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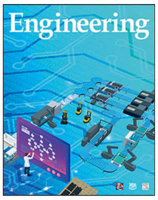

Research
Industrial Wastewater Treatment—Review

Large-Scale Membrane Bioreactors for Industrial Wastewater Treatment in China: Technical and Economic Features, Driving Forces, and Perspectives

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ABSTRACT

Membrane bioreactors (MBRs) have been and will continue playing an important role in industrial wastewater treatment and reuse in China. The sustainable development of MBR technology in its mature-application stage requires reciprocal interactions between engineering and research participants. Thus, in this study, a total of 182 large-scale MBR projects treating industrial wastewater (with individual treatment capacities $\geq$ 5000 $m^3 \cdot d^{-1}$) commissioned and under construction from 2003 to 2019 were analyzed comprehensively. Fast growth of the cumulative treatment capacity was observed, with extension to diverse industries, and the super large-scale was enhanced recently. The treatment processes, pollutant removal efficiencies, and actual operational parameters were summarized regarding the particularity of industrial wastewater compared to municipal wastewater. Economic features including the total investment costs of the projects, their total footprint, and their operational energy consumption were analyzed as well. A vigorous MBR market has formed in China with the fast development of membrane elements and engineering suppliers, continuously increasing official oriented projects, and responsive and innovative business modes. MBR technology has been mostly applied in specific economic zones and water-deficient areas, but its widespread use all over China is foreseeable considering the vast future market for industrial wastewater treatment and recycling. The policy–economy and market–technology driving forces revealed that MBR is consistent with the national development demand. According to the survey and analysis, prospective development in both engineering and research aspects of MBR is proposed to maintain its competitive edge.

1. Introduction

By integrating the conventional activated sludge (CAS) process and membrane filtration, membrane bioreactor (MBR) technology presents advantages including good effluent quality, a small footprint, and so forth. Active research on the technological modification and mechanism insights of MBRs has been conducted to advance their applications [1–4], and the technology has been successfully commercialized worldwide. According to the record of the MBR Site[†] by December 2019, the total treatment capacity of commissioned large MBR projects (with individual treatment capacities $\geq$ 100 000 $m^3 \cdot d^{-1}$) reached 11 399 000 $m^3 \cdot d^{-1}$, and the largest commissioned one was Huaifang Water Recycling Project (Beijing, China), with a treatment capacity of 780 000 $m^3 \cdot d^{-1}$. China has become a hot spot of MBR application, with 41 out of 62 large MBRs occupying 64% of the treatment capacity[†], and the total treatment capacity of commissioned MBRs for municipal wastewater treatment reached 10 000 000 $m^3 \cdot d^{-1}$ by May 2018 [5]. Excellent pollutant removal efficiencies of the chemical oxygen demand (COD), NH_3–N, total nitrogen (TN), and total phosphorus (TP) have been

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achieved by MBRs in treating municipal wastewater (TN > 80% and others > 90%).

Industrial wastewater, with high concentrations of complex and refractory contaminants, demands a high pollutant removal efficiency but is difficult to effectively treat through CAS processes [6,7]. MBRs would be a satisfactory option for industrial wastewater treatment because: ① The complete separation of the sludge retention time (SRT) from the hydraulic retention time (HRT) allows the extension of the SRT, hence increasing the concentration of the activated sludge and the volumetric loading rate; ② the enhanced biological degradation and membrane filtration make the effluent quality good and steady; and ③ the small footprint of MBRs helps reduce the total land usage for the long and complex treatment process. In fact, MBRs have been applied in multiple industries, especially those requiring water reuse and recycling. However, severe membrane fouling can be caused [7], which challenges the application of MBRs currently. Regarding this effect, MBRs with individual treatment capacities of thousands of cubic meters per day, which are classified as medium-scale in municipal wastewater treatment [8], would be categorized as large-scale MBRs in industrial waste water treatment. In this study, large-scale MBRs refers to those with individual treatment capacities $\geq 5000\ \mathrm{m^3 \cdot d^{-1}}$.

Membrane technologies and their integrated treatment processes (including MBRs) have been promoted for wastewater treatment and reclamation in municipal and industrial sectors in China for over 10 years. The grand application of MBRs has witnessed China's economic growth, environmental policy implementation, and technological research and development. It is of great significance to establish a virtuous cycle among the economy, environmental policy, scientific research, and practical applications, so that sustainable development can be achieved in all aspects. Regarding this goal, effective communication between scientific research and practical application should be established to ground scientific research and verify new application-oriented technologies. Thus, it is necessary to investigate the vast MBR market in China. So far, full-scale MBRs treating municipal wastewater have attracted more attention [5,8–11], while those treating industrial wastewater treatment have not been adequately investigated.

Therefore, a survey of large-scale MBRs for industrial wastewater treatment in China was conducted in this study. Data were collected from reports on websites specialized in membrane technologies and water treatment, promotions of related companies, and the literature. The database included 182 large-scale MBRs (with individual treatment capacities $\geq 5000\ \mathrm{m^3 \cdot d^{-1}}$) commissioned or under construction from 2003 to December 2019 in China. Comprehensive analysis was conducted regarding the driving forces, geographic distribution, industrial allocation, investment, operation, and so forth. Finally, perspectives on development of MBRs for treating industrial wastewater were proposed on the basis of engineering data. It should be addressed that the application of MBRs in leachate treatment was not included due to the special properties of leachates. Additionally, considering that an industrial park can consist of a combination of factories engaged in either the same industry or different industries, industrial parks in this study refer to areas labeled as industrial parks, regardless of the variety of industries included.

2. Overview of large-scale MBRs treating industrial wastewater

2.1. Growth of the treatment capacity

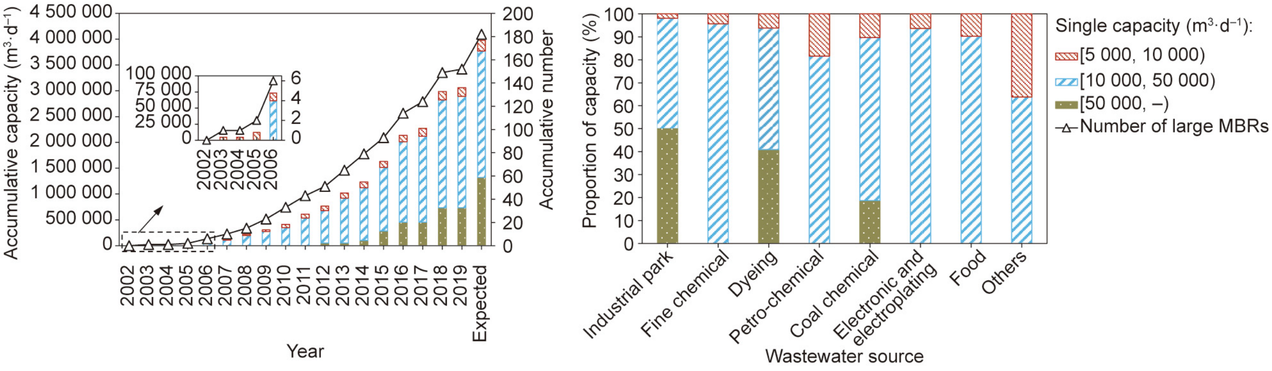
The applications of MBRs for treating municipal and industrial wastewater were developed simultaneously, with gradual enlargement of the individual treatment capacity from the small and medium scale to the super-large scale, achieving wide and mature applications. Regarding industrial wastewater treatment, MBRs were mainly of small and medium scale (with individual treatment capacities $< 5000\ \mathrm{m^3 \cdot d^{-1}}$) before 2003 (Fig. 1(a)). To our knowledge, the first large-scale MBR was commissioned around 2003 (Luoyang Petrochemical Engineering Corporation Ltd./SINOPEC, Henan, China; $5000\ \mathrm{m^3 \cdot d^{-1}}$), and the first MBR with an individual treatment capacity $\geq 10\,000\ \mathrm{m^3 \cdot d^{-1}}$ was commissioned in 2006 (Huizhou Dayawan Petrochemical Industrial Park, Guangdong, China; $25\,000\ \mathrm{m^3 \cdot d^{-1}}$). Afterwards, as both the cumulative number and the individual treatment capacity increased, the cumulative treatment capacity of large-scale MBRs increased quickly, especially after 2010. The first super large-scale MBR with an individual treatment capacity $\geq 50\,000\ \mathrm{m^3 \cdot d^{-1}}$ was commissioned in 2012 (Liutuan Industrial Park, Shandong, China; $50\,000\ \mathrm{m^3 \cdot d^{-1}}$), indicating that the application of MBRs for industrial wastewater treatment entered the maturity period. The number of large MBRs to date has exceeded 180 in China. The cumulative treatment capacity tripled from 2013 (approximately $1 \times 10^6\ \mathrm{m^3 \cdot d^{-1}}$) to 2019 (over $3 \times 10^6\ \mathrm{m^3 \cdot d^{-1}}$). Upon adding projects under construction, the accumulative treatment capacity is expected to exceed $4 \times 10^6\ \mathrm{m^3 \cdot d^{-1}}$ soon.

The majority of large-scale MBRs treating industrial wastewater currently have individual treatment capacities of 10 000–50 000 $\mathrm{m^3 \cdot d^{-1}}$. Through 2019, 113 out of 152 large-scale MBRs were of such a scale, accounting for 70% of the total treatment capacity (Fig. 1(a)), and this proportion was higher in specific industries, such as the fine chemical, petro-chemical, and food industries (Fig. 1(b)). Of note, super large-scale MBRs (with individual treatment capacities $\geq 50\,000\ \mathrm{m^3 \cdot d^{-1}}$) showed development potential as the cumulative treatment capacity grew quickly to reach over $1.3 \times 10^6\ \mathrm{m^3 \cdot d^{-1}}$, as expected, which occupied over 30% of the total cumulative treatment capacity of large-scale MBRs (Fig. 1(a)).

2.2. Expansion in industries

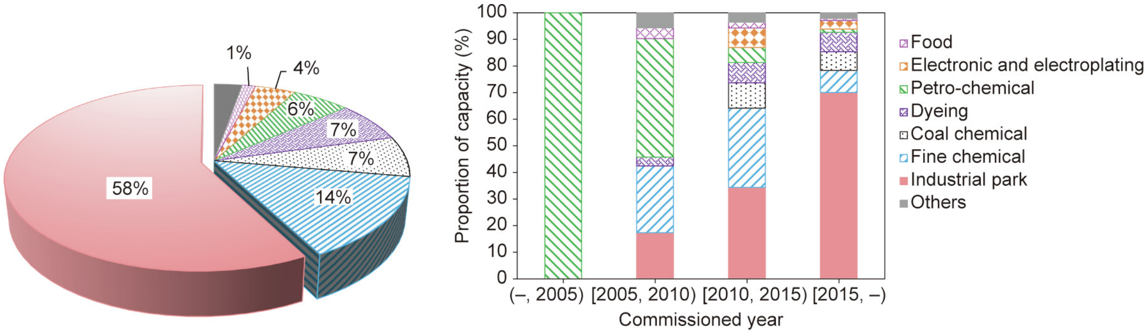
Large-scale MBRs have been widely applied in diverse industries including the fine chemical, petro-chemical, coal chemical, dyeing, electronic and electroplating, food, iron and steel, mining, and industries, among others, as well as integrated industrial parks (Fig. 2(a)). Different from conventional single industries, industrial parks are designed and constructed to aggregate different industries/companies in a designated structure so that resources can be efficiently used in an intensive way. MBRs treating wastewater from industrial parks made up the largest proportion, with 58% of the total treatment capacity, followed by the fine chemical (14%), coal chemical, dyeing, and petro-chemical industries (6%–7%).

Temporal characteristics have been obviously observed in the application of large-scale MBRs among industries (Fig. 2(b)). In the early stage (before 2005), large-scale MBRs were mainly adopted in the petro-chemical industry. Afterwards, the application gradually extended to other industries like the fine chemical, dyeing, and coal chemical industries, and the capacity-proportion of the petro-chemical industry is reduced among newly commissioned MBRs. MBRs had been applied widely across the industries by around 2010; meanwhile, the cumulative treatment capacity started to grow quickly (Fig. 1(a)). Besides acceptance by diverse industries, the growth of large-scale MBRs was attributed to more stringent discharge standards and the construction of industrial parks, especially after 2010. The capacity-proportion of large-scale MBRs in industrial parks rose to 70% of the cumulative treatment capacity of newly commissioned large-scale MBRs after 2015 (Fig. 2(b)). In an industrial park, wastewater from separate factories after necessary pretreatment is collected and treated in a centralized wastewater treatment plant, which is advantageous in terms of cost saving, increasing the resource efficiency, promoting wastewater reuse, and ensuring environmental safety [12,13].



(a) (b)

Fig. 1. (a) Development and (b) industrial distribution of the individual treatment capacity of large-scale MBRs for industrial wastewater treatment. Large-scale MBRs refer to those with individual treatment capacities $\geq$ 5000 $m^3 \cdot d^{-1}$, the data of "expected" are according to the projects under construction; industrial parks are generally those labeled as industrial parks, regardless of the variety of industries included.



(a) (b)

Fig. 2. Distribution of industries adopting large-scale MBRs according to (a) the cumulative capacity and (b) the commissioned year.

However, the wastewater might contain complex and refractory components, requiring a highly robust treatment process (such as MBR) to guarantee the effluent quality. Hence, it could be foreseen that industrial parks will be a main growth sector for large-scale MBRs in the future.

2.3. Geographic demand

The application of large-scale MBRs in Chinese mainland developed along with the development of several specific economic zones, such as the Yangtze River economic zone, Beijing–Tianjin–Hebei economic zone, and Greater Bay area (Fig. 3(a) and Supplementary video 1 in Appendix A), which are the main industrial bases in China with large-scale industrial parks and extremely high productivity. The Yangtze River economic zone, which covers the provinces along both sides of the Yangtze River, included 37% of the national cumulative treatment capacity. Both Jiangsu and Sichuan had treatment capacities > 300 000 $m^3 \cdot d^{-1}$ (Fig. 3(b)). Additionally, the application of large-scale MBRs in Northwest China was also grand. For example, Xinjiang had the largest cumulative treatment capacity (> 5 00 000 $m^3 \cdot d^{-1}$) among the provinces, and that of Inner Mongolia was more than 300 000 $m^3 \cdot d^{-1}$.

The application of large-scale MBRs for industrial wastewater treatment was generally related to the geographical industrial development (as indicated by the industrial value-added (IVA) in this study), with a significant positive correlation between the cumulative treatment capacity and corresponding provincial IVA (Spearman's ρ = 0.58, p = 0.00) (Fig. 3(c)). For instance, the most developed regions, like Jiangsu, Shandong, Zhejiang, and Shanghai, owned diverse and high technological level industries, and thus, the application of large-scale MBRs in these regions was of the highest potential. Further, the limited available land in association with high prices could have also enhanced the application of MBRs. In addition, the application of MBRs was also affected by the local industrial structure and ecological and environmental statuses. Energy industries (e.g., coal chemical and petro-chemical industries) were the dominant industries in regions like Xinjiang and Inner Mongolia. MBRs were enlarged in these regions, aiming at a high effluent quality due to the local water scarcity and fragile ecosystem.

3. Technical features of large-scale MBRs treating industrial wastewater

3.1. Treatment process

The components and concentrations of pollutants in industrial wastewater are different among differing industries and are hard to define within a specific range. Generally, industrial wastewater contains higher concentrations of pollutants compared to municipal wastewater, and some of the components are refractory (e.g., phenolic substances in coal chemical wastewater) or bio-toxic (e.g., heavy metals in electronics and electroplating wastewater). The COD concentrations of industrial wastewater ranged from hundreds to thousands of micrograms per liter (Table 1 [14–25]), while that of municipal wastewater and surface water was 50–300 $mg \cdot L^{-1}$ [14,15,26–28]. Thus, the treatment process for industrial wastewater is mostly long and complex, and the

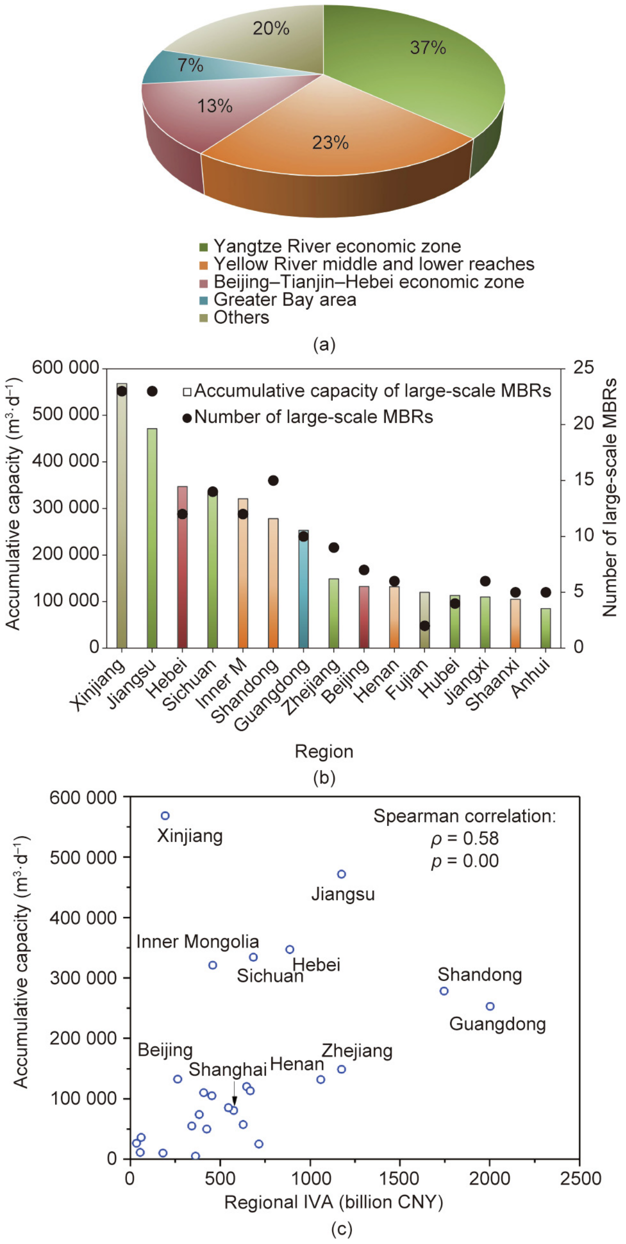


Fig. 3. Geographic demand of large-scale MBRs treating industrial wastewater in Chinese mainland: (a) and (b) geographic distribution of large-scale MBRs for industrial wastewater treatment regarding the cumulative treatment capacity ($m^3·d^{-1}$) (Inner M refers to Inner Mongolia; the columns in (b) are colored corresponding to the regions in (a)); (c) impact from the geographical economy (IVA: industrial value-added; the IVA data were average value from 2002 to 2018 with data collected from *China Statistical Yearbook*; 7 CNY ≈ 1 USD).

HRT is 10–100 h, which is significantly longer than that of municipal wastewater and surface water treatment (mostly 10–20 h) (Table 1 [14–25]).

The treatment process for industrial wastewater mostly consists of pretreatment, biological treatment (including MBR), and advanced treatment (Table 1 [14–25]) to obtain a standard acceptable effluent for discharge or reuse. The pretreatment aiming to improve the biodegradability of the wastewater and reduce the hazards to the biomass in the following biological treatment. It includes pH regulation, deoiling, coagulation, catalytic oxidation, anaerobic (acidification) processes, and so forth. The biological treatment removes most of the pollutants by biological degradation, sometimes with chemical aid. Advanced treatment is applied to further remove pollutants from the MBR effluent to meet stringent standards, especially for reuse. These include biological aerated filters (BAF), advanced oxidation, disinfection, reverse osmosis (RO), and so forth.

An MBR process is herein defined as a biological treatment process including membrane tanks. MBR-based industrial wastewater treatment processes are case-specific due to the characteristics of influents. Generally, the treatment processes could include simple aerobic MBR, anaerobic treatment + membrane tank, anaerobic treatment + aerobic treatment + membrane tank, and so forth. The anaerobic/anoxic/oxic process (or its derivatives) + membrane tank was of preference, constituting 84 out of the 182 cases and 51.4% of the total treatment capacity in this study. Over 90% of the COD, biochemical oxygen demand (BOD), NH_3–N, and TP were removed after the biological treatment process (the amount of TN removed was approximately 70%) (Fig. 4(a)). As the last step of the biological treatment, the membrane tank carried out pollutant removal (10% of COD and 40% of NH_3–N, Fig. 4(b)) as well as separation of the effluent from the mixed liquor [15–17,29,30]. Thus, appropriate operating parameters for the membrane tank are of great importance to guaranteeing the effluent quality.

3.2. Operating parameters

The actual operating parameters of large-scale MBRs treating industrial wastewater are shown in Table 2 [14–17,21,23,24,30]. Compared with the municipal wastewater condition, MBRs treating industrial wastewater had a lower flux (11–25 $L·m^{-2}·h^{-1}$), which was, on average, ~16 $L·m^{-2}·h^{-1}$). The mixed liquid suspended solids (MLSS) concentration in the membrane tank was similar (8–12 $g·L^{-1}$), while the sludge return ratio from the membrane tank to the oxic tank (200%–300%) was lower. Regarding membrane fouling, the specific aeration demand for membrane scouring with respect to permeation in MBRs treating industrial wastewater was 14–25 $Nm^3·(m^{-3}$-permeate) (Nm^3: the volume of the gas under standard condition (0 °C, 1.01 × 10^5 Pa)), which was approximately two-fold that of the municipal wastewater condition. Additionally, membrane recovery cleaning was more frequent in industrial wastewater treatment (with an interval of 4.2 months) than in municipal treatment (with an interval of 6 months). Industrial wastewater contains higher concentrations of pollutants, especially refractory, oily, and metal contaminants. The intrinsic components associated with the degradation products might contain large amount of membrane foulants (colloids, macromolecules, metal ions, etc.), leading to a lower flux, stronger aeration, and a shorter recovery cleaning interval.

4. Economic features of large-scale MBRs treating industrial wastewater

4.1. Project investment and footprint

The total investment of MBR projects for industrial wastewater treatment includes the investment in design and construction, drainage pipe layout, and other non-engineering aspects. It was mostly within the range of 3500–8500 CNY·$(m^3·d^{-1})^{-1}$ (interquartile range; 7 CNY ≈ 1 USD), with average and median values of ~7500 and ~6000 CNY·$(m^3·d^{-1})^{-1}$, respectively (Fig. 5(a)). The total investment increased from earlier to later commissioning times (Jonckheere–Terpstra's $p = 0.000$). The cost after 2015 (4000–10 000 CNY·$(m^3·d^{-1})^{-1}$, on average, ~8500 CNY·$(m^3·d^{-1})^{-1}$) was approximately 2-fold that before 2010 (2500–3500 CNY·$(m^3·d^{-1})^{-1}$, on average, ~3700 CNY·$(m^3·d^{-1})^{-1}$). The increment of the total investment in the later commissioning time might be due to ① the strengthened water pollution control and stringent effluent quality standard with lower pollutant concentrations of treated industrial

Table 1
Cases of MBR plants in China for wastewater treatment.

Industry	Case	Treatment process[a]	Total HRT (h)[b]	Pollutants[c]	Reference
Industrial park	An agricultural product processing industrial park (5 000 $m^3 \cdot d^{-1}$)	→ Regulating → acidification → $A_2/A_1/A_2/O$–M → disinfection → discharged	> 29	COD (350–400 $mg \cdot L^{-1}$), SS (160–310 $mg \cdot L^{-1}$), TN (25–50 $mg \cdot L^{-1}$), NH_3–N (15–25 $mg \cdot L^{-1}$), TP (3.0–5.5 $mg \cdot L^{-1}$)	[14]
Industrial park (coal chemical)	An industrial park (30 000 $m^3 \cdot d^{-1}$), Xinjiang, 2007	→ Air floatation precipitation → acidification → $A_2/A_1/O/A_2/O/A_2/O$–M → disinfection → discharged	> 26	COD (216 $mg \cdot L^{-1}$), SS (162 $mg \cdot L^{-1}$), TN (22 $mg \cdot L^{-1}$), TP (3.2 $mg \cdot L^{-1}$), oil, chroma (20)	[15]
Industrial park (dyeing)	An industrial park (10 000 $m^3 \cdot d^{-1}$), Guangdong, 2015	→ Regulating → pH neutralization → acidification → O–M → advanced oxidation (O_3) → discharged	> 35	COD (1100 $mg \cdot L^{-1}$), NH_3–N (32 $mg \cdot L^{-1}$), pH (10), chroma (460), sulfide (3 $mg \cdot L^{-1}$), aniline (1.8 $mg \cdot L^{-1}$)	[16]
Industrial park (food)	An industrial park (20 000 $m^3 \cdot d^{-1}$), Sichuan, 2016	→ Regulating → acidification → $A_1/A_2/O$–M → disinfection → discharged	> 59	COD (500 $mg \cdot L^{-1}$), NH_3–N (45 $mg \cdot L^{-1}$), Cl^- (500 $mg \cdot L^{-1}$), TP (8 $mg \cdot L^{-1}$)	[17]
Iron and steel	Stainless Steel Branch, Baoshan Iron and Steel (288 $m^3 \cdot d^{-1}$), Shanghai, 2009	→ Regulating → pH regulating → air floatation → EGSB → A_2/O–M → discharged	> 46	COD (13 000 $mg \cdot L^{-1}$), oil (1 300 $mg \cdot L^{-1}$), temperature (50 °C)	[18]
Fine chemical (pharmaceutical)	A Pharmaceutical Group (3000 $m^3 \cdot d^{-1}$), Jiangsu, 2014	→ Sedimentation → pre-acidification → IC → A_2/O–M → BAF → reuse	> 98	COD (14 000 $mg \cdot L^{-1}$), NH_3–N (100 $mg \cdot L^{-1}$), chroma (450), pH (4–6)	[19]
Petro-chemical	Sinopec Luoyang Branch (5000 $m^3 \cdot d^{-1}$), Henan, 2003	→ Regulating → deoiling → air floatation → acidification → O/O → M → sedimentation → BAF → reuse	–	NH_3–N (2 400 $mg \cdot L^{-1}$), oil (2.1 $mg \cdot L^{-1}$), sulfide (6 000 $mg \cdot L^{-1}$), volatile phenol	[20]
Coal chemical	China Shenhua Coal-to-oil Chemical (10 000 $m^3 \cdot d^{-1}$), Inner Mongolia, 2013	Secondary effluent → A_1/O–M → reuse	> 20	COD (250 $mg \cdot L^{-1}$), NH_3–N (35 $mg \cdot L^{-1}$), oil (15 $mg \cdot L^{-1}$)	[21]
Coal chemical	A chemical company (7800 $m^3 \cdot d^{-1}$), Xinjiang, 2017	→ Regulating → EC → A_1/O → sedimentation → M → advanced oxidation (O_3) → discharged	> 65	COD (2180–3250 $mg \cdot L^{-1}$), NH_3–N (102–158 $mg \cdot L^{-1}$), phenol (190–446 $mg \cdot L^{-1}$), chroma (300–600)	[22]
Electronic and electroplating	A thin film transistor liquid crystal display (TFT-LCD) company (10 000 $m^3 \cdot d^{-1}$), Anhui, 2016	→pH regulating → $A_1/A_2/O$–M → disinfection → RO → reuse	> 12	COD (480 $mg \cdot L^{-1}$), NH_3–N (20 $mg \cdot L^{-1}$), TOC (180 $mg \cdot L^{-1}$)	[16]
Municipal wastewater	Meicun Wastewater Treatment Plant (30 000 $m^3 \cdot d^{-1}$), Jiangsu, 2009	→ $A_1/A_2/O$–M → discharged	> 11	COD (200 $mg \cdot L^{-1}$), NH_3–N (30 $mg \cdot L^{-1}$), TN (50 $mg \cdot L^{-1}$), TP (3–5 $mg \cdot L^{-1}$)	[23]
Municipal wastewater	Kunming No. 4 Wastewater Treatment Plant (60 000 $m^3 \cdot d^{-1}$), Yunnan, 2010	→ $A_1/A_2/O/X$–M → disinfection → discharged	> 17	COD (180 $mg \cdot L^{-1}$), NH_3–N (20 $mg \cdot L^{-1}$), TN (26 $mg \cdot L^{-1}$), TP (3 $mg \cdot L^{-1}$)	[24]
Surface water	Wenyu River (100 000 $m^3 \cdot d^{-1}$), Beijing, 2007	→ Sedimentation → A_2–M → disinfection → discharged	–	COD (50 $mg \cdot L^{-1}$), NH_3–N (19 $mg \cdot L^{-1}$), TN (21 $mg \cdot L^{-1}$)	[25]

[a] A_1: anaerobic zone; A_2: anoxic zone; O: aerobic zone; X: switchable zone between anoxic and aerobic; BAF: biological aerated filter; EC: external circulation anaerobic reactor; EGSB: anaerobic expanded granular sludge bed; IC: internal circulation anaerobic reactor; M: membrane tank (aerobic).

[b] HRT: hydraulic retention time; the total HRT was estimated according to the data from corresponding literature and the HRT for primary treatment was not counted.

[c] COD: chemical oxygen demand; TP: total phosphorus; TN: total nitrogen; SS: suspended solid.

wastewater, especially with local standards issued/updated after 2015 (Appendix A Table S1). In response, integrated and longer treatment processes were adopted, namely, the processes were more complicated after 2015. Additionally, the enhanced requirements of the layout of drainage pipes and sludge treatment could also increase the total investment. ② Diverse industries were included after 2015 compared with those before 2010, which were concentrated in the petro-chemical industry (Fig. 2(b)). The corresponding treatment processes were altered with the variation of wastewater properties and the standards of the effluent quality. Regarding the individual treatment capacity, larger treatment capacities tended to have lower total investments (Fig. 5(c)) (data of municipal-large, industrial-large and surface water were collected from Refs. [5,8] with individual treatment capacity of more than 10 000 $m^3 \cdot d^{-1}$). The average total investment for projects with individual treatment capacities of 5000–10 000 $m^3 \cdot d^{-1}$ was ~9000 CNY·$(m^3 \cdot d^{-1})^{-1}$, while it was reduced to ~5500 CNY·$(m^3 \cdot d^{-1})^{-1}$ as the individual treatment capacity increased to over 50 000 $m^3 \cdot d^{-1}$.

The total footprint of MBRs treating industrial wastewater (including the footprints of all process structures and related facilities) was in the range of 0.8–2.2 $m^2 \cdot (m^3 \cdot d^{-1})^{-1}$, with average and median values of 2.0 and 1.4 $m^2 \cdot (m^3 \cdot d^{-1})^{-1}$, respectively (Fig. 5(b)). MBRs commissioned after 2015 had larger footprints (on

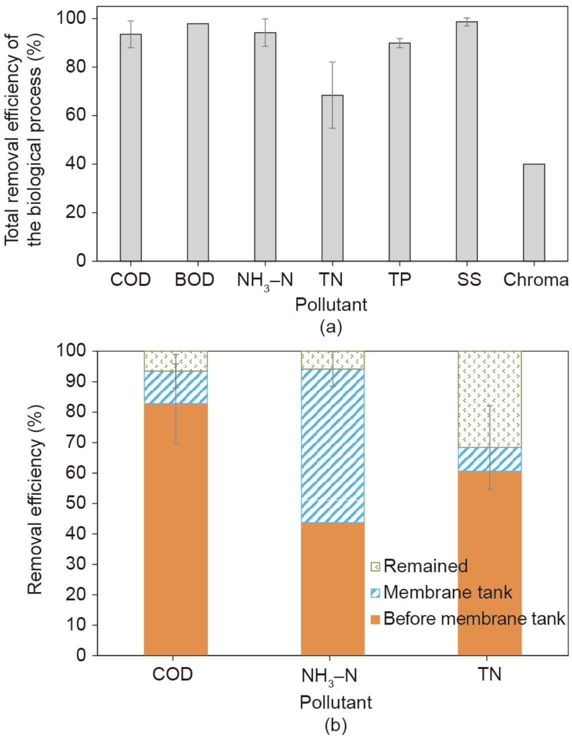


Fig. 4. Pollutant removal efficiencies of large-scale MBRs treating industrial wastewater: (a) the total removal efficiencies of biological treatment processes and (b) the removal efficiencies of treatment units. Error bars stand for standard deviations.

Table 2
Actual operating parameters of large-scale MBRs treating industrial and municipal wastewater[a].

Parameter	MBRs treating industrial wastewater[b]	MBRs treating municipal wastewater[c]
Flux ($L\cdot m^{-2}\cdot h^{-1}$)	11–25 (average 15.9)	11–40 (average 20.9)
MLSS ($g\cdot L^{-1}$)	8–12 (average 10.3)	6–17 (average 10.3)
SRT (d)	24	12–25 (average 18.6)
Sludge return ratio (%)[d]	200–300 (average 250)	300–400 (average 380)
SAD_p ($Nm^3\cdot(m^{-3}$-permeate))[e]	14–25 (average 18.6)	6–15 (average 10)
Membrane recovery cleaning interval (month)	1–6 (average 4.2)	6

[a] Regarding submerged MBRs.
[b] Data collected from this survey and publications of Refs. [14–17,21,30].
[c] Data collected from this survey and publications of Refs. [23,24].
[d] Sludge return from membrane tank to oxic tank.
[e] SAD_p: specific aeration demand with respect to permeate flow; Nm^3: the volume of the gas under standard condition (0 °C, 1.01×10^5 Pa).

average, 2.2 $m^2\cdot(m^3\cdot d^{-1})^{-1}$) compared with those commissioned before 2010 (on average, 1.0 $m^2\cdot(m^3\cdot d^{-1})^{-1}$). The complicated treatment process required to meet the stringent effluent quality standards might be the reason for the larger footprints after 2015. Similar to the total investment, larger individual treatment capacities tended to reduce the total footprint. The average total footprint of MBRs with individual treatment capacities of 5000–10 000 $m^3\cdot d^{-1}$ (~5.5 $m^2\cdot(m^3\cdot d^{-1})^{-1}$) was about two-fold that of those with individual treatment capacities of 10 000–25 000 $m^3\cdot d^{-1}$ and was about four-fold that of those with individual treatment capacities of $\geq$ 50 000 $m^3\cdot d^{-1}$. The reduction of both the total investment and the total footprint of MBRs with larger individual treatment capacities indicated the cost effectiveness of centralized wastewater treatment, supporting the construction of integrated industrial parks under the current background of intensive economic development. Large-scale MBRs are the major capacity type under construction currently, and super large-scale MBRs are promisingly increasing with the advancement of industrial park construction. Thus, lower total investments and total footprints should be expected in the future.

Overall, the total investment in MBRs for treating industrial wastewater was mostly $\geq$ 4000 CNY$\cdot(m^3\cdot d^{-1})^{-1}$, and the total footprints were mostly $\geq$ 0.9 $m^2\cdot(m^3\cdot d^{-1})^{-1}$. The average values were ~7500 CNY$\cdot(m^3\cdot d^{-1})$ and 2.0 $m^2\cdot(m^3\cdot d^{-1})^{-1}$, respectively, which were significantly higher than those for municipal wastewater treatment (on average, ~4000 CNY$\cdot(m^3\cdot d^{-1})^{-1}$ and 0.85 $m^2\cdot(m^3\cdot d^{-1})^{-1}$, respectively) and those for surface water treatment (on average, ~2500 CNY$\cdot(m^3\cdot d^{-1})^{-1}$ and 0.5 $m^2\cdot(m^3\cdot d^{-1})^{-1}$, respectively) (Fig. 5(c)). This was determined by the specific properties of the wastewater and the corresponding treatment processes. The pollutant concentration increased in the order of micro-polluted surface water, municipal wastewater, and industrial wastewater, as was the case for the difficulty to remove the pollutants. Thus, the total investment and the total footprint were increased inevitably as the treatment processes became longer and more complicated (Table 1 [14–25]).

4.2. Operating expenditure

The operating expenditure for MBRs treating industrial wastewater mainly included the energy consumption, chemical expenditure, element replacement, and so forth [9]. The higher energy consumption by MBRs compared with CAS processes was regarded a major obstacle to the wider application of MBRs. Thus, great amounts of research and applications have been conducted to develop/verify energy-reduction technologies. However, in this study, MBR consumed about 17% of the total energy consumption of the biological treatment processes for industrial wastewater treatment, which was lower than the municipal wastewater condition (48% [31]), that is, other biological processes consumed the majority energy to remove the pollutants to the designated concentration. In further considering advanced treatments (e.g., RO), the trade-off between energy consumption and effluent quality might make MBRs an energy-efficient option as part of the treatment process for refractory industrial wastewater. Different processes had different marginal costs for treating the same pollutant. According to comparing the environmental benefits and energy consumption costs obtained from the removal of pollutants in the industrial wastewater treatment process, the net profit of MBRs might be more competitive. It should also be noted that the specific energy consumption of MBRs treating industrial wastewater was generally higher than that of MBRs treating municipal wastewater, but the difference was reduced as the individual treatment capacity increased (Fig. 6(a)) (data of municipal wastewater collected from Refs. [28,31–37]). MBRs with individual treatment capacities of 5000–20 000 $m^3\cdot d^{-1}$ had a specific energy consumption of 0.5–1.5 $kW\cdot h\cdot m^{-3}$ for industrial wastewater and of 0.5–0.9 $kW\cdot h\cdot m^{-3}$ for municipal wastewater. For individual treatment capacities $\geq$ 50 000 $m^3\cdot d^{-1}$, the specific energy consumption was reduced to 0.3–0.5 $kW\cdot h\cdot m^{-3}$ for both industrial and municipal wastewater. Higher energy was demanded for membrane fouling suppression because of the high concentration of potential foulants in industrial wastewater. Centralized treatment at the super-large scale is advantageous in terms of increasing the energy efficiency, and the inclusion of small amounts of municipal wastewater or secondary effluent with the industrial wastewater (e.g., wastewater from industrial parks) could also reduce the energy consumption of industrial wastewater treatment.

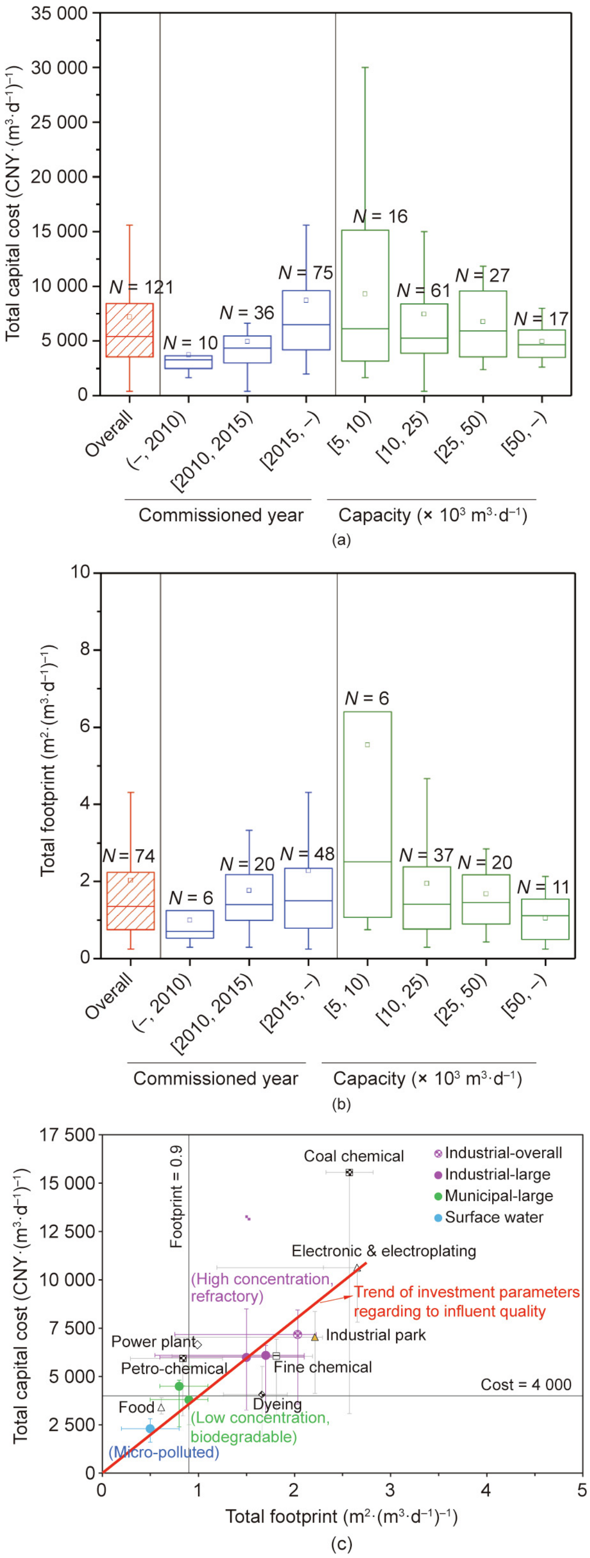


Fig. 5. Investments of MBR projects for treating industrial wastewater: (a) total investment and (b) total footprint (the boxes represent lower and upper quartiles with medians: the squares represent arithmetic means and the whiskers represent 5th to 95th percentiles); and (c) the investment of MBR projects with diverse influent properties (data were the average value with interquartile ranges as the error bars).

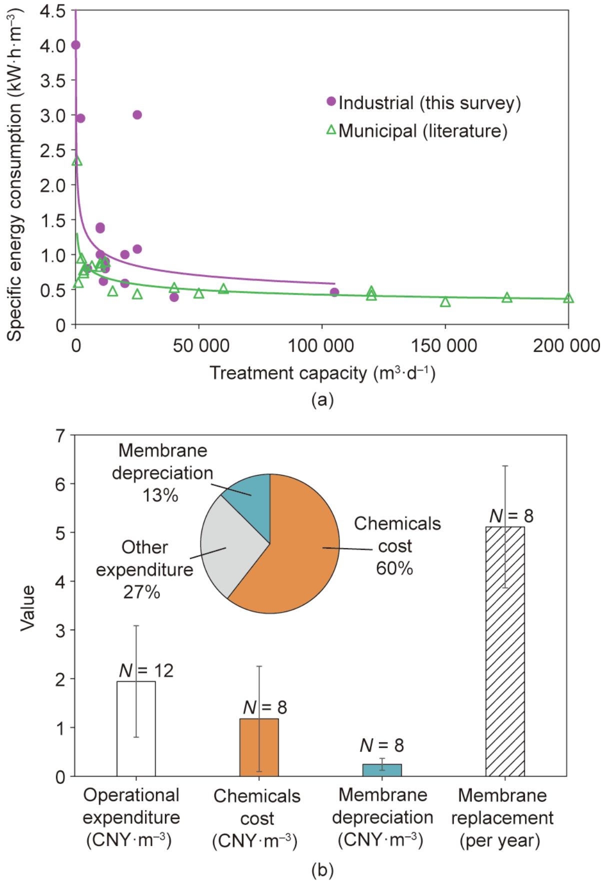


Fig. 6. Operating expenditures of full-scale MBR plants: (a) specific energy consumption of full-scale industrial and municipal wastewater treatment plants adopting MBR and (b) other key expenditure parameters of large-scale MBR plants treating industrial wastewater. Error bars in (b) stand for standard deviations.

The refractory and toxic pollutants in industrial wastewater required more chemical aids to be broken down and degraded. The total chemical cost for industrial wastewater treatment processes adopting MBRs averaged 1.17 CNY·$(m^3{\cdot}d^{-1})^{-1}$, constituting about 60% of the total operational expenditure of the treatment process (averagely 1.94 CNY·$(m^3{\cdot}d^{-1})^{-1}$) (Fig. 6(b)) [28,31–37]. The chemical cost of membrane tanks was mainly associated with the chemical cleaning of the membrane modules, including maintenance cleaning and recovery cleaning. The chemical cost in maintenance cleaning (frequent but with low dosages) and recovery cleaning (with high dosages, averaging an interval of 4.2 months, Table 2 [14–17,21,23,24,30]) should occupy a tiny proportion of the total chemical cost of the plant.

Continuous research and development has enhanced the cost-effectiveness of MBR and accelerated its development. Benefiting from the improvements in membrane manufacturing and material property control, the price of membrane elements has been reduced significantly from ~940 CNY·$(m^3{\cdot}d^{-1})^{-1}$ in 2013 to an average of ~370 CNY·$(m^3{\cdot}d^{-1})^{-1}$ in 2019 (Appendix A Fig. S1) [27,32–37], while the membrane lifespan has been within the range of 4–7 years (average of 5 years; Fig. 6(b)), leading to the reduction of annual expenditures on membrane elements. The membrane depreciation cost averaged 0.24 CNY·m^{-3}, constituting 13% of the total operational expenditure (Fig. 6(b)). However, the membrane modules were mostly replaced after a lifespan of 4–5 years according to our survey (4 out of 8 cases). The relatively steady membrane lifespan, regardless of the commissioning time, required further investigation for a reasonable explanation of whether this attribute was due to technical reasons (e.g., membrane damage, membrane aging, and irreversible fouling) or was following an empirical number.

5. Market of MBRs treating industrial wastewater

5.1. Membrane elements and suppliers

High-quality membrane elements are the core of MBRs treating industrial wastewater. Polyvinylidene fluoride (PVDF) was the most used membrane material, and hollow fiber was the most popular type of membrane module. Examples of the membrane suppliers are given in Table 3, such as Tianjin Motimo (China), OriginWater (China), and Mitsubishi Rayon (Japan). Additionally, flat-sheet membrane modules were also accessible—for example, Toray (Japan) and Kubota (Japan) provided flat-sheet membrane modules. Regarding more materials, polyvinyl chloride (PVC), polyether sulfone (PES), and polysulfone (PSF) membranes were provided by suppliers such as Zhaojin Motian (China) and Litree (China), while the applications of such membranes were of limited capacity. Ceramic membranes (mostly flat-sheet for submerged MBRs and tubular for side-stream MBRs) were also adopted in industrial wastewater treatment, taking advantage of the chemical stability, mechanical strength, and anti-biofouling property. Such membrane elements were provided by suppliers such as Jiuwu Hi-Tech (China) and ItN (Germany; currently owned by SafBon, China).

The vast Chinese market has attracted both domestic and overseas membrane suppliers (Table 3). Overseas suppliers, such as Asahi Kasei (Japan), Memstar (Singapore; currently owned by CITIC, China), and Canpure (Canada), were experienced in membrane production in the earlier stage. They provided 64%–75% of the membrane elements for large-scale MBRs treating industrial wastewater in China before 2015 (Fig. 7). In recent years, domestic suppliers in China including Tianjin Motimo, OriginWater, Scinor, and so forth have developed rapidly with improved product quality and production abilities. Accordingly, domestic suppliers have gradually increased their market share to become the major suppliers and to expand their business abroad. In total, 76% of the membrane elements of large-scale MBRs treating industrial wastewater were from domestic suppliers after 2015 (Fig. 7).

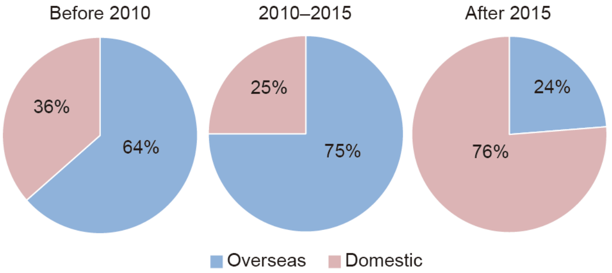


Fig. 7. Market share of the membrane elements according to the cumulative treatment capacity of large-scale MBRs treating industrial wastewater.

5.2. Business modes and engineering suppliers

MBRs treating industrial wastewater included company-oriented projects (the self-supporting environmental protection projects of enterprises) and official-oriented projects, with the ownership belonging to the company or the government. The early application of MBRs was majorly by companies. Company-oriented projects occupied about 80% of the cumulative treatment capacity of large-scale MBRs before 2010. Afterwards, with the officially led adjustment of industrial distribution and the construction of industrial parks, the proportion of official-oriented MBR projects for industrial wastewater treatment increased gradually to 87% of the cumulative treatment capacity of commissioned and under-construction projects after 2015 (Fig. 8(a)). The enlargement of both the number and the treatment capacity of official-oriented MBRs indicated the increasing recognition and acceptance of MBRs by mainstream society.

Multiple business modes have been adopted in projects involving MBRs for treating industrial wastewater. Regarding company-oriented projects, engineering–procurement–construction (EPC) was the most adopted business mode. Engineering suppliers took such projects by bidding, while enterprises would put up the capital and operate the projects after

Table 3
Main membrane element suppliers of MBRs for industrial wastewater treatment in China.

Element supplier	Headquarter location (established year)	Membrane material/module	Project example (capacity; commissioned year)
Tianjin Motimo	China (1992)	PVDF/hollow fiber	One petro-chemical company in Sichuan (10 000 $m^3 \cdot d^{-1}$; 2009)
OriginWater	China (2001)	PVDF/hollow fiber	Tianjin Panzhuang Industrial Park (10 000 $m^3 \cdot d^{-1}$; 2017)
Scinor	China (2004)	PVDF/hollow fiber	One industrial park in Jiuyuan district, Baotou (50 000 $m^3 \cdot d^{-1}$; 2014)
Filcore	China (2008)	PVDF/hollow fiber	Wuhai Energy, Shenhua Group (10 320 $m^3 \cdot d^{-1}$; 2017)
Zhaojin Motian	China (1988)	PVDF, PES, and PSF/hollow fiber	CNOOC Zhongjie Petrochemical Co., Ltd. (5 000 $m^3 \cdot d^{-1}$; 2013)
Litree	China (1991)	PVC and PVDF/hollow fiber	FOVO Food Group (12 000 $m^3 \cdot d^{-1}$; 2007)
Jiuwu Hi-Tech	China (1997)	Ceramic/tubular	–
Asahi Kasei	Japan (1931)	PVDF/hollow fiber	Huizhou Dayawan Petrochemical Zone (25 000 $m^3 \cdot d^{-1}$; 2006)
Mitsubishi Rayon	Japan (1933)	PVDF/hollow fiber	Centralized treatment of dyeing wastewater in Fengxin Industrial Park (25 000 $m^3 \cdot d^{-1}$; 2013)
GE-Zenon (currently owned by SUEZ, France)	Canada (1980)	PVDF/hollow fiber	Wastewater treatment plant of Wanhua Chemical (15 000 $m^3 \cdot d^{-1}$; 2014)
Canpure	Canada (2003)	PVDF/hollow fiber	Sinopec Sichuan Vinylon Works (28 800 $m^3 \cdot d^{-1}$; 2015)
Memstar (currently stake-controlled by CITIC, China)	Singapore (2005)	PVDF/hollow fiber	Xiaohu Island Fine Chemical Industrial Area (10 000 $m^3 \cdot d^{-1}$; 2007)
Toray	Japan (1926)	PVDF/hollow fiber and flat sheet	China Shenhua Coal-to-oil Chemical, Ordos branch (10 000 $m^3 \cdot d^{-1}$; 2013; flat sheet)
Kubota	Japan (1890)	CPE and ceramic/flat sheet	Kunshan Banknote Paper Co., Ltd. (9 000 $m^3 \cdot d^{-1}$; 2011; flat sheet)
ItN (currently stake-controlled by SafBon, China)	Germany (2000)	Ceramic/flat sheet	China National Coal Group, Ordos branch (9 000 $m^3 \cdot d^{-1}$; expected)

PVDF: polyvinylidene fluoride; PES: polyether sulfone; PSF: polysulfone; PVC: polyvinyl chloride; CPE: chlorinated polyethylene.

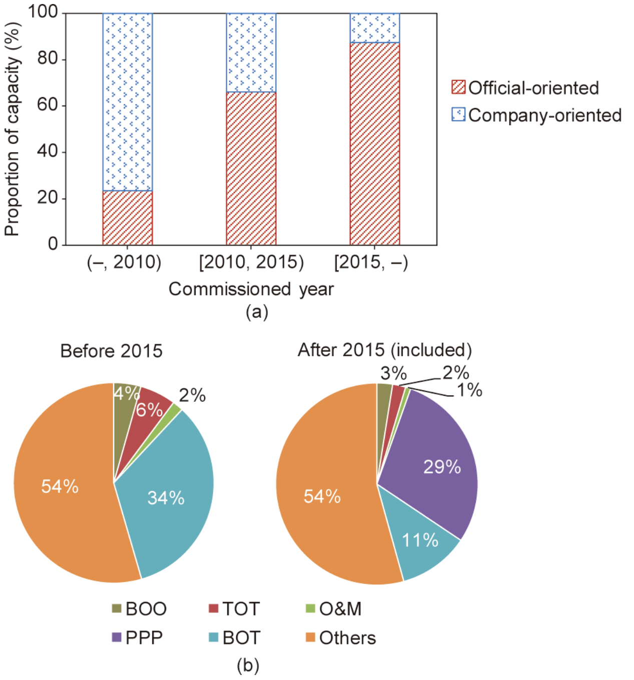


Fig. 8. Proportion of newly commissioned large-scale MBRs treating industrial wastewater according to the cumulative treatment capacity: (a) company-oriented and official-oriented projects; (b) business modes for official-oriented projects. BOO: build–own–operate; BOT: build–operate–transfer; O&M: operation and maintenance; PPP: public–private partnership (the PPP mode in this figure refers to those clearly marked as PPP, and such projects appeared after 2015); TOT: transfer–operate–transfer.

delivery. Official-oriented projects always have large treatment capacities and deep influence, requiring grand capital input. Half and even more of such projects were operated in the mode of public–private partnership (PPP) (Fig. 8(b)). Build–operate–transfer (BOT) was the main PPP mode (in a broad sense) before 2015, with 34% of the cumulative treatment capacity, followed by transfer–operate–transfer (TOT) and build–own–operate (BOO) (10% together). The concept of PPP was proposed and promoted officially after 2015. The special purpose vehicle (SPV) was formed, and social capital was introduced so that governments and private enterprises could cooperate and share both the development and the risk. The PPP business mode facilitated the implementation of large-scale infrastructure projects (e.g., wastewater treatment projects for large-scale industrial parks), and it eventually became the main mode. Projects clearly marked as PPP mode (in a narrow sense, via SPV) occupied ~30% of the cumulative treatment capacity of large-scale MBRs treating industrial wastewater.

Both domestic and overseas engineering suppliers are participating in the Chinese MBR market (some of them are listed in Table 4, and most are listed companies), of which domestic suppliers were the most active, such as OriginWater, Beijing Capital, Beijing Enterprises Water Group, and Sound Group. The expanding market of MBRs treating industrial wastewater promoted the development of engineering suppliers, with fierce competition among them. On one hand, some membrane suppliers developed into engineering suppliers (such as Tianjin Motimo and Jiuwu Hi-Tech). They extended their experiences in membrane production and application to full-chain service. On the other hand, some investment and construction companies in the wastewater treatment field enhanced their competitiveness through mergers, cooperation, and research and development (R&D). Such engineering suppliers included OriginWater, CITIC, E&E Technologies, Poten Enviro, and so forth.

6. Driving forces of MBR application in industrial wastewater treatment

6.1. Policy–economy driving forces

Industrialization in China has developed at a globally attractive high speed in the past decade. Simultaneously, China has been undergoing adjustments of its industrial and energy structures, alongside strengthening the improvement and protection of environment and ecosystem. Building a beautiful China and an ecological civilization have been written into the Chinese Constitution to reconcile economic development and ecological protection. Chinese President Xi Jinping listed pollution control as one of the *Three Critical Battles* for building a moderately prosperous society in all respects. In companies with steady economic growth goals, action plans for pollution prevention and control have been prepared and effectively implemented nationwide, driving the development of relevant treatment technologies. The powerful national administration system has advanced the development of the Chinese wastewater sector to own a global leading total market value and include the world's largest innovation team [38].

Table 4
Main investment and engineering suppliers of MBRs for industrial wastewater treatment in China.

Engineering supplier	Headquarter location	Established year	Business modes
OriginWater	China	2001	EPC, PPP, BOT
Sound Group	China	1993	EPC, BOT, PPP
Beijing Capital	China	1999	EPC, PPP, BOT
Beijing Enterprises Water Group	China	1992	EPC, TOT, BOT, BOO, DBO, OEM, PPP
Xingyuan Environment	China	1992	EPC, PPP, O&M
General Water of China	China	2003	EPC, BOT
CITIC Envirotech	China	2015	EPC, BOO, O&M, BOT, TOT, PPP
Gezhouba Group Water Operations	China	2016	EPC, BOT, PPP, PPP + EPC
China Construction Water & Environment	China	2013	EPC, PPP, BOT, BOO, O&M
Poten Enviro	China	1995	EPC, BOT
SafBon	China	1999	EPC, BOT, BOO, PPP
Tianjin Motimo	China	1992	EPC, EPC + C, BT, BOT, BOO, PPP
Beijing E&E Technologies	China	2007	PPP, TOT, BOT, BTO, MC
Veolia	France	1853	ABS, BOT, BOOT, BOO, BT, BTO
Suez Environment	France	1880	BOT
United Envirotech (owned by CITIC from 2015)	Singapore	1996	BOO, O&M, BOT, TOT
McWONG Environmental Technology	The United States	1997	EPC, BOO, BOT
Hyflux	Singapore	1989	BOO, BOT

ABS: asset backed securitization; BOOT: build–own–operate–transfer; BT: build–transfer; BTO: build–transfer–operation; DBO: design–build–operation; EPC + C: engineering–procurement–construction & commission; MC: managing contractor; OEM: original entrusted manufacture.

With regard to the prevention and control of water pollution, legislation has been strengthened with newly issued and continuously revised laws and regulations. The *Law on Water Pollution Prevention and Control* was revised in 2008 and 2017, addressing the concepts of sustainable development and the construction of an ecological civilization, respectively. The implementation of the strictest water resources control system with "three-red-line" regulations was proposed in the *No. 1 Central Document* in 2011, and afterwards, *Opinions of the State Council on Applying the Strictest Water Resources Control System* was released in 2012. In the same year, the strategic decision of *Vigorously Promoting the Construction of Ecological Civilization* was proposed at the Eighteenth National Congress of the Communist Party of China. The *Action Plan for Prevention and Control of Water Pollution* (also known as "Ten Measures for the Water") issued by the State Council in 2015 claimed to tighten environmental law enforcement and supervision, making it the new normal of China's pollution treatment and environmental protection [39].

Specifically, in the aspect of industrial water usage, total quantity control and wastewater reuse were explicitly encouraged in the 13th Five-Year Plan period (2016–2020). It was proposed in *the 13th Five-Year Plan for Economic and Social Development of the People's Republic of China (2016–2020)* to comprehensively push forward the construction of a water-saving society, to advance the reconstruction of water reservation in industries, to encourage measures for higher water use efficiency, and to implement projects for the reuse of reclaimed water [40]. The *Industrial Green Development Plan (2016–2020)* also addressed a higher industrial water use efficiency and the reuse of industrial wastewater by promoting intensive water utilization in industrial parks and the implementation of the gradient optimization of water resources as well as centralized wastewater treatment and reuse, aiming at a reduction of 23% in the specific water use per unit of IVA by 2020 relative to that in 2015 [41]. Regarding legislation, "Ten Measures for the Water" suggested strengthening the recycling of industrial water to advance cyclic development, including the comprehensive utilization of mining water, recycling of coal washing sewage, and advanced treatment and reuse of industrial wastewater from high-water consumption industries such as iron and steel, textile painting and dyeing, and papermaking [42].

Corresponding to the central policies, local standards were issued/revised one after another with stricter quality standards for the effluent of wastewater treatment plants and to advance projects on water resource protection with the concepts of "low impact development (LID)," "sponge city," "treatment of black and odorous water bodies," and so forth.

Besides action plans on environmental protection, relevant advanced technologies have also been officially promoted, including membrane technologies. Membrane materials and modules have been listed in the national current prior key areas of high-tech industrialization since 2007 by the National Development and Reform Commission (NDRC) (mentioned in item 56 Membrane Material and Module, item 116 Industrial and Urban Water Reservation, Wastewater Treatment Technology and Equipment [43], and in the key technologies for green transformation of traditional industries [41]).

Hence, with the attractive economic development and the fast implementation of top-down policies, MBRs could be widely applied in the treatment and reuse of industrial wastewater, playing an important role in the further economic and social development of China.

6.2. Market–technology driving forces

A vast market of industrial wastewater treatment and recycling exists in China, which has been committed to water conservation for decades. As the industrial water demand has increased year by year, industrial water reuse and recycling has played an important role in water saving in industries. According to statistics, with a steady annual fresh water use of ~1×10^{10} m^3 for decades, recycled water from treated municipal and industrial wastewater was consistently the major resource for industrial water use (Fig. 9(a)). The actual quantity of water used in 2017 by urban industries was 9.172×10^{10} m^3, of which 89.5% was recycled water. Additionally, the quantity of water saved from urban industries in 2017 was 4.65×10^9 m^3, constituting 70% of the total urban water savings (Fig. 9(b)). With continuous efforts, the specific fresh water demand per unit of IVA (10^4 CNY-IVA is regarded a unit of IVA in this study) in industries was gradually reduced to 45.88 $m^3\cdot(10^4\ \text{CNY-IVA})^{-1}$ in 2017, which was ~1/3 of that in 2007 (Fig. 9(b)). It will be further reduced by 20% in 2020 relative to that in 2015 (i.e., from 56.44 to 45.15 $m^3\cdot(10^4\ \text{CNY-IVA})^{-1}$) according to the *13th Five-Year Plan for Water-saving Society Construction* jointly issued by the NDRC, Ministry of Water Resources (MWR), and Ministry of Housing and Urban–Rural Development (MOHURD) of the People's Republic of China in 2017. Typical high-water consumption industries were given specific and clear water-saving goals by 2020.

The recycling of treated industrial wastewater should become an essential water-saving measure supported by ① stricter policies and laws for water pollution control and water reservation, as mentioned in Section 6.1; ② increasing investment in water-saving measures, as was the case after the "Ten Measures for the Water" was issued, when the total investment in water-saving measures significantly increased to 5993.12 million CNY (~840 million USD) in 2017 (Fig. 9(b)), with contributions from both official and private capital; and ③ upgraded treatment technologies with diversified reuse channels.

Owing to the advantages of a good and steady effluent quality, small footprint, reduced sludge production, alleviated loads for advanced treatment (e.g., reducing membrane foulants for RO), and so forth, MBR has been widely accepted in the wastewater treatment sector in line with the market demand. The engineering achievements in this study and consistently increasing publications and patents [5] reflect the innovations and improvements of MBR from both engineering and research aspects. With the joint forces from high-tech friendly policy, research and development, and capital input in engineering applications, MBR has grown fast to become a competitive mature technology, especially in industries and regions requiring high effluent quality while offering limited land. Considering this aspect, the cumulative treatment capacity and investment in MBRs for treating industrial wastewater should grow considerably in the future; thus, further efforts should be put into both the engineering and the research and development of MBRs.

7. Perspectives

MBRs have been extensively applied across China with considerable treatment capacity in diverse wastewater sectors covering municipal wastewater, industrial wastewater, and leachate [44]. These engineering projects have accumulated abundant operating experiences and lessons. The reciprocated interaction between engineering applications and R&D would accelerate the development of MBR technology. Based on this study on the large-scale application of MBRs treating industrial wastewater in Chinese mainland, the following perspectives are proposed.

7.1. Further efforts toward engineering development

Maintaining long-term steady operation, increasing water production, and reducing costs and energy consumption are necessary

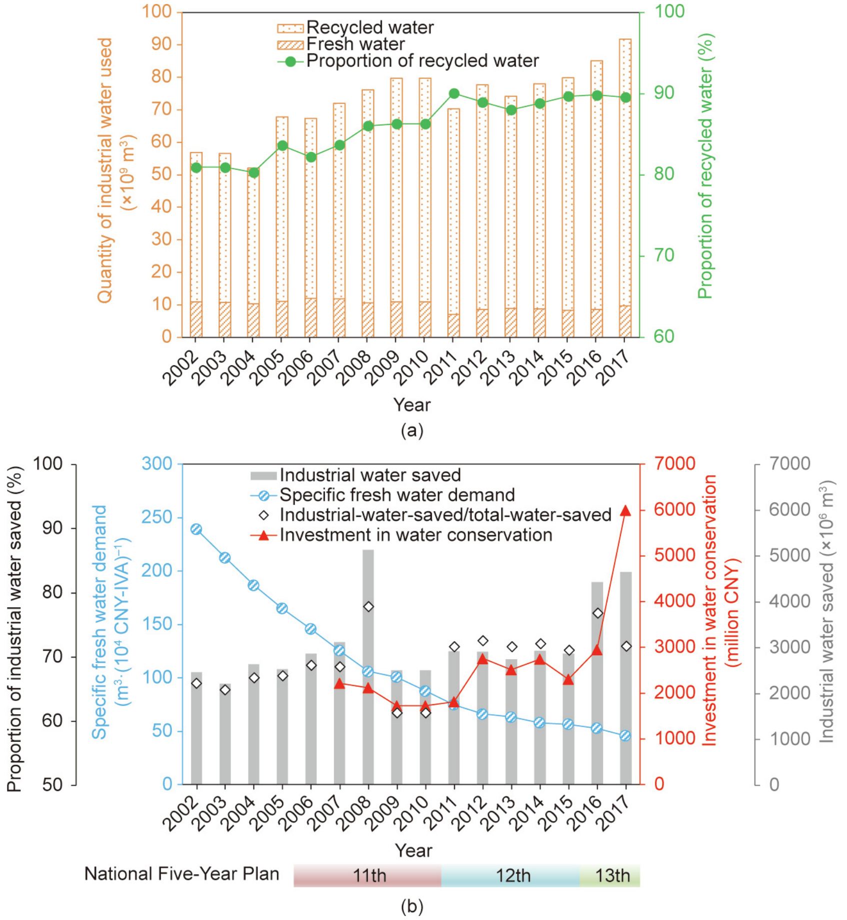


Fig. 9. (a) National urban industrial water consumption and (b) development of urban water reservations and the national specific fresh water demand in Chinese mainland (data collected from *China Statistical Yearbook* and *China Urban–Rural Construction Statistical Yearbook*).

measures to maintain the competitive edge of MBRs in industrial wastewater treatment. Further development of MBRs for treating industrial wastewater is expected in the following aspects.

7.1.1. Long-term steady operation with higher flux

Innovations of treatment processes, the coordination of MBRs with other technologies/processes, and the optimization of cost-effective MBR configuration are essential to guaranteeing long-term steady operation. Distinguishing specific conditions (influent quality, geographic climate, etc.), regulating the pollutant removal efficiencies among processes to reduce the reliance on membrane rejection, regulating mixed liquor properties, and big-data based precise control are essential aspects for achieving a designated performance. Additionally, the manufacturing of advanced membrane materials (with high flux, high strength, and anti-fouling properties) is key to enhancing the MBR advantages.

7.1.2. Lower cost and energy consumption

MBRs, especially underground MBRs, are advantageous in terms of footprint reduction, and such an advantage would be enhanced with the increment of the individual treatment capacity. Thus, MBRs are good for reducing the total investment of the treatment projects. In addition, realizing the mass production and manufacturing of advanced membrane elements with longer lifespans and lower prices could also reduce the cost of MBRs.

Energy reduction is needed due to both environmental and economic concerns. Lower specific energy consumption is expected with the construction of more industrial parks in which the comprehensively mixed wastewater could be regulated, and the individual treatment capacity would thus be enlarged. On the other hand, precise automatic control of innovative aeration strategies based on analyses of pollutant removal and membrane fouling should be developed in the future.

7.1.3. Full-scale application of anaerobic MBRs

Anaerobic MBRs (AnMBRs) can produce methane-rich biogas and treated wastewater simultaneously, making this treatment type a more energy-sustainable process compared to aerobic MBRs. Industrial wastewater with high-strength organics is suitable for the full-scale application of AnMBRs for treating industrial wastewater, as has been reported in Japan, the United States, and several European countries. However, large-scale AnMBRs have yet to be established in China according to our survey, though associated research has been conducted. AnMBRs are promising for commercialization in the future, with the expectation of experience and development regarding full-scale configuration design, element selection, fouling control and strategies, and efficient methane recovery measures.

7.2. Further efforts toward research development

Targeting better engineering performances (as mentioned in Section 5.2) and wider promotion, the research of MBRs should be conducted with joint forces from environmental, material, chemical, and information science and technologies, and the following aspects are strongly demanded in the future.

7.2.1. Advanced membrane materials and elements

Advanced membrane materials and elements support the sustainable development of MBRs, facilitating both performance improvement and cost reduction. The qualities of high strength, high flux, and anti-fouling are expected for advanced membrane materials, and innovation and modification in the development of membrane element configurations are also important. Besides polymeric hollow-fiber membranes, inorganic flat membrane modules could also be thoroughly evaluated for use in industrial wastewater treatment.

7.2.2. In-depth understanding of the fouling mechanism and innovative anti-fouling strategies

Membrane fouling control is the permanent goal in MBR-related research. Generally, novel fouling control approaches, aeration strategies, and auto-intelligent precise regulating systems are expected. Of note, frequent recovery cleaning and a shorter lifespan indicated the quick development of irreversible fouling in MBRs for treating industrial wastewater. Research on the mechanisms of the development of irreversible fouling and corresponding suppression strategies is needed in the future. Additionally, effective and efficient chemicals for recovery cleaning are also needed in engineering applications.

7.2.3. Information-based assessment and control system

Assessments and evaluations of MBRs are urgently needed. The establishment of accurate testing and evaluation systems for membrane products could help define key parameters (e.g., the membrane lifespan) instead of empirical values. On the other hand, based on theoretical calculations and big data from engineering experience, guidelines could be established in the future for the application of MBRs, such as parameters and conditions. Additionally, investigations of life cycle assessment (LCA) and economic models are currently inadequate, and it would be of great benefit to conduct in-depth research and wide applications of MBRs with the aid of cost-effectiveness assessment tools. Based on the comprehensive consideration of the environmental impact and economic benefits of MBRs, it is helpful to quantify and evaluate the cost, profit, and efficiency of MBRs to make the best decision for the application of MBR under certain circumstances.

It should also be noted that communication between research and engineering applications could be an effective way to further pursue advantages of MBRs. Applying research achievements in reality or conducting research related to real engineering projects will be of great significance for the development of MBRs for industrial wastewater treatment.

8. Conclusions

MBRs have been applied to treat industrial wastewater in China for almost 20 years. A timely review of full-scale MBRs is conducive to the further development of the technology. The survey of large-scale industrial wastewater MBRs (with individual treatment capacities $\geq$ 5000 $m^3 \cdot d^{-1}$) provided conclusions as follows:

A vigorous MBR market has been formed, involving fast-developing domestic membrane suppliers and engineering companies, with an expected cumulative treatment capacity of over 4×10^6 $m^3 \cdot d^{-1}$ from large-scale MBRs in diverse industries. The total investment of the treatment project was at the level of $\geq$ 4000 CNY$\cdot(m^3 \cdot d^{-1})^{-1}$ (~570 USD$\cdot(m^3 \cdot d^{-1})^{-1}$), and the footprint was $\geq$ 0.9 $m^2 \cdot (m^3 \cdot d^{-1})^{-1}$. The energy consumption was 0.3–1.5 $kW \cdot h \cdot m^{-3}$. Additionally, industrial wastewater MBRs have a lower flux (15.9 $L \cdot m^{-2} \cdot h^{-1}$), higher SAD_p (18.6 $Nm^3 \cdot (m^{-3}$-permeate)), and shorter recovery cleaning interval (4.2 months) compared to municipal wastewater MBRs.

Large-scale MBRs have been applied mostly in economic zones and water-deficient areas. Strengthened policies from central to local governments with stringent quality standards, limited land supplies, and increasing land prices have made MBRs competitive in the large potential market of industrial wastewater treatment and recycling. The sustainable development of MBRs requires effort in both practical improvement and advanced research to enhance the technology's advantages in industrial wastewater treatment and recycling.

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Compliance with ethics guidelines

Jiao Zhang, Kang Xiao, Ziwei Liu, Tingwei Gao, Shuai Liang, and Xia Huang declare that they do not have a conflict of interest or financial conflicts to disclose.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2020.09.012.

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