membrane separation technology was reported in the early 20th century. Until 1960s, membrane separation technology had achieved a huge development, with advantages of high separation efficiency, acceptable energy consumption, and highly reliable equipment. Since then, membrane separation had been widely explored and attempted in wastewater treatment.

According to the membrane pore size, separation membrane can be divided into microfiltration membrane (MF), ultrafiltration membrane (UF), nanofiltration membrane (NF), etc. As we know, microfiltration and ultrafiltration have been explored in water and wastewater treatment for a long time, which proves to be mature and suitable when high water quality is needed [1]. Meanwhile, better water quality could be observed with nanofiltration and reverse osmosis (RO) membrane than microfiltration and ultrafiltration, but the operating cost proved to be higher [2]. Due to the tiny membrane pore size in MF, UF, NF, and RO, membrane fouling and membrane cleaning has limited the continuous development and application [3]. As it is known, the anti-fouling measures for membrane bioreactor (MBR) have been studied for the optimization of membrane material, membrane structure, operating condition, and so on.

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Specially, membrane hydrophilic modification, optimization of membrane structure and operating condition can be used for membrane fouling control. Slug bubbling technique belongs to the optimized operating condition in membrane separation process. High wall shear stress could be induced by periodic slug bubbles in MBR, which is more effective and economic to enhance the mass transfer coefficient with a modest consumption of air [4]. Besides, the decreasing membrane flux in membrane separation and high operating cost also restricted the development of membrane separation technology. But high effluent quality was not always needed, such as the pretreatment process and sludge separation in wastewater treatment. Hence, larger pore size membrane is expected to be applied to reduce the membrane cost and improve the membrane flux, meeting the essential demand in wastewater treatment, which facilitated the presence and application of dynamic membrane technology.

The first original report of primary dynamic membrane could be dated back to 1966 for salt removal with dynamically formed hydrous oxide membrane by Marcinkowsky et al. [5]. Since then, dynamic membrane technology has been explored on conventional membrane with different formation materials [6]. However, dynamic membrane on large pore size supporting membrane has gradually attracted much attention due to the advantages of high filtration flux, low energy consumption, and easy cleaning, which showed tremendous potential in wastewater treatment than conventional membranes, such as sludge retaining [7], sludge dewatering [8], microparticle removal [9,10].

Anantharaman et al. [11] presented a detailed review on formation and regeneration, fouling mitigation, application, and technical and economic assessment of pre-deposited dynamic membrane. Hu et al. [12] discussed the bioreactor configurations, dynamic membrane (DM) layer formation and cleaning in anaerobic dynamic membrane bioreactor for wastewater treatment. Despite the detailed introduction of dynamic membrane in recent years, few studies on the comparison of characteristics of conventional membrane and dynamic membrane have been reported. The distinction and connection between conventional membrane and dynamic membrane have not been clearly explained in previous research.

Therefore, the main objective of this study was to analyze and compare the physical characteristics, membrane flux, operating pressure and application range of conventional membranes and dynamic membrane, and reveal the developing trend of membrane in future. Besides, the characteristics and performance of membrane bioreactors coupled with conventional membrane and dynamic membrane technology were also discussed and evaluated. Finally, the problems and future development of membrane separation technology and membrane-coupled bioreactor were briefly introduced.

2. Characteristics of MF, UF, NF and DM

2.1. Microfiltration

The pore size of microfiltration membrane generally locates in 0.01~10 μm [13], with operating pressure of 0.1~0.3 MPa as the driving force. Generally, microfiltration membrane was characterized with uniform pore size, high filtration accuracy, high flow rate, etc. Thus, microfiltration membrane was commonly used to reject impurities in wastewater, such as tiny, suspended particles and bacteria, which could be screened and retained by microfiltration membrane [14].

Owing to the excellent solid separation efficiency in wastewater treatment, more application of microfiltration was explored in combination with other technical process, such as MBR process, coagulation–microfiltration, and multifiltration process. The combination of microfiltration with biological and chemical process significantly improves the applicability in industrial wastewater and domestic sewage treatment [15]. Chemical oxygen demand (COD) removal rate of 90% was achieved in submerged anaerobic membrane bioreactor for the treatment of the organic fraction of municipal solid waste leachate [16]. The membrane-based bioreactor significantly improved the dissolved organic matter removal rate.

To avoid serious membrane fouling, the physical and chemical properties of the membrane surface can be changed by membrane modification, membrane coating and membrane grafting. Besides, coagulation, adsorption and oxidation can also be used to alleviate membrane fouling. Chellam and Sari [17] found that electrocoagulation pretreatment could enhance the removal of suspended and dissolved macromolecular substances before microfiltration, effectively reducing membrane fouling. Much work on fouling control in microfiltration has been conducted, which still remained to be solved in future.

2.2. Ultrafiltration

Ultrafiltration membrane is commonly characterized with pore diameter of 1–100 nm, and operating pressure ranging from 0.2 to 0.4 MPa. Macromolecules and colloids in the process could be separated in ultrafiltration process. Similar to microfiltration, the separation of target pollutants in ultrafiltration process can be attributed to the mechanical screening effect of membrane [18]. Therefore, ultrafiltration process could ensure the stable water quality in water purification. As we known, ultrafiltration is commonly utilized in drinking water treatment [19], domestic sewage and industrial wastewater treatment [20].

Among the common ultrafiltration membrane modules, hollow fiber ultrafiltration membranes have been widely used due to their large filtration area, no supporting carrier, small equipment, and low cost. Similar to microfiltration, membrane fouling is one of the obstacles hindering the development of ultrafiltration membrane technology, so the modification of ultrafiltration membrane materials has become a research hotspot in ultrafiltration research. Meng et al. [21] found that irreversible fouling degree and membrane fouling rate could be decreased by improving the hydrophilicity of UF membrane and increasing the solution pH value in humic acid (HA) rich water. The fouling control strategy also indicated the necessary exploration of membrane modification in future. Optimization of operating conditions were also confirmed to be able to reduce the membrane fouling rate, such as the optimizing of membrane driving pressure, flux, aeration rate, filtration cycle, pretreatment and so on [22,23].

2.3. Nanofiltration

RO is used to produce water by applying pressure difference across the membrane [24]. Due to its high desalination rate and high purification efficiency, reverse osmosis membranes have been widely applied in seawater desalination and water purification. Nanofiltration was taken as the process intermediate with the separation efficiency between ultrafiltration and reverse osmosis [25]. The nanofiltration membrane pore size locates between 0.5–5 nm, with operating pressure of 0.3~1 MPa.

Generally, it is believed that pollutants separation in nanofiltration is achieved by sieving and charge repulsion effect (Donnan Effect), during which the negative charge on nanofiltration membrane can attract positive ions and repel negative ions [26]. Therefore, the substance with molecular weight of 200~1,000 and multivalent ions could be separated in nanofiltration due to the negative charge on the membrane surface [27]. Ions could be selectively trapped by nanofiltration membranes, with lower operating pressure and costs than reverse osmosis membranes. Based on selective separation of low molecular weight organic matter and ions, nanofiltration showed great advantages in desalination, pollutant removal, and advanced drinking water treatment [28]. The removal of arsenic, pesticides, endocrine disruptors in nanofiltration was found to be much better than ultrafiltration. Donnan–Steric pore model with dielectric exclusion confirmed the unique separation of multivalent ions and permeation of monovalent ions from solution, making it possible for the low-pressure softening process with nanofiltration [29]. Thus, water softening has been one important application of nanofiltration. On the other hand, membrane fouling and cleaning were also unavoidable problem in nanofiltration. The unneeded membrane fouling in nanofiltration suggested necessary pretreatment before nanofiltration process. Sari and Chellam [30] verified the effective reduction of colloid and organic pollution in nanofiltration process by electrocoagulation–microfiltration (EC-MF) process for inland natural salty surface water treatment.

Nowadays, composite nanofiltration membrane is getting more and more attention. By adding inorganic nanomaterials into the selective membrane layer, the permeability, solute resistance, cycling stability and fouling resistance of composite nanofiltration membrane could be greatly improved, which contributed to the innovation and development of nanofiltration technology [31].

2.4. Dynamic membrane

With the wide application of membrane separation technology, the negative effect of membrane fouling could not be ignored any more, which might be attributed to the colloids and suspended particles adsorbed or trapped on the membrane surface. Despite the negative effect on membrane filtration, it was found that the membrane fouling formed on membrane surface could positively improve the separation efficiency, which acted as the main filtration media on large pore size membrane. Gradually, the newly formed fouling layer was taken as secondary membrane (dynamic membrane). This fascinating phenomenon also promoted the comprehensive study of dynamic membrane technology [32]. Dynamic membrane is the combination of secondary membrane and supporting membrane, formed by precoating suspension or influent solution on large pore membrane to obtain newly formed layer with low energy consumption. As reported in previous studies, dynamic membrane technology presents the advantages of low-cost membrane materials [32–35], high membrane flux [36–38], low maintenance cost, and low energy consumption [39–41].

In recent years, most dynamic membrane technology focused on wastewater treatment. Vergine et al. [42] established two self-forming dynamic membrane bioreactor systems for the treatment of real canning wastewater and simulated winery wastewater. They found that the DM system presented excellent organic matter removal rate and good activated sludge retention rate. The COD removal rate could remain to be larger than 90%, which proves to be a suitable technology for the treatment of agricultural and industrial wastewater. Ye et al. [43] made the dynamic membrane with powdered activated carbon (PAC) attached on polyester filter cloth. The PAC dynamic membrane was coupled with activated sludge for municipal wastewater treatment. The average removal rates of COD and NH_4^+–N in dynamic membrane bioreactors were found to be much higher than (that in) conventional hollow membranes. Besides, it was demonstrated that precoated dynamic membrane with appropriate thickness could prevent diffusion and deposition of pollutants into the interior of support membrane, thereby reducing supporting membrane fouling. Nyobe et al. [44] utilized PAC to form pre-coated dynamic membrane on a large pore support membrane with extra adsorption ability to remove dye chromaticity and toxicity in textile wastewater. The COD removal efficiency proved to be 99%, indicating that low-pressure dynamic membrane filtration is sustainable and effective in textile wastewater treatment. Therefore, DM technology can be applied in pulp and paper, chemicals, food and petroleum industries.

However, before the formation of secondary membrane, the effluent quality may be affected by the penetration of formation material. The tiny particles could pass through the large pore size supporting membrane. There is no doubt that the effluent quality will be influenced when DM layer is not stably formed. Hence, the application of DM layer should be control to the stage after the DM layer is formed. Meanwhile, if the DM layer is not stably formed, the self-detachments will influence the effluent quality. To solve these issues, further studies should be conducted to clarify the adhesion intensity and mechanism between supporting membrane and formation material. Based on the key mechanism, the adhesion intensity between the supporting membrane and formation material can be strengthened to avoid the negative effect on effluent quality in future. With the development of DM technology, dynamic membrane has become one potential membrane separation technology in wastewater treatment.

2.5. Comparison of MF, UF, NF, and DM

To have a comprehensive understanding of the detailed characteristics of membrane separation process, key parameters in MF, UF, NF, and DM are summarized in Table 1. The operating pressure presented to be the quite different

Table 1
Operating parameters and membrane characteristics with microfiltration, ultrafiltration, nanofiltration, and dynamic membrane

Types	Membrane pore size	Flux	Operating pressure (MPa)	Application scenarios	References
Nanofiltration	0.65~0.91 nm	10~110 L/m²·h	0.20~1.0	Demineralization of water, heavy metals wastewater, dye wastewater, textile wastewater	[45–48]
Ultrafiltration	3~14 nm	70~300 L/m²·h·bar	0.09~0.7	Drinking water, heavy metals wastewater, nickel-contaminated waters	[49–51]
Microfiltration	0.148~1.12 μm	61.0~5,000 L/m²·h	0.12~34.2	Industrial wastewater, domestic sewage, emulsified oil-water, greywater	[52–54]
Dynamic membrane (supporting membrane)	0.01~75 μm	0.1~105 L/m²·h	0~0.1	Industrial wastewater, domestic sewage, domestic wastewater, sludge reduction, oily wastewater treatment	[55–58]

at different conventional membranes and dynamic membrane, which might be due to the different membrane pore size. The operating pressure with dynamic membrane was much lower than that in NF, UF, and MF, which indicated the lower operating cost under the same conditions. The transmembrane pressure of less than 5 kPa was reported in diatomite dynamic membrane filtration by Li et al. [9], which could be easily achieved by gravity driven. Except for nanofiltration, the filtration flux in UF, MF, and DM was very close to each other. The high flux in UF might be attributed to the application condition with drinking water, with less pollutants affecting the blocking of membrane pores. While the similar filtration flux in dynamic membrane might be caused by the low driving force applied. Despite the membrane pore size of MF and DM was much larger than UF, the actual application for wastewater treatment made it much easier to be fouled by the pollutants in wastewater. Thus, the membrane flux was indirectly affected by the membrane fouling process. The pollutants removal performance in DM has been confirmed in previous research [6], which was not discussed further.

All in all, the membrane pore size, operating pressure and filtration flux in dynamic membrane filtration made it possible to be widely applied in wastewater treatment, which could be an entirely new choice of membrane separation technology under certain conditions.

3. Characteristics of MBR and dynamic membrane bioreactor

As known to all, biological technology was cost-effective for organic pollutants removal in wastewater treatment. Membrane bioreactor presented to be the perfect combination of membrane separation and biological technology, showing the advantages of both technologies with improved performance. Hence, membrane bioreactor (MBR) and dynamic membrane bioreactor (DMBR) are briefly introduced to explore the differences between conventional membrane and dynamic membrane.

3.1. Membrane bioreactor

In membrane bioreactor, activated sludge was retained by the membrane module from the effluent, which could guarantee longer sludge retention time. Thus, MBR are characterized with high-efficient solid–liquid separation, high sludge concentration [59], stable and high-quality effluent [60], no sludge bulking [61], independent hydraulic retention time (HRT) and sludge retention time (SRT) [62].

According to the difference of configuration, membrane bioreactor included aeration membrane bioreactor, extraction membrane bioreactor and solid/liquid separation membrane bioreactor [63]. In extraction membrane bioreactor, the phase interface was used to extract the organic pollutants in wastewater, which was transferred to the bioreactor for biodegradation regardless of the impact of concentrated salt and microorganisms. Extraction membrane bioreactor was mainly used for the treatment and recovery of priority pollutant in industrial wastewater. The aeration membrane bioreactor is suitable for aerobic treatment by introducing oxygen into the wastewater. The biological functional area and oxygen transfer area occupied little space of the whole module, which could avoid the odor and reduce energy consumption in aeration process. Aeration membrane bioreactor is mainly suitable for oxygen supply in aerobic degradation process. At present, the solid/liquid separation membrane bioreactor is widely employed for solid–liquid separation in wastewater treatment. Based on the different configuration of membrane module and bioreactor, MBR can also be divided into side stream MBR and immersed MBR. In side stream MBR, membrane module could be easily washed, with high flux and reliable effluent quality, but high energy was needed to conduct the operation; Immersed MBR presented the advantage of low energy consumption, small volume, and high integration, but low membrane flux and membrane fouling was common in this configuration. Even so, immersed MBR was widely applied in wastewater treatment [64–66].

Owing to the advantages induced by combining of membrane separation technology and biological technology, membrane bioreactor has attracted more and more attention in sewage treatment, especially for the improvement and application under the current conditions. To have a comprehensive understanding of the MBRs, the characteristics of different MBRs are summarized in Table 2.

Despite membrane bioreactors have been widely used in actual sewage treatment, there still exists problems in the

Table 2
Characteristics of different membrane bioreactors for wastewater treatment

MBR type	Types of water	Removal efficiency	Superiority	Existing problem	References
Membrane bioreactor-nanofiltration	Textile wastewater	COD, NH_3–N, NO_3^-–N, TP, turbidity, color: 97%,96%, –632%, 86%, 99%, 96%	Treatment of textile wastewater with high recovery rate can be realized and the process economic feasibility can be improved	Accumulation of TDS, nitrogen, phosphorus under shortened HRT	[67]
Electro-membrane bioreactor	Young leachate	COD, NH_3–N, chroma, Cr, Mn, Zn and Fe: 87%, 86%, 92%, 85%, 98%, 98%, 98%	Enhanced removal rate of COD, metals and other pollutants in the process, prolonged membrane fouling and reduced cleaning	Sustainability for leachate in different stages remained to be confirmed	[68]
Osmotic membrane bioreactors	Olive processing wastewater	COD, TP, TN: 100%, 82.92%, 70%	Mixed municipal and industrial wastewater treatment with no cost for the regeneration of draw solution	Accumulation of salinity, non-biodegradable organic matter, and generated SMP needs to be controlled	[69]
Fixed-bed membrane bioreactor	Paper-recycling wastewater	COD, ammonium, nitrite, nitrate and TN: 92%–99%, 59%–97%, 78%–97%, 59%–98% and 68%–92%	Simultaneous removal of the carbonaceous and nitrogenous pollutants; high biomass content and reduced reactor volume	/	[70]
Osmotic membrane bioreactor	Tannery wastewater	COD: around 80%	Efficient COD removal in leather wastewater, reduced cost of draw solution regeneration by using actual industrial effluent	Inhibited nitrification with accumulation of COD and ammonia nitrogen, decreased membrane flux with increasing salinity	[71]

operation of MBR, such as membrane fouling, high energy consumption, high membrane module cost and large investment [72]. As shown in Table 2, the current research of MBR mainly focused on the coupling of MBR with different water treatment technology to improve the treatment efficiency of high-concentration and refractory sewage. Based on the existing research and application of MBR, the further developing direction of MBR was expected to be: exploration of efficient and cheap membrane materials, controlling of membrane fouling, and optimization of the MBR process.

3.2. Dynamic membrane bioreactor

Despite the advantages of MBR, high membrane cost, membrane fouling, and high energy consumption still remain to be solved for the further development of MBR technology. However, DM provides a new way to solve these problems. Thus, DMBR is drawing more and more attention in recent years. The significant variation of DMBR was the replacement of the micro/ultrafiltration membrane in the conventional MBR with cheap micromesh materials, such as non-woven cloth, screen, industrial filter cloth, etc. Certainly, the separation process in DMBR was achieved through the DM layer forming on the surface of the supporting material with pre-coating agent or activated sludge [73,74]. Due to the utilization of dynamic membrane and biological technology, dynamic membrane bioreactor was not only retained with the advantages of conventional MBR, but also enhanced with new characters [75–78], such as low energy consumption, low filtration resistance, high filtration flux, easy cleaning and regeneration of membrane, and low-cost membrane material.

In order to deal with anthraquinone dye wastewater, internal micro-electrolysis was used to enhance MBR [79]. Iron ions addition was found to reduce membrane fouling by improving the flocs settleability. But series membrane permeability was also resulted by the accumulation of iron in the last stage. In contrast, more than 93% COD and 96.7% color removal was observed with anaerobic DMBR for anthraquinone dye wastewater treatment by Berkessa et al. [80]. Besides, the driving pressure was maintained below 400 mbar in DMBR, which confirmed the low energy consumption of DMBR in wastewater treatment process.

Anaerobic dynamic membrane bioreactor (AnDMBR), self-forming dynamic membrane bioreactor (SFD-MBR), intermittently aerated dynamic membrane bioreactor (intermittently aerated DMBR), pre-anoxic and aerobic dynamic membrane bioreactor (pre-anoxic and aerobic DMBR), PAC-DMBR, integrated fixed film activated sludge – self-forming dynamic membrane bioreactor (IFAS-SFD-MBR).

Table 3 summarized the characteristics and parameters of DMBR in wastewater treatment. As shown in Table 3, the large pore size membrane is widely used in DMBR due to its low cost. The transmembrane pressure (TMP) and filtration

Table 3
Operating parameters and performance of dynamic membrane bioreactor

DMBR type	Supporting membrane (material)	Pore size (μm)	Wastewater type	Influent COD (g/L)	MLSS (g/L)	HRT	Formation time	TMP (kPa)	Flux (L/m²·h)	Removal rate (%)	References
AnDMBR	Acrylonitrile butadiene styrene (ABS) filament	100	Textile wastewater	4.5	10.8	5/2.5 d	–	15~40	14~28	COD > 93; color > 96.7; TSS > 98.8	[80]
AnDMBR	Conductive carbon cloth	200	High-strength brewery wastewater	1–5	2.6	5 d	5 d	0~–20	4.125	COD = 98	[81]
SFD-MBR	Nylon mesh	50	Agro-industrial wastewater	1–1.9	2.5	–	1–10 d	Up to 10	38	COD > 90	[42]
AnDMBR	Nylon mesh	75	Domestic wastewater	0.2–1	5.6	8 h	–	0–30	22.5	COD = 70~90	[82]
Intermittently aerated DMBR	Flat nylon mesh	53/20	Textile wastewater	0.5	5.0	7–18 h	10–14 h	Up to 50~60	26 ± 2.5	COD > 92	[83]
Pre-anoxic and aerobic DMBR	Nylon mesh	52	Landfill leachate	1.47	5.5	6–7 d	–	Up to 15	2.7~30.1	TN > 90	[84]
PAC-DMBR	Nylon mesh	75	Domestic wastewater	0.13–0.27	2.5–3.5	1.2–7.5 h	14 d	1	50~510	COD > 74; ammonia > 96; color > 83	[85]
IFAS-SFD-MBR	Nylon mesh	50	Municipal wastewater	0.37–0.45	1.4–2.1	8 h	–	<–10	67	COD > 90	[86]

flux in Table 3 indicated the economic and efficient of DMBR in wastewater treatment process [74]. Presently, the research on dynamic membrane bioreactor still remained in the initial stage, most of the research focused on the performance, influence and mechanism in DMBR in wastewater treatment. On the whole, the treatment performance of DMBR technology was satisfactory, with low operating cost and easy membrane cleaning. Therefore, in order to promote the application of DMBR in industrial wastewater treatment, more exploration of formation and filtration of dynamic membrane, the structure of bioreactor, operating conditions and sludge characteristics in DMBR should be further conducted in future.

At the same time, there are also shortages in DMBR system. The operation of DM technology is commonly comprised of formation, filtration and regeneration, which presents to be more complicated than conventional membrane. The formation and regeneration of DM layer will reduce the effective working time for DM technology. Continuous operation is a critical issue that affects the performance of DMBRs. Meanwhile, the specific formation stage in DMBR before the application stage also increases the application complexity of DM technology. As a new membrane separation technology, the disadvantage in DM technology still remains to be solved for better application of DM technology. Thus, the further optimization of DM technology is the key task for the following decades.

3.3. Comparison of MBR and DMBR

To have a deep understanding and comparison of MBR and DMBR, the filtration performance, pollutants removal, and cleaning strategy in DMBR and MBR were summarized in Table 4. Due to the replacement of conventional membrane with large pore size membrane, different filtration and cleaning performance in DMBR has been reported with MBR, as shown in Table 4. The filtration flux in DMBR ranged from 7–75 L/m^2·h, which was slightly larger than that in MBR (1–33 L/m^2·h). Hence, high filtration efficiency could be observed at the same conditions with MBR. While the TMP in the operating process in DMBR ranged in a large scale from 2 to 73 kPa, which was close to the operating pressure in MBR. The increase of TMP in DMBR could be attributed to the occurrence of microbials and extracellular polymeric substance (EPS) on the new layer, which facilitated the formation and fouling of DM layer and guaranteed the better effluent quality. The DM layer was similar to the fouling layer in MBR, thus the final operating pressure in DMBR and MBR was very close to each other. But the actual cleaning frequency in DMBR was lower than that operated in MBR, which confirmed the advantage of less cleaning times in DMBR. The cleaning strategy of physical backwashing in DMBR was commonly used, which could meet the demand of membrane cleaning in DMBR at most conditions. Occasionally, chemical cleaning was used when the TMP was beyond the routine values. However, chemical cleaning presented to be necessary for the membrane regeneration in MBR operation, which indicated the complicated cleaning operation than that in DMBR.

Besides, much difference could be observed between the pollutants removal rate in DMBR and MBR. It was clearly shown in Table 4 that COD removal rates in DMBR and MBR were larger than 85%, which indicated that DMBR could be taken as an alternative for MBR in some cases. The comparison of MBR and DMBR in different operating conditions is summarized for the primary evaluation of membrane technologies. The comparison will be much more meaningful at the same influent condition. It is a great pity that the operating conditions of MBR and DMBR are not the same in previous studies. And systematic comparative studies between MBR and DMBR are rarely reported. Thus, the operating characteristics and the operating efficiency of MBR and DMBR under the same conditions still remains to be compared in future. Overall, DMBR presented to be advantageous at the filtration flux and membrane cleaning over conventional MBR, which could be used for the pretreatment process and sludge retention in wastewater treatment.

4. Future perspectives

With increasing requirement for higher effluent quality in wastewater treatment, membrane separation technology is gradually getting more attentions. However, membrane fouling, membrane cost, maintenance and cleaning of membranes have hindered the further development of membrane separation technology. Hence, the main developing directions of membrane technology is focused on the problems.

Membrane fouling is attributed to the adsorption and deposition of particles, colloidal particles or solute macromolecules on the membrane surface or membrane pores, which can influence the permeation flux and membrane separation efficiency [93,94]. With the accumulation of irreversible membrane fouling, membrane fouling remains to be cleaned and controlled to improve the applicability of membrane separation technology in long term operation. Therefore, the controlling strategy of membrane fouling will be one of the most important areas to be studied, which focuses on: (1) anti-fouling membrane materials; (2) the replacement of conventional MF with DM if possible; (3) novel combined technology to avoid membrane fouling; (4) process optimization to extend the efficient filtration time; (5) exploration of new membrane cleaning strategy and technology. However, membrane fouling is taken as functional layer in DM system. The influence of adhesion stability on dynamic membrane technology cannot be ignored. Owing to the unquantified adhesion stability of dynamic membrane, it is hard to evaluate and enhance the adhesion stability of formation materials in dynamic membrane system. To clarify the adhesion intensity and mechanism, the optimal operating conditions and interaction mechanism between formation material and supporting membrane still remains to be explored. And the adhesion intensity should be quantified and assessed for stable application in wastewater treatment. Therefore, more information on formation mechanism and adhesion stability of dynamic membrane layer should be revealed and evaluated in future.

Membrane cost is another problem limiting the application of membrane separation technology. In practical application of membrane separation technology, membrane module will be replaced periodically due to the serious irreversible membrane fouling, which also increases the maintenance cost. Therefore, to reduce the membrane cost in membrane

Table 4
Comparison of influent condition, operating condition, and cleaning strategy in DMBR and MBR

Reactor type	Influent COD (g/L)	Influent MLSS (g/L)	HRT (d)	SRT (d)	TMP (kPa)	Flux (L/m²·h)	Removal rate (%)	Cleaning strategy	References
DMBR	4.5	10.8	5 and 2.5	–	15~35	14, 28	COD > 93; color > 96.7; TSS > 98.8	–	[80]
	0.4	5.0–10.0	0.87	106 and 245 d	68.3~73.2	18	COD > 88; TSS > 99; TN 16.9~17.7; TP 9.1~9.4	Periodical backwashing	[87]
	3.0–4.5	3.0	0.5–1.3	–	5~20	60~75	COD = 97; BOD = 85	*In-situ* physical backwashing	[88]
	1.0	10.0	2.2	–	0~50	7–8	Dye > 97; COD = 91	Biogas backwash and chemical cleaning	[89]
	1.0	10.0	–	–	40~45	8	Color > 99; COD = 95~97	Gas scouring, tap water flushing, and chemical cleaning	[90]
	0.5	5.0	0.3–0.75	–	2 ± 1.1	22~29	COD > 94; ammonia > 95	Pressurized air cleaning	[83]
MBR	0.06–0.28	6–10	4–5	20	MBR: 4~20 NF: 600~850	6.2~12 5–5.3	Color > 72.4; turbidity = 99; TOC 73~85; ammonia > 96	Chemical cleaning and air flushing	[67]
	0.5–1.0	4–10	–	–	<25	33	COD > 90	Physical and chemical cleaning	[91]
	65	18–20	5	15	<60	1	COD = 87; color = 92	Physical and chemical cleaning	[68]
	1.4–1.6	1.1–1.3	1.5	2	<18.4	12	COD = 92~99	Air scouring	[70]
	8.6	20	0.67	30	<60	5	COD = 93.1~98.5; color = 87.1~89.5	Physical or chemical cleaning	[92]
	1.5–3.5	5	–	–	/	1.5~3.5	COD ≈ 100	Backflushing and chemical cleaning.	[71]

separation technology, the strategies can be taken as follows: (1) developing new low-cost and high-efficient membrane materials; (3) replacing the conventional MF with low-cost DM technology. However, as far as we know, existing studies on dynamic membranes mainly focus on laboratory scale, which lacks economic analysis of its precoating process and application process. Therefore, it is hard to estimate its precoating cost accurately. The economic analysis and evaluation of dynamic membrane technology remains to be conducted in the following stage, which can also provide accumulated data for economic comparison between DM and MF/UF in future.

The complicated maintenance of membrane module also makes it difficult for the wide application of membrane separation technology. Since membrane fouling is inevitable in membrane separation process, controlling of membrane fouling is necessary to maintain the separation efficiency. To simplify the membrane maintenance, future research can be focused on: (1) structure optimization of the membrane module, to avoid the accumulation of pollutants; (2) exploration of effective membrane cleaning strategy, such as ultrasonic, plasma, electric field cleaning, etc.; (3) taking full use of the membrane fouling layer as new filtration layer to improve the filtration efficiency, such as DM technology.

5. Conclusion

Membrane separation technology has obtained widespread application in wastewater treatment, showing different separation performance with NF, UF, MF and DM. DM technology presented advantageous with low-cost membrane, low operating pressure, high filtration flux, and easy cleaning. But continuous application in actual wastewater treatment, the adhesion stability of DM layer, and adhesion mechanism still remained to be further studied in future. Better pollutants removal performance could be observed with MF, UF, and NF in wastewater and water treatment. But membrane fouling and membrane cost still limit the developing of conventional membrane separation technology. Therefore, more attention should be paid to the limiting factors in conventional membrane and dynamic membrane, which could facilitate the development of membrane technology in wastewater treatment from both directions.

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Conflict of interest

The authors have no competing interests to declare.

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