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Identify driving forces of MBR applications in China

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HIGHLIGHTS

• Provide a unique historic sequence of MBR application development in China
• Identify specific historic events roles to promote MBR applications in China
• Examine driving forces of MBR applications
• Explore the trend of MBR applications in China

GRAPHICAL ABSTRACT

A B S T R A C T

During the last two decades, MBR applications in China grow exponentially with the first pilot test of 10 m³/d in 1999 and the first application with capacity of 110,000 m³/d commissioned in 2009. It is critical to examine the drivers of MBR applications in China, which can provide sound scientific basis for future development of MBR applications. This study summarized the historical development of MBR applications and analyzed the driving forces by survey, literature review and interviews with MBR suppliers. The results showed that: (1) technical advantages of MBR and public policy related to water resources and environment promoted MBR beyond lab and pilot test into wide commercial applications in China; (2) petrochemical industry needs for wastewater treatment and reuse promoted medium-scale MBRs as public policy and regulation on water resources and environment tightens; (3) when the breakthrough of capacity of a single project above 10 thousand m³/d, the Green Olympic Games and Asian Games and tightening effluent regulations in environmentally sensitive areas incentivized MBR applications; and (4) the emergence of 100,000 m³/d MBR was mainly stimulated by water resources stress. Water resources stress and public policy related on resources and the environment are the primary driving forces in the last several decades. The future drivers of MBR applications in China appear to be decreasing operation cost.

1. Introduction

MBR applications in China started as early as 1990 (Zheng et al., 2003; Zheng et al., 2010; Huang et al., 2010; Abass et al., 2015; Xiao et al., 2014). In 1999, the first pilot scale membrane bioreactor (MBR) application in China was tested, which was used to treat industrial
wastewater with a scale of only 10 m$^3$/d (Zheng et al., 2003). Since then, MBR research and applications in China have been growing dramatically in that the first MBR application with the treatment capacity of 100,000 m$^3$/d was commissioned within 8 years in Beijing (Zheng et al., 2010; Huang et al., 2010; Abass et al., 2015). The total capacity of large-scale MBRs (≥10,000 m$^3$/d) reached 1.7 × 10$^8$ m$^3$/d in 2010 (Fig. 1). Both the capacity and number of MBR applications increased rapidly. A national survey of membrane manufacturers and operators was conducted to characterize MBR applications in China. Based on the survey, the number of large-scale MBRs in China approached 192, with the total capacity exceeding 11.17 × 10$^6$ m$^3$/d by 2017. Taking the under-construction projects into account, the number of large-scale MBRs is expected to approach 210 with the total capacity exceeding 14.04 × 10$^6$ m$^3$/d by 2018. The MBR applications with a capacity of 50,000 m$^3$/d or more are shown in Appendix A.

Nowadays, MBR has been widely accepted and applied as an efficient wastewater treatment process in China, due to its clean effluent and rapid performance improvement in many aspects, such as membrane lifespan, fouling mitigation, and energy consumption reduction. The scientific and technical perspectives of MBR have received much attention in literature and engineering operations of MBR applications have also been investigated extensively in China (Wang et al., 2013; Liu et al., 2010; Zheng and Liu, 2006; Sun et al., 2014; Shen et al., 2012; Zheng and Liu, 2007; Zheng et al., 2005; Li et al., 2006). A number of membrane materials and modules, such as hollow fiber membranes, flat-sheet membranes, tubular membranes, have been employed in municipal and industrial wastewater treatment facilities in China since the 2000s (Huang et al., 2010; Abass et al., 2015; Zhu et al., 2013; Zhang et al., 2008; Zhao et al., 2014; Yu et al., 2015; Wang et al., 2008). The various anaerobic-anoxic-aerobic MBR (AAO-MBR) processes for municipal wastewater treatment have been extensively investigated and denitrification on these occasions was enhanced since the 2010s, such as Hefei Tangxih WWTP and Wuxi Chengbei WWTP (Xiao et al., 2014).

China’s research on MBR technology started in 1990. The first paper on MBR technology was published in Chinese journals and introduced the application of MBR in other countries (Li, 1990). Since then, some universities and research institutes have involved in MBR research including Chinese Academy of Sciences, Tsinghua University, Tongji University, Tianjin University, Zhejiang University and Harbin Institute of Technology, etc.

The Chinese economy increased by about 9.7% per year from the Economic Reform in 1978 until 2014 to become the second largest economic body in the world (Lau and Zheng, 2017). In the last two decades, many historic events occurred in addition to the unprecedented long-term economic growth. In 2003, the severe acute respiratory syndrome (SARS), a contagious and sometimes fatal respiratory illness, occurred in China, which highlighted the importance of public health management and drew the attention of government and public into sanitary safety (Sun and Gu, 2007). The Olympic Games in 2008 were held in Beijing and the Asian Games in 2010 took place in Guangzhou. Both events were aimed to be green games to improve the environment and promote the games (Zheng et al., 2016). In 2014, the South-to-North Water Transfer (SNWTP) project started transport water to northern China to relieve water resources stress in North China (Zheng et al., 2016). The SNWTP project is a mega-project and has far-reaching impact on social economic and environment. Are these historic events related to the rapid growth of MBR applications?

How the scientific and technical advancement of MBR and the social economic factors interact with each other and impact the MBR applications is not well understood. The driving forces and factors which have resulted in the rapid growth of MBR applications are rarely examined. The study is aimed to summarize the history of MBR applications in China since 1999. The driving forces and historic events’ impact on MBR applications are examined, which is critical to the rapid growth of MBR applications. The MBR applications have been constantly impacted by the general factors in one way or another. Besides they have been promoted by the specific factors under specific historic context.

To fully analyze the driving factors, the historical development, general social economic development, water resources stress, water pollution, and historic events which may potentially impact on MBR applications are collected and examined. Published literatures are extensively reviewed to understand the research on MBR and a comprehensive national survey based on face-to-face or telephone interviews with senior scientists or executives of benchmark or major MBR applications was conducted to understand the context of those applications. Why MBR applications have been increasing dramatically in the last two decades in China? The study contributes to literature with the new understanding of MBR applications in China and provides insights of the driving forces of MBR applications. The study provides a unique observation and point of view of MBR applications in China.

2. Research on MBR

The initial researches and studies on MBR started in 1960s and the progress in the next several decades provided sound scientific and technical basis for industrial and commercial applications of large scale MBR. In 1969, Smith first combined bench-scale membrane separation system and aerobic activated sludge process to treat municipal sewage (Smith et al., 1969). The first membrane bioreactors were developed commercially by Dorr-Oliver in the late 1960s, with application to ship-board sewage treatment (Bembers et al., 1971). The initial designs, specifically the sidestream MBR configuration are tailored towards a direct hydrodynamic control of membrane fouling and offer the advantages of easier membrane replacement and high flux production but at the expense of high energy consumption. The typical energy consumption of sidestream MBR was 6–8 kWh·m$^-3$, almost ten times higher than conventional activated sludge process (CAS, 0.3–0.4 kWh·m$^-3$). The high energy consumption by sidestream MBR limited its applications (Le-Clech et al., 2006; Judd, 2012).

To expand MBR applications, it is vital to reduce the energy consumption by MBR. In 1989, Yamamoto invented submerged MBR and removed the circulating pump which greatly reduced energy consumption (Yamamoto et al., 1989). By the early 1990s, Zenon introduced a series of immersed hollow fiber membrane modules (Urbain et al., 1996). Over this period, Kubota also developed flat-sheet membrane products with improved overall energy efficiency, introducing a double-decker design in 2003. The energy consumption for sidestream systems is usually one or two orders of magnitude higher than that of submerged systems, regardless of whether the system is used for municipal or industrial wastewater treatments (Gander et al., 2000). Generally, the external configuration provides more direct hydrodynamic control of fouling and offers the advantages of easier membrane replacement.

Fig. 1. Development of engineering application of large-scale MBRs (≥10,000 m$^3$/d) in China since 2006.
and high fluxes at the expense of high energy consumption (of the order of 10 kWh m⁻³) (Le-Clech et al., 2006). Several distinct advantages of submerged configuration are their much lower energy consumption, only 0.6-2 kWh m⁻³, which is only 10 to 20% of sidestream MBR (Lin et al., 2012). The invention of submerged MBR remarkably improved MBR efficiency and promote applications of MBR worldwide. The research in China has improved membrane flux capacity from 8 to 12 L/m²/h to about 15-25 L/m²/h as well.

The advancement of scientific and engineering research on MBR promote its commercial applications. MBR was employed to treat water and wastewater worldwide. Before 2000, MBR was primarily applied in disposal of a broad range of wastewater, such as landfill leachate, municipal sewage, fecal sewage, and industrial sewage. The largest MBR application before 2000 could treat 15,500 m³/d municipal sewage (Brindle, 1997).

The research of MBR in China started in the 1990s which was much later than the first study on MBR abroad, but it developed dramatically. In 1990, Li (1990) firstly published a review of MBR and introduced MBR to China (Li, 1990). Fan et al. (1998) later used MBR to treat petrochemical wastewater. In 1999, Zheng et al. (2003) conducted a pilot test of MBR to treat textile wastewater and laid a foundation for the commercial applications of MBR in China (Zheng et al., 2003). The study of sidestream MBRs was dominant before 2001 while submerged MBRs were more popular since 2001 because of its lower operational cost. Since 2003, a modified sidestream MBR (also called as airlift external circulation MBR), replacing the recirculation pump by H-type recycling pipe, has been well studied for the treatment of toilet wastewater and municipal wastewater (Fan et al., 2006; Li et al., 2007; Fan et al., 2005). Another innovative submerged anaerobic membrane bioreactor (SAMBR) was developed in 2004. The membrane fouling was controlled by recirculating the biogas and inducing the mixed liquor turbulence (Wang et al., 2008). Since 2004, many efforts have been dedicated to the study of this SAMBR for the treatment of high-strength alcohol-distillery wastewater. In order for broader applications of MBR, self-forming dynamic membrane bioreactor (SFDMBR), a process even without manufactured membrane, has been proposed, with cheap coarse pore-sized materials such as dacron mesh, stainless steel mesh, glass fiber, nonwovens, etc., employed as filtration media (Fan and Huang, 2002; Wu et al., 2005; Chu et al., 2008; Yuan et al., 2010). In general, among these studies submerged MBRs were mostly utilized for municipal wastewater treatment while the sidestream MBRs were commonly applied for particular industrial wastewater treatment. The objectives of research on MBR may lie in two aspects: utilization and optimization. Research on the utilization of MBR includes the exploration of new functions, pragmatization, scaling up and operation maintenance. The optimization aims at higher operational efficiency better performance for target pollutants removal, lower constructional and operational cost and lower energy consumption during operation. While the scientific research and studies in China are progressing continuously, the much more prominent phenomenon since commercial applications of MBR started in China is the remarkably growth in a short period. The summary of the MBR applications history is presented in the following section.

3. History of MBR applications

3.1. Global MBR applications

To understand the driving forces of MBR applications, it is vital to examine the development history of MBR applications. The first commercially developed MBR was by Dorr-Oliver in the late 1960s (Smith et al., 1969; Bemberis et al., 1971). Although MBR systems did not gain wide attention in North America, it was considerably successful in Japan in the 1970s and 1980s. In 1991, the first large-scale sidestream MBR system for treating industrial wastewater was constructed in North America at the GM Mansfield plant (Judd, 2012). Following this development, numerous MBR systems for treating industrial wastewater were installed in the United States and Canada. From the late 1980s to early 1990s, the government incentivized water recycling program prompted pioneering work by Yamamoto to develop an immersed MBR process in Japan. By 1996, 60 immersed flat-sheet MBR plants had been installed in Japan providing a total capacity of 5500 m³/d (Zheng et al., 2016; Judd, 2012).

In Europe, MBR was used for industrial wastewater treatment in the early 1990s and the first full-scale MBR plant for treatment of municipal wastewater was constructed in Porlock of United Kingdom in 1998 with a capacity of 1900 m³/d (Judd, 2012). In 2002, one MBR line was commissioned in Brescia, Italy with a nominal capacity of 38,000 m³/d. In 2004, Nordkanal MBR plant was commissioned with a design capacity of 45,000 m³/d in Kaarst, Germany, which, at the time, was the largest MBR plant in the world (Frechen et al., 2008).

By 2005, ~2200 MBR plants were in operation or under construction worldwide. Although plant capacities of MBR systems have been increasing, most of the plants in operation in the world are medium-scale or small-scale in terms of capacity. There are 219 MBR plants for treatment of municipal wastewater in North America, with only 17 plants exceeding a capacity of 10,000 m³/d (Yang et al., 2006). By 2008, 37 MBR plants having a capacity higher than 5000 m³/d were operating, while ~800 commercial MBR applications were in use in Europe (Lesjean and Huisjes, 2008). The Henriksdal wastewater treatment plant (WWTP) in Stockholm will be upgraded to an MBR that will treat 864,000 m³/d of wastewater, making it the largest MBR plant in the world, when it is commissioned in 2018 (Krzeminski et al., 2017).

3.2. MBR applications in China

Based on the wastewater treatment capacity of MBR applications, roughly five phases are identified (Xiao et al., 2014), which are demonstrated in Fig. 2 and summarized below. The starting point of each phase is marked by benchmark tests or MBR applications.

Phase 1: laboratory and pilot test (1990–1999). Phase 1 started in 1990 when Li published the first review of MBR in China and then laboratory tests on MBR developed quickly. The first pilot test of MBR with capacity of 10 m³/d wastewater was completed in 1999 by Zheng who examined the performance of MBR treating dyeing wastewater (Zheng et al., 2016).

Phase 2: the treatment capacity of hundreds m³/d wastewater (2000–2003). In 2000, MBR was applied in printing and dyeing wastewater of Kangda Gloves Co., LTD with the capacity only 11 m³/d (Liu et al., 2017) and this marked the beginning of the commercial MBR application China. In the same year, a MBR application was completed in Tianjing with the treatment capacity of 25 m³/d. In 2002, a hospital in Guangdong used MBR to treat the hospital wastewater with the capacity of 100 m³/d. In this period, MBR were mainly applied to treat hospital wastewater with the treatment capacity of hundreds m³/d (Liu et al., 2010).

Phase 3: the treatment capacity of thousands m³/d wastewater (2004–2005). The first MBR applications with treatment capacity of thousand m³/d were completed in 2004 which treated 5000 m³/d petrochemical wastewater. During this phase, the MBR applications with capacity of thousand m³/d were primarily applied in petrochemical industry, such as Luoyang Petrochemical Engineering Corporation (5000 m³/d, 2004) and Baling Petrochemical Engineering Corporation (7200 m³/d, 2005) (Zheng et al., 2016).

Stage 4: the capacity of 10 thousand m³/d wastewater (2006–2010). The Miyuan WRP was commissioned in 2006 with a MBR application to treat 45,000 m³/d municipal wastewater. Since then, many wastewater treatment plants (WWTP) started to apply MBR to treat municipal wastewater with the capacity of 10 thousand m³/d or larger. The geographic distribution of MBR applications in 2010 is show in Fig. 3. MBR applications in this period were mainly located in Beijing, Jiangsu, Guangdong and Hubei. By the end of 2017, there were 192 large-scale
MBRs (≥10,000 m³/d) applied in China, with a total capacity of 11.17 × 10⁶ m³/d.

Stage 5: the capacity of 100 thousand m³/d wastewater (2011–present). With the advancing engineering and technology of MBR, the capacities of MBR applications in municipal wastewater treatment dramatically increased to beyond 100 thousand m³/d. In 2007, the first 100 thousand m³/d MBR application were completed in Beijing Wenyuhe River WWTP. Since 2007, 35 MBR applications with 100 thousand m³/d capacity were completed in China which accounted for over a half of the 51 MBR applications worldwide with the capacity (Dong, 2017). The geographic distribution of MBR applications in 2017 is shown in Fig. 4. After 2010, MBR applications expanded to Southwest, Northwest and Northeast China. MBR applications with capacities of 10 thousand and 100 thousand m³/d were mainly used to treat municipal wastewater in China. Due to increasing land price and limited land availability in urban areas, underground space is utilized to build municipal WWTPs. For example, there are 13 underground MBR applications in China for treating municipal wastewater. The Guangzhou Jingxi WWTP (with the capacity of 100 thousand m³/d), Kunming No. 10 WWTP (with the capacity of 150 thousand m³/d), and Taiyuan Jingyan WWTP (with the capacity of 120 thousand m³/d) employed MBR for underground wastewater treatment facility.
4. Driving forces of MBR applications

The driving forces of MBR in China could be classified to public policy, petrochemical industry, green Olympic Games, water environmental stress, water resources stress, and advantage of MBR technology. The petrochemical industry and green Olympic Games were also derived from water environmental and resources stresses. Timing of the forcing is critical as well. Public policy, water environmental stress and water resources stress is the general forcing which continuously impact MBR applications and will continue to be the driving forces. It should be noted advantage of MBR has been discussed in previous section. It also interacts with every other driving force to affect MBR applications and thus is not discussed separately. The public health concerns caused by the SARS event in 2003 warranted better treatment of hospital wastewater which was a potential field for commercial MBR applications. The petrochemical industry need and green Olympic Games each increased the MBR application capacity by roughly a magnitude. Public policy, water environment and water resources stress drive the magnitude of MBR applications up to one more magnitude. The five driving forces are discussed in detail in this section, sequentially.

4.1. Public policy

Public policies play a critical role in MBR applications in China. To strengthen the regulation of pollutant discharge and wastewater reuse, Chinese governments adopted a series of national policies and plans, such as 12th Five-Year Plan of High Performance Membrane Material and Technology Development and 12th Five-Year Plan of New Material Industry Development (Abass et al., 2015; Xiao et al., 2014), which promote environment protection and resources conservation practices. Appendix A provides a list of national plans and policies that has promoted MBR applications in the last decade. According to the Water Pollution Prevention and Control Plan, the wastewater reclamation rate in China should reach 20% by 2020, which provided a great opportunity for MBR technology to be widely used in the upgrading WWTPs due to MBR’s distinct technical advantages of high treatment efficiency (Zheng et al., 2016). Additionally, the development of membrane materials has been outlined in the 12th National Five-Year Plan (2011 to 2015), such as Strategy of Accelerating Cultivation and Development of Emerging Strategic Industries, from both aspects of environmental protection and technological development. These national policies provided enormous opportunity for MBR applications (Huang et al., 2010; Abass et al., 2015; Xiao et al., 2014; Wang et al., 2013). In general, public policy in China increase the demand on MBR application as it often...
promotes wastewater treatment and reclamation. Public policy also promotes the supply of MBR as it incentivizes the development of MBR technology and applications.

The SARS event increased public awareness of public health concern and lead Chinese government to tighten regulation on hospital sewage which contains many pathogens such as bacteria, viruses, etc. (Liu et al., 2010). Therefore, the demand on advanced technology to treat hospital sewage is increasing. In addition, as large hospitals in China are often located in the city centers, where land prices and office rentals are prohibitively high, the ideal hospital sewage treatment systems should use minimal land and space. Generally, hospital wastewater is treated with primary treatment and disinfection process (often by chlorine, ozone and ultraviolet light) and infectious hospitals must use secondary treatment (Chen et al., 2006). MBR is an effective technology in removing pathogenic microorganism. Its low SS of effluent is helpful to improve the efficiency of disinfection processes, minimize disinfectant, and reduce disinfection by-products (Zheng and Liu, 2007; Zheng et al., 2005). It improves disinfection effects and reduces the toxicity of effluent. In addition, it does not require secondary sedimentation tank and thus reduce land and space usage for wastewater treatment, which made it an ideal potential technology for treating hospital wastewater (Lv et al., 2006). The SARS event promoted MBR applications for treating hospital wastewater (Zheng et al., 2016). Table 1 demonstrates some typical MBR applications for treating hospital wastewater. It is noted that MBR treatment capacity for hospital wastewater is a small portion of those for industrial wastewater.

### 4.2. Petrochemical industry needs

The petrochemical industry needs a huge amount of water and discharges lots wastewater containing a great deal of toxic pollutants and hard biodegradation. About 90% of the raw water used in the petrochemical industry is used for circulating cooling system and chemical system (Hansen et al., 2018). Water consumption is limited and thus most of the used water is discharged as wastewater. To make it worse, >60% of the Sinopec subordinate enterprises are in regions with serious water shortage issues (Zheng et al., 2016). Therefore, the water resources stress and wastewater discharge stress are pressing for the petrochemical industry.

According to the requirement of energy conservation and emissions reduction in China, the petrochemical industry enterprises has to treat wastewater to meet effluent quality standard and increase wastewater reuse rate (Yu et al., 2017). Therefore, recycling and reusing effluent is important for the industry. MBR is an effective technology for oil refineries, saline, phthalate, caprolactam wastewater, etc. (Li, 2008), because effluent from MBR can meet the 1A effluent standard and be reused for cooling or landscape irrigation purposes (Qin et al., 2007; Liu, 2013a). Therefore, MBR have been widely employed to treat wastewater for the petrochemical industry since 2004. Table 2 shows the representative MBR applications in petrochemical industry in the period of 2004 to 2009. It can be seen that MBR application capacities increased from 5 thousand m³/d to 25 thousand m³/d in this field.

#### 4.3. The green Olympic Games and Asian Games

The 2008 Olympic Games was held in Beijing, which is a mega population center and faces severe water resources stress. The average water resource was about 200 m³ per capita in Beijing. Therefore, water supply and water security were a challenge that Beijing has to address to successful host the 2008 Olympic Games. Increasing wastewater reuse rate to 50% was one of the key policy to address water supply issue in Beijing (Zheng et al., 2016; Zhang, 2001). The Olympic Park, the National Stadium (Bird’s Nest), and the Olympic Forest Park were all designed with various water-saving devices and measures such as rainwater collection systems, wastewater reuse projects, etc. After the 2008 Beijing Olympic Games, the Asian Games was held in 2010 in Guangzhou where water pollution was a big issue to address. Both the Beijing Olympic Games and Guangzhou Asian Games were aimed to be green games based on national and local government goals.

In the meantime, MBR applications in China to treat hospital wastewater and petrochemical industry wastewater spread widely through China and MBR applications reached thousands m³/d already. It was a feasible option for achieving the green games goal. For instance, Beixiaohu WWTP used MBR to treat the wastewater. Beixiaohu WWTP

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### Table 2

Representative MBR applications in petrochemical industry (Zheng et al., 2010; Li, 2008).

| MBR applications                              | Capacity (m³/d) | Commission year | Location   |
|----------------------------------------------|-----------------|-----------------|------------|
| Luoyang Petrochemical Engineering Co.        | 5000            | 2004            | Henan      |
| Yueyang Petrochemical Engineering Co.        | 7200            | 2004            | Hunan      |
| Jinling Petrochemical Engineering Co. (phase 2) | 6000            | 2005            | Jiangsu    |
| Jinling Petrochemical Engineering Co. (phase 1) | 6000            | 2005            | Jiangsu    |
| Baoting Petrochemical Engineering Co.        | 7200            | 2005            | Hunan      |
| Xiaohuacao Fine Chemical Industry Park       | 10,000          | 2006            | Guangzhou  |
| Hainan Shihua Petrochemical Engineering      | 12,000          | 2006            | Hainan     |
| Huizhou Dayawan Petrochemical Industrial Park| 25,000          | 2006            | Guangdong  |
| Harbin Petrochemical Engineering Corporation | 10,000          | 2006            | Heilongjiang|
| Changqing Petrochemical Engineering          | 9600            | 2008            | Shaanxi    |
| Jiuzhang Petrochemical Engineering Co.       | 12,000          | 2009            | Jiangxi    |
| Taixing Fine Chemical Industry Park          | 25,000          | 2009            | Jiangsu    |

### Table 3

MBR installations for Olympic Games and Asian Games (Zheng et al., 2010; Zheng et al., 2016).

| MBR installations    | Capacity (m³/d) | Commission year | Membrane suppliers |
|----------------------|-----------------|-----------------|--------------------|
| Miyun WRP            | 45,000          | 2006            | Mitsubishi Rayon   |
| Beixiaohu WWTP       | 60,000          | 2007            | Siemens            |
| Huairou WRP          | 35,000          | 2007            | Asahi Kasei        |
| Wenyuhe Water Treatment System (phase 1) | 100,000 | 2007 | Asahi Kasei |
| Beijing Olympic Tennis and Badminton Center | 200    | 2008    | Toray             |
| Beijing Olympic Training Center for the Disabled | 400   | 2008    | Toray             |
| Beijing Olympic Swimming Center                 | 500   | 2008    | Toray             |
| State General Administration of Sport           | 100   | 2008    | Toray             |
| Hong Kong Equestrian Game WWTP                  | 500   | 2008    | Motimo            |
| Asian Games Equestrian Game WWTO                | 550   | 2010    |                    |
as well as Qinhe River WWTP provided 80,000 m$^3$/d irrigation water for the Olympic Park. Table 3 lists representative MBR applications for the two games. The successful application of MBR in Beijing Olympic Games and Guangzhou Asian Games, appeared to promote the brand image of MBR applications to other fields and locations through China.

### 4.4. Water environment stress: regulation on wastewater discharges

Water environment stress in China has been increasing ever since 1978 when the economy started to grow rapidly. It is one of the latent but constant driving forces for wastewater treatment technology including MBR. Dianchi Lake has seen many massive blue-green algae outbreaks since early 1990s (Wu et al., 2014). In 2003, Chaohu Lake had cyanobacteria break-out (Cai et al., 2012). In the late 1990s, frequent blue algal blooms occurred in the northern and western portion of Taihu Lake (Yang and Liu, 2010). In 2007, the algae blooms in Taihu Lake caused severe contamination of drinking water for millions of people and resulted in water crisis in Wuxi (Zhang et al., 2010). After the cyanobacteria break-out in 2007, the regulation on wastewater discharge became increasingly strict and WWTPs in Taihu basin had to meet 1A effluent standard of "Discharge standard of pollutants for municipal wastewater treatment plant (GB18918-2002)" (Anon., 2002). The provincial government required 169 WWTPs near the Taihu Lake be upgraded and rebuilt to meet the new wastewater discharge standard (Liu, 2013b).

Nitrogen and phosphorus are the main pollutants of eutrophication. MBR is a potential technology in removing nitrogen and phosphorus and naturally is used to treat wastewater for meeting the new wastewater discharge standard (Dong et al., 2010). Table 4 shows representative MBR applications in Wuxi.

Throughout China, there are 2759 lakes (area ≥ 1 km$^2$) with the total area about 91,019 km$^2$, while about 900 of which are facing eutrophication issues (Shen et al., 2014). The tightening effluent regulations continue to be the driving force of MBR applications.

### 4.5. Water resources stress

The average water resources per capita in China are only about a quarter of the world average, which makes it the 108th in the world and a severe water shortage country (Li et al., 2017). The uneven geographic distribution of precipitation and water resources increases water resources stress for arid and semi-arid regions in China. The average water resources per person each year in Beijing, Tianjin, Hebei, Shanghai, Shandong and Ningxia was under 300, which is considered extremely low water resources (Li et al., 2017). Over 400 cities among about 600 cities in China are confronted with serious water shortage (Song et al., 2018). Although water resources are relatively rich in southern China, water pollution results in water shortage for many cities in southern China.

To address the long-term water resources stress, wastewater reuse is one of effective and efficient ways. MBR technology can provide high quality reclaimed water for landscape irrigation, agricultural irrigation, industry, etc. The increasing need of reused water will promote MBR applications.

Another way to relieve water resources stress in northern China is the South-to-North Water Transfer Project (SNWTP) (Ma et al., 2016). On December 12, 2014, the water system of the middle line of SNWTP begun to convey 9.5 billion m$^3$ water per year. The conveyed water was used for public water supply, ecosystem, and other purposes (Sheng and Webber, 2018). The water source of SNWTP includes many rivers and reservoirs whose water quality is critical for the success of the SNWTP (Xiong et al., 2006). For example, Shiyan City is the core region of water source and water conservation area of SNWTP. The municipal wastewater of Shiyan is discharged into Shending River and thus effective and efficient treat of the municipal wastewater in Shiyan is warranted. A large MBR WWTP was constructed in Shiyan in 2009 for this purpose.

Table 5 listed representative MBR applications with capacity of 100 thousand m$^3$/d, which primarily were driven by local water resources stress. All these large-scale MBR applications were used to treat municipal wastewater except Wenyu River Water Plant which was designed to treat polluted river water.

### 5. Driving forces in the future

The five driving forces discussed in previous section have resulted in the status of MBR applications in China. While water environment and water resources stresses will continue to promote MBR applications, the return of invest and operation cost will be the driving forces in the future that expand MBR applications into more fields and regions.

#### 5.1. Return on investment

The total capital investment cost of MBR and conventional WWTP are shown in Table 6. The total capital investment of MBR WWTP for municipal wastewater is higher than that of conventional WWTP. However, if the effluent must meet 1A of national standard (Anon., 2002), the conventional municipal WWTPs have to include additional facilities,

Table 4

| MBR applications | Capacity (m$^3$/d) | Commission year | Membrane suppliers |
|------------------|-------------------|-----------------|--------------------|
| Wuxi Meicun WWTP (phase 2) | 30,000 | 2009 | GE |
| Wuxi Xincheng WWTP (phase 2) | 30,000 | 2008 | Siemens |
| Wuxi Shuofang WWTP | 20,000 | 2009 | Origin Water |
| Wuxi Chengbei WWTP (phase 4) | 50,000 | 2009 | |

Table 5

| MBR applications | Capacity (m$^3$/d) | Commission year | MBR supplier | Note |
|------------------|-------------------|-----------------|--------------|------|
| Wenyu River Water Plant (phase 2) | 100,000 | 2011 | Origin Water | Surface water |
| Qinghe WWTP (phase 3) | 150,000 | 2012 | Origin Water | |
| Daxing Huangrun WRP | 120,000 | 2013 | Origin Water | |
| Kunming No. 10 WWTP | 150,000 | 2013 | Origin Water | |
| Zhuzhou Longquan WWTP (phase 3) | 100,000 | 2014 | Tianjin Motimo | |
| Sanjinian WWTP | 200,000 | 2015 | Origin Water | |
| Jilin WWTP | 150,000 | 2015 | Origin Water | |
| Beijing Huafang WR | 600,000 | 2016 | Meinstar | Underground MBR |
| Xi’an Caotan WWPT | 200,000 | 2016 | Origin Water | |
such as layout cloth-media filter or sand leach for advanced treatment, its total investment cost will be similar with that of MBR applications. MBR process becomes more and more attractive for municipal/domestic wastewater treatment when a compact technology is required due to a lack of space or the high cost of additional land in urban areas. The average footprint areas of a MBR municipal WWTP (with a capacity of 50,000–200,000 m³/d) are 0.4–0.6 m²·m⁻³·d⁻¹, respectively. In contrast, the standard footprint area of a conventional municipal WWTP (including tertiary treatment) is 1.2–1.6 m²·m⁻³·d⁻¹. Land price in many Chinese cities is as high as 1500 RMB/m² nowadays. When cost for land is considered, the MBR invent will closer to that of conventional WWTPs.

The available locations for new WWTPs in big cities are extremely limited because drainage systems are often completed and could not be changed easily. In this situation, MBR has an advantage over conventional WWTPs as MBR need less space and has small footprint. From Table 6, the average footprint of MBR municipal WWTPs is 0.9 m²·m⁻³·d⁻¹, less than that of conventional municipal WWTPs. In addition, underground MBR WWTPs have been constructed with the total investment of 3000–6000 RMB/m³ to save space and reduce environmental impact in big cities (Cao et al., 2012). Table 7 shows representative underground MBR WWTPs. When land prices in big cities are considered, MBR applications may be preferred in big cities. With the rapid urbanization, MBR applications will be stimulated by the shortage of land resources and high price of land.

Table 6
The footprint and average capital investment of MBR and conventional municipal WWTP (Xiao et al., 2014).

| Water               | Footprint (m²·m⁻³·d⁻¹) | Capital investment (RMB·m⁻³·d⁻¹) |
|---------------------|------------------------|----------------------------------|
|                     | MBR                    | Conventional                     |
| Municipal wastewater| 0.9                    | 1.2–1.6                          |
| Industrial wastewater| 1.7                    |                                  |
| Polluted surface water| 0.5                    |                                  |

4 MBR capacity is larger than 10 thousand m³/d.
5 Conventional municipal WWTP (10–50 thousand m³/d) includes tertiary treatment.

5.2. Operation issues, cost and energy consumption

The essential focus points in full scale MBR design and operation include operation issues such as membrane fouling, energy consumption and associated cost. The comparison of operation cost and energy consumption of MBR and conventional process are shown in Table 8. Energy consumption accounts for 50%–70% of MBR operation cost (Zheng et al., 2016; Meng et al., 2012; Gabarrón et al., 2014). For municipal wastewater, both operation cost and energy consumption of MBR are higher than those of conventional WWTPs.

For high COD concentration wastewater such as high concentration organic industrial wastewater and landfill leachate, energy consumption, COD removal energy consumption and operation cost are lower than those of conventional WWTPs. Thus, MBR is preferred when treating high concentration organic wastewater or landfill leachate.

Given that energy demand contributes significantly to the running cost of an MBR system, it is important to optimize the process energy consumption to make the technology more competitive. The high energy consumption of MBR plants is due to membrane fouling and clogging and high DO concentrations for a large amount of biomass. Energy cost of aeration plays a key role in the total energy consumption in MBR processes. Optimization of aeration is consequently believed as the most effective way to cut down energy requirement and eventually lower operating cost. Energy consumption was reduced in China by elevating the aeration efficiency for membrane scouring by bettering the configuration of membrane module, aeration system, and tank geometry. Much of the MBR plants development over the past 12 years has focused on maximizing the mixing imparted by membrane air scouring while minimizing the amount of air required for this, resulting in significant improvements in energy efficiency. According to some surveys, the energy consumption could be as low as 0.5 kWh/m² for large MBR plants. Table 9 lists the specific electrical consumption of integrated/submerged-MBR. It indicates that the specific electrical consumption of integrated/submerged-MBR ranges from 0.31 to 0.70 kWh·m⁻³, and a little higher than that of average electrical consumption of CAS (0.34–0.38 kWh·m⁻³) in China.

Membrane fouling is a critical operation issue as it impacts membrane lifespan and energy consumption. Membrane fouling could be reduced in these major ways: gas sparging, sustainable flux operation,

Table 7
Representative underground MBR applications (Chen et al., 2016; Jia et al., 2016).

| MBR applications                         | Capacity (m³/d) | Commission year | Location       |
|-----------------------------------------|-----------------|-----------------|----------------|
| Binhu Tangxi River WWTP                 | 30,000          | 2008            | Hefei, Anhui   |
| Tiantang River WWTP (phase 1)           | 40,000          | 2009            | Beijing        |
| Jingxian WWTP                           | 100,000         | 2010            | Guangzhou, Guangdong |
| Bujj WWTP                               | 200,000         | 2011            | Shenzhen, Guangdong |
| Jingang WWTP                            | 50,000          | 2012            | Zhangjiagang, Jiangsu |
| Kunming No. 10 WWPT                     | 150,000         | 2013            | Kunming, Yunnan |
| Gu County WWTP (phase 2)                | 60,000          | 2013            | Yantai, Shandong |
| Kunming No. 9 WWTP                      | 100,000         | 2014            | Kunming, Yunnan |
| Taosi Bay WWTP (phase 2)                | 150,000         | 2014            | Yantai, Shandong |
| Qindao Hi-Tech Zone WWTP                | 180,000         | 2014            | Qingdao, Shandong |
| Zhengding Baw District WWTP             | 100,000         | 2015            | Shijiazhuang, Hebei |
| Huaiyang WR | 600,000         | 2016            | Beijing        |

Table 8
Energy consumption and operation cost of MBR and conventional WWT (Xiao et al., 2014; Wang and Fan, 2012).

|                     | Hospital wastewater | Municipal wastewater | High concentration organic wastewater | Landfill leachate |
|---------------------|---------------------|----------------------|---------------------------------------|------------------|
| MBR                 | Energy consumption (kWh·m⁻³) | 0.58–0.95 | 0.45–0.91 | 0.68–1.87 | 2.00–11.28 |
|                     | COD removal energy consumption (kWh/kg COD) | 1.40–4.17 | 1.40–2.76 | 0.24–0.76 | 0.34–0.98 |
| Operation cost (RMB/m³) | 0.91 | 0.5–0.9 | 1.88 | 8.42 |
| Conventional process | Energy consumption (kWh·m⁻³) | 0.24–0.37 | 0.46–1.80 | 3.65–17.05 |
|                     | COD removal energy consumption (kWh/kg COD) | 1.01–1.54 | 0.32–1.8 | 0.42–2.12 |
| Operation cost (RMB/m³) | 0.62 | 2.97 | 15.83 |
Appendix A. Related public policy on membrane industry

| Year adopted | Title | Agency | Main policies |
|--------------|-------|--------|---------------|
| 2017         | Water Conservation Society Construction Plan for 13th Five-Year Period | National Development and Reform Commission, Ministry of Water Resources, Ministry of Housing and Urban Construction | Incentivize technology development for water conservation, wastewater treatment and reuse, rainwater collection, reclaimed water. Promote advanced treatment and reuse of wastewater with membrane technology in power generation and textile industries. By 2020, all counties and major townships in China shall be able to collect and treat sewage. The sewage treatment rate of counties and cities should reach 85% and 95%, respectively. Promote utilization rate of reclaimed water in water-deficient cities and in the Beijing-Tianjin-Hebei region reach 20% and 30%, respectively. Promote the development of high-strength, anti-pollution MBR membrane materials, large-scale membrane manufacturing technology, and large-scale MBR devices. Promote membrane technology as one of the key technologies of the top ten environmental protection industries. Promote research and development on high-performance membrane materials and membrane modules, aiming to reduce costs, increase membrane flux, extend membrane material life, and improve pollution resistance. Identify MBR technology and equipment as the focus of research. |
| 2015         | Water Pollution Prevention and Control Plan | State Council of the People's Republic of China. | |
| 2012         | 12th Five-Year Plan of High Performance Membrane Material and Technology Development | Ministry of Science and Technology | |
| 2012         | 12th Five-Year Plan of Energy Conservation and Environmental Industry | State Council of the People's Republic of China | |
| 2012         | 12th Five-Year Plan of Constructing Urban Sewage Treatment and Reuse Facilities | State Council of the People's Republic of China | |
| 2012         | 12th Five-Year Plan of New Material Industry Development | Ministry of Industry and Information Technology | |

6. Conclusions

The study summarizes the development history of MBR applications in China and the associated driving forces which resulted in the rapid growth of MBR applications in the last two decades. The following conclusions are reached.

The SARS event increased demand on hospital wastewater treatment and the technical advantages of MBR made MBR an ideal technology to treat hospital wastewater in China. The need of petrochemical industry in mid-2000s promoted MBR applications and increased the scale to thousands m³/d. Olympic Games in 2008 and Asian Games in 2010 took place when MBR applications needed further stimulation and the MBR application scale expanded to 10 thousand m³/d.

Public policy of water resources and environment and membrane industry promoted MBR applications continuously. The other driving forces are water environment and water resources stresses that China has been facing for a long time. Water stresses promoted MBR applications to a much larger scale (100 thousand m³/d) and to broader geographic regions.

The future driving forces for MBR applications include declining capital investment and decreasing operation cost as well as water environment and water resources stresses. It should be noted that government policy on MBR technology, water and environment has significant impact of MBR applications in the future as well.

The comprehensive understanding of the driving forces of MBR applications is not only valuable for reflecting the past but also for looking forward to the future as it provides insights on how MBR applications may be promoted in the future.

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(continued on next page)
modules (i.e. roll membranes, curtain membranes, tubular membranes, and flat membranes) and membrane equipment for seawater desalination and water treatment purposes.

Promote research of high-performance membrane material technology, develop water treatment membrane materials, and promote the application of membrane technology in water treatment, steel, petrochemical and environmental protection.

Appendix B. MBR applications with a capacity of 50 thousand m$^3$/d or more in China

| MBR applications             | Capacity (m$^3$/d) | Commission year | MBR supplier     | Wastewater type | Location          |
|------------------------------|-------------------|-----------------|------------------|-----------------|------------------|
| Beixiacheng WWTP (phase I)   | 60,000            | 2007            | Memcor           | Municipal       | Beijing          |
| Wenyu River WWTP             | 100,000           | 2008            | Asahi Kasei      | Surface water   | Beijing          |
| Shiyi Shending River WWTP    | 110,000           | 2009            | Mitsubishi Rayon | Municipal       | Hebei            |
| Kunming No. 4 WWTP           | 60,000            | 2010            | Origin Water     | Municipal       | Yunnan           |
| Taiying WWTP                 | 60,000            | 2010            | Memstar          | Municipal       | Jiangsu          |
| Wuxi Chengbei WWTP (phase IV)| 50,000            | 2010            | Origin Water     | Municipal       | Jiangsu          |
| Guangzhou Jinjiangi WWTP     | 100,000           | 2010            | Memstar          | Municipal       | Guangdong        |
| Shijiazhuang Hi-tech Ind. Development Zone WWTP | 80,000 | 2011 | Origin Water     | Municipal       | Hebei            |
| Daqing Dongcheng District WWTP | 50,000           | 2011            | Asahi Kasei      | Municipal       | Heilongjiang     |
| Wenyu River Water treatment Plant (phase II) | 100,000 | 2012 | Memstar          | Municipal       | Liaoning         |
| Liaoyang Central District WWTP (phase II) | 200,000 | 2012 | Memstar          | Municipal       | Yunnan           |
| Qinghe WWTP (phase III)      | 150,000           | 2012            | Origin Water     | Municipal       | Beijing          |
| Kunming Luolonghe Rainwater Treatment Plant | 50,000 | 2012 | Origin Water     | Municipal       | Yunnan           |
| Liaoyang Central District WWTP (upgrade) | 80,000 | 2012 | Memstar          | Municipal       | Liaoning         |
| Dongting WWTP                | 60,000            | 2012            | Origin Water     | Municipal       | Jiangsu          |
| Wuxi Meicun WWTP (phase IV)  | 50,000            | 2012            | Origin Water     | Municipal       | Jiangsu          |
| Fengtai Hexi WRP             | 50,000            | 2013            | Origin Water     | Municipal       | Beijing          |
| Daxing Huangcun WRP          | 120,000           | 2013            | Origin Water     | Municipal       | Beijing          |
| Nanjing Chengdong WWTP (phase III) | 150,000          | 2013            | Origin Water     | Municipal       | Jiangsu          |
| Kunming No. 10 WWTP          | 150,000           | 2013            | Origin Water     | Municipal       | Yunnan           |
| Kunming No. 9 WWTP           | 100,000           | 2013            | Origin Water     | Municipal       | Yunnan           |
| Baotou nine raw WWTP         | 50,000            | 2014            | Scinor Membrane  | Municipal       | Inner Mongolia   |
| Huaier WRP (phase III)       | 60,000            | 2014            | Origin Water     | Municipal       | Beijing          |
| Zhuzhou Longquan WWTP (phase III) | 100,000          | 2014            | Tianjin Motimo   | Municipal       | Hunan            |
| Macao WWTP                   | 150,000           | 2014            | Zenon            | Municipal       | Macao            |
| Liaoyang WWTP                | 80,000            | 2014            | Menstar          | Municipal       | Liaoning         |
| Daxing Lake WRP              | 80,000            | 2014            | Origin Water     | Municipal       | Beijing          |
| Yantai Taizhwan WWTP         | 150,000           | 2014            | Origin Water     | Municipal       | Shandong         |
| Jilin WWTP (phase II)        | 150,000           | 2014            | Origin Water     | Municipal       | Jilin            |
| Changsha Xianghu WWTP        | 140,000           | 2014            | Origin Water     | Municipal       | Hunan            |
| Urumqi Gangquanba WRP        | 105,000           | 2014            | Origin Water     | Municipal       | Urumqi           |
| Zhengding WWTP               | 100,000           | 2014            | Origin Water     | Municipal       | Hebei            |
| Fuzhou Yangli WWTP (phase IV)| 200,000           | 2015            | Menstar          | Municipal       | Fujian           |
| Wuhan Sanjinian WWTP         | 200,000           | 2015            | Origin Water     | Municipal       | Hebei            |
| Jilin WWTP (phase I)         | 150,000           | 2015            | Origin Water     | Municipal       | Jilin            |
| Nanjing Xianlin WWTP         | 100,000           | 2015            | Origin Water     | Municipal       | Jiangsu          |
| Beiyuan WRP                  | 80,000            | 2015            | Origin Water     | Municipal       | Beijing          |
| Dali WWTP (phase II)         | 75,000            | 2015            | Origin Water     | Municipal       | Yunnan           |
| Zhuhai Gongbei WWTP (phase II) | 70,000            | 2015            | Origin Water     | Municipal       | Guangdong        |
| Hohhot Balingyiing WWTP      | 70,000            | 2015            | Origin Water     | Municipal       | Inner Mongolia   |
| Jinyang WWTP (phase I)       | 120,000           | 2015            | Origin Water     | Municipal       | Sharii           |
| Lintong District Green Source Municipal WWTP | 50,000 | 2016 | Tianjin Motimo   | Municipal       | Shanxi           |
| Qinhuangdiao Jia River WWTP  | 70,000            | 2016            | Origin Water     | Municipal       | Hebei            |
| Miyun New Town WWTP          | 65,000            | 2016            | Origin Water     | Municipal       | Beijing          |
| Beijing Huafang WRP          | 600,000           | 2016            | Menstar          | Municipal       | Beijing          |
| Chengdu No. 2 WWTP           | 200,000           | 2016            | Menstar          | Municipal       | Sichuan          |
| Chengdu No. 4 WWTP           | 150,000           | 2016            | Menstar          | Municipal       | Sichuan          |
| Chengdu No. 5 WWTP           | 200,000           | 2016            | Menstar          | Municipal       | Sichuan          |
| Chengdu No. 8 WWTP           | 200,000           | 2016            | Menstar          | Municipal       | Sichuan          |
| Xi’an Caotan WWTP            | 200,000           | 2016            | Origin Water     | Municipal       | Shanxi           |
| Zhuhai Qianjian WWTP         | 100,000           | 2016            | Origin Water     | Municipal       | Guangdong        |
| Shunyi WWTP                  | 180,000           | 2016            | Zenon            | Municipal       | Beijing          |
| Zhangzhou Dong Dun WWTP (phase I) | 130,000          | 2016            | Origin Water     | Municipal       | Fujian           |
| Jiaxing Lianhe WWTP          | 160,000           | 2017            | Menstar          | Municipal       | Zhejiang         |
| Shenzhen Luofang WWTP        | 400,000           | 2017            | Zenon            | Municipal       | Shenzhen         |
| Macao WWTP (upgrade)         | 200,000           | 2017            | Zenon            | Municipal       | Macao            |
| Fuqing Rong yuan WWTP        | 120,000           | 2017            | Menstar          | Municipal       | Fujian           |
| Puzhen WWTP (phase I)        | 100,000           | 2017            | Origin Water     | Municipal       | Shanxi           |
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