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Applications of membrane technology in treating wastewater from the dyeing industry in China: current status and prospect

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ABSTRACT

The membrane technology has become one of the promising techniques to promote cleaner production and emission reduction in the printing and dyeing industry. It is important to understand the current situation and prospect of membrane technology applications to treat wastewater from the dyeing industry, which provides comprehensive overview of wastewater treatment by the technology in the industry. The research history of the membrane technology applications in the dyeing industry was investigated by literature metrology with National Knowledge Infrastructure (CNKI) and Web of Science™ (SCI). A national survey was conducted to collect information of current applications and prospect, complemented by literature investigations. Results showed that: (1) the membrane technology was initially applied in recycling dyes and gradually was spread to treat and reuse wastewater. Three development stages of the research history are identified: pre-1998 (slow development), 1998–2008 (rapid growth), and 2009 to present (steady development). (2) China is leading in publishing SCI papers in related filed. The top domestic institutes include Donghua University, South China University of Technology, Dalian University of Technology, Zhejiang University, Zhejiang University of Technology, and Tianjin University. (3) By 2015, the total capacity of the membrane technology in dyeing wastewater treatment in China was about 662,000 $m^3 \cdot d^{-1}$ and the number of applications was 128 (with capacity ≥500 $m^3 \cdot d^{-1}$). Geographical distribution is also analyzed and most applications are located in Zhejiang, Jiangsu, Guangdong, Fujian, and Shandong. (4) "Ultrafiltration (UF) + 'reverse osmosis' (RO)" was the most widely applied process of membrane technologies in dyeing wastewater treatment, the "membrane bioreactor (MBR) + RO" and "Continuous Membrane Filtration (CMF) + RO" were closely behind. The operational cost of membrane technology applications is relatively higher than that of conventional technology applications in the dyeing industry. However, the membrane technology treats wastewater more effectively and efficiently, and thus could provide reclaimed water for reuse. It is a promising and important technology in dyeing wastewater treatment and reuse in near future because of environmental stress, strict water management, increasing water price, decreasing membrane cost, and increasing life span of membranes.

Keywords: Membrane technology; Wastewater; China; Driving forces; Dyeing industry

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1. Introduction

According to the China Dyeing and Printing Association (CDPA), the production of dyeing cloth increased rapidly after 2001 and peaked in 2010 (Fig. 1). The dyeing industry is concentrated toward the five eastern coastal provinces (Zhejiang, Jiangsu, Guangdong, Fujian, and Shandong). More than 60% of the national production of dyeing clothing is located in Zhejiang and 41% of the national production is in one city, Shaoxing, Zhejiang [1]. The increasing clustering of the dyeing industry in the coastal provinces resulted in increasing pollutant discharges and mounting regional environmental stress. About 21.5 million tons of wastewater per year was discharged by the textile industry in China, which made it one of the largest industrial wastewater sources, accounting 10.2% of the total industrial wastewater discharge [2]. Dyeing and finishing, important procedures for textile product upgrades, generate about 80% of the textile industry wastewater. In addition, wastewater from the dyeing industry has serious pollution risk because of high chromaticity, non-biodegradable ability, and toxicity [3,4].

Furthermore, the dyeing industry has been facing energy and environmental challenges after the new national standard “GB 4287-2012” [5] and many local industry standards were published during the Twelfth Five-Year Plan of China (from 2011 to 2015). The industry is also confronted with: (1) the stress on energy conservation and emission reduction; (2) the elimination of outdated industrial capacity; and (3) the new Environmental Protection Act. To reduce water usage and decrease wastewater discharge is thus increasingly important for the dyeing industry’s survival and development.

Most enterprises in the dyeing industry are of the small to medium scales, facing intensive market competition and dwindling profits and clustered in coastal provinces where water resources and environment stress is intensive. In addition, the Ministry of Industry and Information Technology (MIIT) of China started to regulate the dyeing industry using the Dyeing Industry Access Standard (DIAS) in 2010. The standard setup stringent criteria for new enterprises in the dyeing industry, limiting access to regions with high water resources or environment stress and requiring all new enterprises constructed in industry parks in water rich regions. Water resources in inland China are not as rich as coastal provinces and thus the relocation of the dyeing industry from coastal China is not an optimal option. The increasing percentage of production capacity in the dyeing industry in the coastal provinces confirmed the relocation of the dyeing industry has not occurred. Besides, the regulation of zero liquid discharge (ZLD) for all industries was encouraged by the government. Therefore, the only solution to the dyeing industry is to upgrade technology and treat wastewater to minimize water use and wastewater effluent.

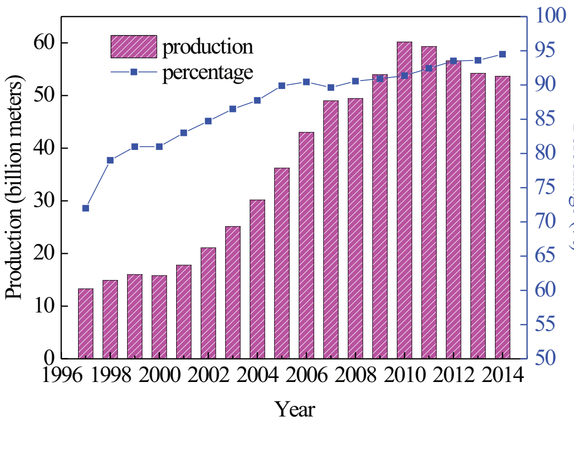

Fig. 1. The total production of dyeing cloth in China and the ratio of the production of dyeing cloth in the five eastern coastal provinces to the total dyeing cloth production in China (from 1997 to 2014).

The current approaches for treating dyeing wastewater include physical methods (coagulation–flocculation, adsorption, and membrane filtration), oxidation methods (advanced oxidation and chemical oxidation) and biological methods (aerobic, anaerobic, or combination thereof) [6,7]. Coagulation–flocculation is low efficient to remove reactive dyes. In addition, the coagulation–flocculation generates large amount of sludge, which limits its applications [8]. Adsorption is another widely used and efficient technology for dyes removal. Both adsorption and coagulation–flocculation transfer dyes to another phase. Difficult regeneration of the adsorbent also limits the application of adsorption processing [9]. The oxidation methods, including direct chemical oxidation and advanced oxidation processes, can degrade and mineralize dyes, while many applications are of laboratory scales [6,10]. The biological methods are widely used in China and abroad because of its benefits such as eco-friendly and cost competitive [6]. However, the effluent often need additional advanced treatments before it could be reclaimed [7]. These conventional approaches (coagulation–flocculation, adsorption, oxidation method, and biological method) mainly are aimed to degrade or remove dyes, without consideration of recovering dyes and salt from wastewater [8,9].

The membrane technology is an attractive and competitive method for treating wastewater from the dyeing industry, due to small footprint, simple operation, and high efficiency, which is extremely valuable to address the energy, resource, and environment challenges faced by the industry. It also has been successfully and widely applied to treat municipal wastewater, bathing wastewater, restaurant wastewater, landfill leachate, hospital wastewater, petrochemical wastewater, etc. [11,12]. The membrane technology is critical for the dyeing industry to conserve water resources, minimize wastewater effluent, and recycle specific contaminants in effluents [13]. Hence, the membrane technology was applied in dyeing wastewater 40 years ago in the USA [14]. Nowadays, the membrane technologies, such as reverse osmosis (RO), nanofiltration (NF) membrane, membrane distillation (MD), etc. are the most important ZLD technologies applied in dyeing wastewater in many countries [13,15].

However, the status of membrane technology research and applications in the dyeing industry in China has not been comprehensively investigated. Previous studies have often been focused on engineering processes [16–20], membrane materials [21,22], and technoeconomic analysis [13] of the membrane technology. With the mounting resources and environment pressure in China, it is essential to examine the overall status of membrane technology research and applications in the dyeing industry to better understand of its role and prospect in treating wastewater and conserving resources.

In the present study, the membrane technology research and its applications in treating wastewater from the dyeing industry in China was investigated. The research history of membrane technology on treating wastewater from the dyeing industry was analyzed via literature metrology using sources of National Knowledge Infrastructure (CNKI) and Web of Science™ (SCI). A national survey on wastewater treatment plants in the dyeing industry was conducted to explore the status of the membrane technology applications in treating wastewater from the dyeing industry. Based on the results of the national survey, the geographic distribution, technological processes, and driving forces were examined to provide scientific base for wastewater treatment and resources conservation using the membrane technology in the dyeing industry.

2. Methodology

The literature metrology analysis and the national survey on the membrane technology applications to treat wastewater from the dyeing industry are described as follows.

The research history of the membrane technology in treating wastewater from the dyeing industry was examined by literature metrology analysis with CNKI and SCI. The used keywords include membrane technology (including all types of membrane technologies such as ultrafiltration [UF], microfiltration [MF], membrane bioreactor [MBR], RO, and NF, etc.), wastewater, and dyeing. The two databases were searched with data until the end of 2015. For literature in the SCI, only English publications were included to avoid the overlap with Chinese publications in the CNKI.

A national survey on wastewater treatment plants in the dyeing industry was conducted to explore the status of membrane technology application status. The data were supplemented with information gathered from 17 membrane manufacturers and engineering providers, such as Hangzhou Tianchuang Environmental Technology Co., Ltd., Zhejiang Kaichuang Environmental Technology Co., Ltd., Hangzhou Creflux Membrane Technology Co., Ltd., etc. Only the wastewater treatment plants with a designed capacity of at least 500 $m^3 \cdot d^{-1}$ that have been commissioned by the end of 2015, are included in the survey.

3. Membrane technology research

The papers published in SCI and CNKI showed very similar patterns from 1975 to 2015. The total number of papers published during the period for SCI and CNKI are 968 and 945, respectively. Three stages are identified based on the temporal pattern as shown in Fig. 2. The first stage is between 1975 and 1998, which demonstrated slow progress with annual papers of 10 or less, for SCI or CNKI. The earliest study published in SCI in this field was in Textile Institute and Industry in 1975 [23]. The first paper in CNKI was published in 1976 [24], which discussed the UF technology for recycling dyes by Shanghai No. 1 Dyeing Factory. In this stage, the researches were mainly focused on recycling dyes. The period between 1999 and 2008 is the second stage, which characterized a rapid increase in papers published in both SCI and CNKI. There were 278 and 312 papers in SCI and CNKI, respectively. The third stage is a steady progress period from 2009 to present. There were 651 and 563 papers published in SCI and CNKI, respectively, in this stage. About 67% of the total number of SCI papers of membrane technology applied in dyeing industry was published in this stage. For CNKI, about 60% of the total papers of the membrane technology applied in the dyeing industry were published in this stage. China has published the most papers in this field with 244 papers, accounting about 25% of the total SCI papers of membrane technology applied in the dyeing industry (Table 1). For CNKI papers, Donghua University (Shanghai) is the leader with 86 papers, followed by South China University of Technology (Guangdong, 32 papers), Dalian University of Technology (Liaoning, 32 papers), Zhejiang University (Zhejiang, 29 papers), Zhejiang University of Technology (Zhejiang, 26 papers), and Tianjin Polytechnic University (Tianjin, 23 papers).

The research on membrane technology applications in the dyeing industry grew rapidly since 1999, which is coincident with the rapid development of the dyeing industry in China. The advancement of membrane technology and the increasing demand of better treating wastewater from the dyeing industry stimulated the research on membrane technology applications in the dyeing industry. Most of the Chinese research institutions that have published in this field are located in the coastal provinces that provided the technology support and human resources support for the membrane applications in the dyeing industry.

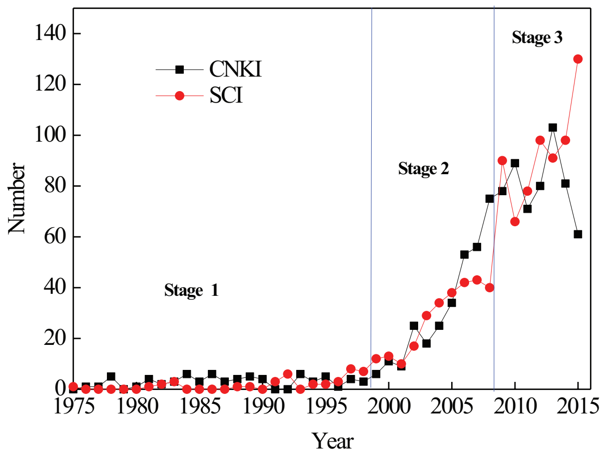

Fig. 2. The number of papers published in CNKI and SCI related to membrane technology in treating wastewater from the dyeing industry (1975–2015).

Table 1
The percentage of China SCI papers on membrane technology applied in the dyeing industry

Period	Global	China	Percentage
Pre-1998	40	4	10
1999–2008	278	39	14
2009–2015	650	201	32
1975–2015	968	244	25

4. Membrane technology applications

4.1. Application history in China

The development history is graphically shown in Figs. 3 and 4, which are derived from the national survey results. By the end of 2015, the total number of wastewater treatment plants using membrane technology to treat wastewater from the dyeing industry in China are 128 with total capacity of 662,000 $m^3·d^{-1}$. Before 2008, the applications of membrane technology increased very slowly. The applications of membrane technology increased much faster since 2009, with respect to both the capacity and numbers of treatment plants.

A history of representative applications of the membrane technology to treat wastewater from the dyeing industry is shown in Fig. 4. The membrane technology was mainly applied in recycling dyes before 1999 and was later applied in wastewater treatment and recycling. Shanghai No. 1 Dyeing Factory applied UF to recycle dyes from dyeing wastewater in 1976 [24], which was the first known application of the membrane technology in the dyeing industry in China. In 1984, Baoji Dyeing Factory applied polyamide UF membrane to recycle dyes from wastewater [25]. However, UF technology is efficient for recycling solid dyes but not water-soluble dyes. Gradually, applications of membrane technology were expanded to wastewater treatment. In 1999, Research Centre for Eco-Environmental Sciences and Tsinghua University applied the pilot scale of separate MBR and submerged MBR to treat wool-spinning wastewater, which were the earliest attempts of MBR applied in wastewater treatment in the dyeing industry [26,27]. In 2001, the first large scale membrane technology applied in dyeing wastewater, the Ordos Cashmere Group Corporation, applied continuous membrane filtration (CMF) and RO to treat 1,500 $m^3·d^{-1}$ printing and dyeing wastewater, and the water recovery rate was 70% [28]. In 2008, the Jiangsu Shenghong Group Corporation applied UF and RO to treat and reuse about 12,000 $m^3·d^{-1}$ dyeing wastewater, which was the largest membrane technology application in dyeing wastewater in China at that time [29,30].

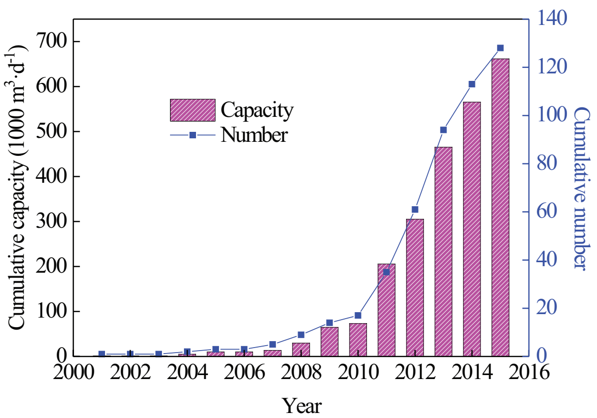

Fig. 3. Cumulative capacity and numbers of membrane technology for treating wastewater from the dyeing industry in China (≥500 $m^3·d^{-1}$).

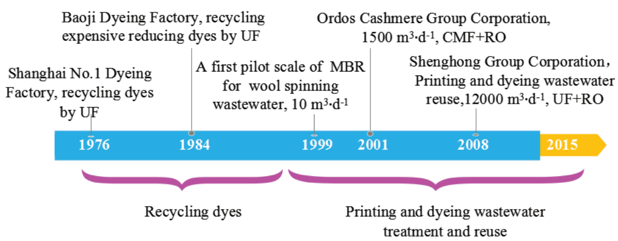

Fig. 4. The history of membrane technology applications to treat wastewater from the dyeing industry in China.

5. Current status of membrane technology applications

5.1. Geographic distribution

The production of dyeing cloth showed a clear geographic pattern. According to CDPA, there were 1,891 dyeing and printing enterprises in 2013 with main business revenue of 20 million Renminbi (RMB) or more. The dyeing and printing enterprises were mainly concentrated in the five eastern coastal provinces including Zhejiang, Jiangsu, Fujian, Guangdong, and Shandong. In 2014, the dyeing cloth productions in these five provinces accounted for 94.5% of the national total production (53.7 billion meters). Zhejiang was the largest producer, which produced 32.4 billion meters, accounting 60.4% of the national total [31]. Accordingly, the geographic distribution of the membrane technology applications in the dyeing industry shows the same pattern. By 2015, the total capacity of the membrane technology in dyeing wastewater treatment was >662,000 $m^3·d^{-1}$ and the number of applications were 128. The geographic distribution of the membrane technology applications is shown in Fig. 5, with the five eastern coastal provinces accounting for the majority of the applications.

Most of the membrane technology applications are clustered in the five eastern coastal provinces due to the following reasons. Over 90% of the dyeing enterprises are located in these five provinces. Furthermore, these five provinces are confronted with serious water resources and environment challenges. For example, Zhejiang and Jiangsu quantitatively

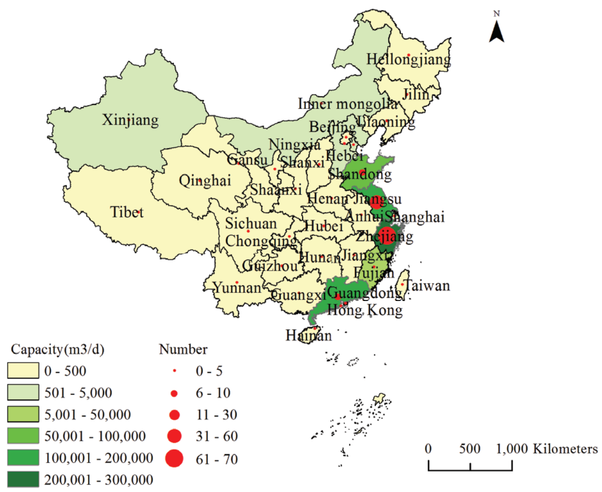

Fig. 5. The geographic distribution of the membrane technology applications in dyeing wastewater in China.

have enough water but the poor water quality caused water shortage in the provinces. Guangdong has similar water issues due to poor water quality. On the other hand, Shandong has a severe water shortage issue due to the huge water demand and low water availability.

5.2. Technology processes

Based on the results of the national survey, the commonly used technology processes in membrane technology applications include NF, UF, MBR, CMF + RO, UF + RO, and MBR + RO. The distribution of treatment capacity and the number of applications of various technology processes are graphically shown in Fig. 6. From the perspectives of both the treatment capacity and the number of applications, the process of "UF + RO" is the most applied membrane technology in dyeing wastewater treatment, accounting 51.9% of total treatment capacity and 56.5% of the total number of applications. "MBR + RO" is the secondly commonly used process with 27.5% of total treatment capacity and 17.6% of total application number.

Interestingly, RO is >80% (both capacity and application number) of membrane technology applications. RO has to be used with some pretreatment process, including UF, MRB, and CMF. UF is one of the effective pretreatment technologies

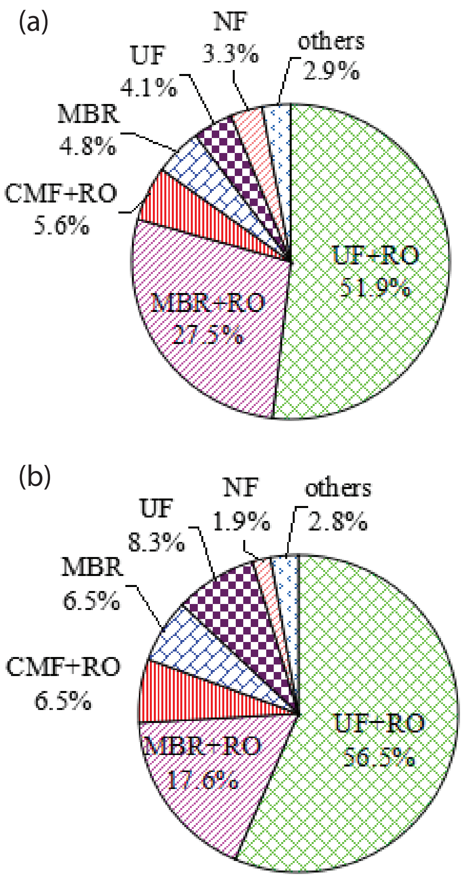

Fig. 6. The technology processes used in the membrane technology applications in dyeing wastewater (a) the percentage of the treatment capacity, (b) the percentage of the application number.

for RO membrane [32]. MBR uses less space by saving air flotation and sand leach devices. CMF is external pressure type UF/MF membrane for NF/RO pretreatment. RO has become the dominant technologic process in the membrane technology applications, due to water reuse incentive and water quality standards. The water use by the dyeing industry was 4 ton per 100 m cloth before 2005 and was cut down to 2.5 ton per 100 m cloth in the period of the Eleventh Five-Year Plan [33]. The water reuse rate increased from 7% to 15% in the same period and it was further increased to 30% by the end of the Twelfth Five-Year Plan period [33]. The industry is facing mounting pressure to increase reuse rate in the future. In addition, the dyeing industry needs higher water quality as it is moving to manufacture better and higher quality products. RO is the technology that could increase the quality of effluent so that it could be recycled and reused by the industry.

6. Driving force analysis

6.1. Environmental pressures

From the wastewater discharge perspective, the standards in China are increasingly stringent. In the standard GB4287-1992 published in 1992 [34], the chemical oxygen demand (COD) discharge standards for Grade I, II, and III are 180, 240, and 500 mg·L^{-1}, respectively. When the standard of GB4287-2012 was revised in 2012 [5], the COD discharge standards are 100 mg·L^{-1} for existing discharges, 80 mg·L^{-1} for new discharges, and 60 mg·L^{-1} for environmental sensitive areas. Some coastal provinces even adopt standards that are stricter than the national standards. For example, the COD discharge standard in Jiangsu province is 60 mg·L^{-1} [35]. The COD discharge standard from the dyeing industry in China is often higher than that used in developed countries including the USA and Germany [36]. From water resources availability perspective, the dyeing industry is also facing mounting pressure due to newer standards. In 2010, the MIIT of China started to regulate the dyeing industry by using the DIAS. The standard setup stringent criteria for new enterprises in the dyeing industry, limiting access to regions with high water resources or environment stress and requiring all new enterprises constructed in industry parks in water rich regions. The standard GB/T 18916.4-2012 sets limit of 2 tons per 100 m cloth on water usage for the dyeing industry. To address both the water environmental and water resources stress, the dyeing industry has no option but to better treat wastewater and reuse it.

6.2. The demand of water reuse

The "Outline of Chinese Water-saving Technology Policy" [37] published in 2005 was proposed to promote water reuse and ZLD technologies in industrial wastewater. In 2015, "Water Pollution Control Action Plan" was adopted to improve low liquid discharge technologies in the dyeing industry [38]. To materialize ZLD, improving water use efficiency is critical. High quality water is needed for reusing in rinse or dyeing processes while other purposes such as floor cleaning, toilet flushing, irrigation, or car washing do not require high quality water. Table 2 shows the water quality requirement of different purposes of reusing dyeing wastewater. The most strict water quality was for dyeing processing.

Table 2
The water quality index of different reusing ways of dyeing wastewater [39–43]

Indicators	Rinse processing	Dyeing processing	Toilet flushing	Green irrigation or car washing	Industrial cooling water	Boiler feedwater
pH	6.0–9.0	6.5–8.5	6.0–9.0	6.0–9.0	6.5–8–5	6.5–8.5
SS	≤30	≤10	≤10	≤5	≤30	–
COD_{Cr} ($mg·L^{-1}$)	≤50	–	50	50	≤60	≤60
Chromaticity	≤25[a]	≤10[a]	30[b]	30[b]	≤30[b]	≤30[b]
Fe ($mg·L^{-1}$)	0.2–0.3	≤0.1	0.4	0.4	≤0.3	≤0.3
Mn ($mg·L^{-1}$)	≤0.2	≤0.1	0.1	0.1	≤0.1	≤0.1
Water hardness (calculated as $CaCO_3$) ($mg·L^{-1}$)	450	[c]	≤450	≤450	≤450	≤450
Conductivity/($\mu s·cm^{-1}$)	≤1,500	–	–	–	–	–
Turbidity (NTU)	≤30.5	≤30.5	≤5	≤10	≤5	≤5

[a]Dilution multiple method (DMM).
[b]Platinum–cobalt method (PCM).
[c]When water hardness is <150 $mg·L^{-1}$, all the water can be used in dyeing processing, when it is between 150 and 325 $mg·L^{-1}$, most of them can be used, but soluble dyes should use below 17.5 $mg·L^{-1}$, and it must be not >150 $mg·L^{-1}$ when reused for soaping and lye. The cooling water for ejector condenser often used below 17.5 $mg·L^{-1}$.

Table 3
The water quality of influent and effluent from different processing phases

	COD_{Cr} ($mg·L^{-1}$)	Suspended solids (SS) ($mg·L^{-1}$)	Chromaticity (DMM)	pH	Conductivity ($\mu s·cm^{-1}$)
Dyeing wastewater	900	400	650	7–9	500
Secondary effluent	70	50	20	6–9	830
UF effluent	45	0	0	6–9	830
RO effluent	<10	0	0	5–7	<50

Ren [44] studied "hydrolysis + contact oxidation + UF + RO" process in dyeing wastewater treatment of a dyeing and printing enterprise in Zhejiang, with the design capacity of 3,000 $m^3·d^{-1}$ and design reuse water capacity of 2,000 $m^3·d^{-1}$. The quality of primary effluent is shown in Table 3. The secondary effluent can meet the standard GB4287-1992, but cannot meet the reusing water quality requirement. When the effluent is treated with RO technology, the water could be reused in rinse and dyeing processing. The biochemistry combined with membrane technologies is a typical process to treat the dyeing wastewater [45]. Conventional biochemical treatment process can degrade the organic matter, suspended solids (SS), and chromaticity but the effluent can only reach the wastewater discharge standard. The secondary effluent is not suitable for reuse. The membrane technology is an excellent option to treat wastewater from the dyeing industry to reduce wastewater discharge and increase water reuse rate [45].

6.3. Economic analysis of typical cases

However, the cost of the membrane technology applications has to be taken into account when it is considered as a potential wastewater treatment technology for the dyeing industry. Table 4 shows six membrane and conventional technology applications of dyeing wastewater treatment. The six applications include four membrane technology applications (Nantong Dyeing Factory, Shaoxing Dyeing Factory, Foshan Datang Textile Printing and Dyeing Industrial Park, and Guangdong Yida Textile Co., Ltd.) and two conventional technology applications (Ningbo Shenzhou Knitting Co., Ltd. and a printing and dyeing enterprises in Ningbo). These six cases are referred to as cases 1–6, respectively.

In case 1, Jiangsu Jiuwu Hi-Tech Co., Ltd., ceramic UF membrane was used to pretreat wastewater. Though the total operating cost was 6.4 $RMB·m^{-3}$, much higher than the local industrial water price, the factory reused water and alkali from the wastewater, which could save cost and decrease COD discharge. The net benefit was estimated as 18 RMB per ton of wastewater, and thus it was economically feasible and eco-friendly. Cases 2–6 have the total operating cost less than the corresponding local industrial water price. The cases 2, 3, and 4 applied "UF + RO" as their advanced treatment. The influent of case 2 was light color rinsing wastewater, the operational cost was 1.06 $RMB·m^{-3}$. The membrane application allowed case 2 save 4.6 million RMB of annual water cost and reduce 85 tons of annual COD discharge, which provided both economic and environmental benefits. The cases 3 and 4 used similar technology process but had different capacities and their influent water was the secondary biochemical effluent, so the total operation cost did not include the cost of secondary biochemical processing. Their total operational costs were very close, 1.8 and 1.76 $RMB·m^{-3}$, respectively. The cost of membrane system of case 3 was 1.2 $RMB·m^{-3}$, including the cost of membrane

Table 4
Cost analysis of six membrane technology and conventional technology applications in dyeing wastewater treatment [47–51]

Cases	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
	Nantong Dyeing Factory	Shaoxing Dyeing Factory	Guangdong Foshan Datang Textile Printing and Dyeing Industrial Park (I)	Guangdong Yida Textile Co., Ltd.	Ningbo Shenzhou Knitting Co., Ltd.	A printing and dyeing enterprises in Ningbo
Treatment capacity ($m^3 \cdot d^{-1}$)	500	3,600	30,000	5,000	15,000	2,400
Commissioned time ($m^3 \cdot d^{-1}$)	2014	2009	2012	2012	2004	2007
Purpose	Recycling alkali and water	Water reuse	Reuse water 20,000 $m^3 \cdot d^{-1}$ for boiler water	Product water 3,500 $m^3 \cdot d^{-1}$ for dyeing processing	Water reuse	Water reuse
Influent	Desizing wastewater	Light color rinsing wastewater	Second biochemical effluent	Secondary biochemical effluent	Less polluted dyeing wastewater	Less polluted dyeing wastewater
Technological process	Ceramic UF	Flocculation precipitation + multimedia filter + UF + RO	Ozone + UF + RO	Ozone BAF + UF + RO	Biological contact oxidation + activated carbon	Multilevel filter + ion exchange
Pretreatment operation cost ($RMB \cdot m^{-3}$)			0.6	0.45		
Membrane operation cost ($RMB \cdot m^{-3}$)			1.2	1.31		
Total operational cost ($RMB \cdot m^{-3}$)	6.4	1.06	1.8	1.76	1.00–1.20 (2009)	1.54
The local industrial water price ($RMB \cdot m^{-3}$)	3 (2014)	4.1 (2009), 6.2 (2015)	4 (2012)	4 (2012)	3.5 (2009), 6.75 (2015)	5.1 (2004), 6.75 (2015)

replacement and electric cost. The UF and RO membrane replacement were membrane made in China, so the cost of membrane replacement was about 0.35 $RMB \cdot m^{-3}$ of case 3. The electric cost was 0.5 $RMB \cdot m^{-3}$ in membrane system because the electricity charge was 0.6 $RMB \cdot kWh^{-1}$ in Foshan Datang Industrial Park. In addition, the temperature of RO effluent was about 15°C higher than river water, which saves 3 $RMB \cdot m^{-3}$ when it was reused for boiler feedwater. The RO effluent of case 4 was reused for dyeing processing. The cost of advance treatment was lower than the local water price and can save 2.24 $RMB \cdot m^{-3}$ of the cost of production. The cases 5 and 6 used conventional treatment technologies for dyeing wastewater reuse. Their influent was less polluted wastewater that was similar to case 2. The effluent of case 5 was mixed with freshwater then reused for dyeing processing and the operational cost was 1.0–1.2 $RMB \cdot m^{-3}$. The operational cost excluding labor cost was 1.54 $RMB \cdot m^{-3}$ for case 6.

The operational cost of membrane technology applications is relatively higher than that of conventional technology applications in the dyeing industry, but it is comparable with local industrial water price as the dyeing industry is often located in developed coastal provinces. Local industrial water price are usually 3–7 RMB per ton water and the water softening cost is about 2.1 RMB per ton water [46]. The cost of water in dyeing processing is between 5 and 9 $RMB \cdot m^{-3}$ as it requests higher water quality. This cost is actually higher than the cost of treating wastewater with membrane technology. Both the industrial water price and wastewater discharge fee are expected to increase and thus reusing wastewater in the dyeing industry could save cost. The membrane technology has its advantage as the treated wastewater has better quality and could be reused. Therefore, the membrane technology applications are economically feasible to treat wastewater from the dyeing industry.

7. Typical cases

This section presents two typical cases of "UF + RO" applications, which were the typical and widely used membrane technology in dyeing wastewater in China. The influent information of cases A and B is shown in Table 5. Case A is Toray Sakai Weaving and Dyeing Co., Ltd. (TSD) in Nantong, Jiangsu province. There are three types of wastewater from

TSD, originating from refining processing, dyeing processing, and weaving machine. In case A, the secondary effluent from dyeing processing, the largest wastewater source of TSD, is the influent to the membrane system. Case B is the phase one of Foshan Datang Wastewater Treatment Plant (FDWTP), which is located in Foshan Datang Textile Printing and Dyeing Industrial Park. The wastewater of FDWTP is mainly from textile printing and dyeing enterprises in the industrial park. The designed treatment capacity of case B is about 30,000 $m^3 \cdot d^{-1}$ which is the half of the total designed capacity of FDWTP. About 20,000 $m^3 \cdot d^{-1}$ is reused for industrial purpose in phase one. The membrane system influent of case B is the secondary effluent from FDWTP. The wastewater treatment processes of cases A and B are shown in Fig. 7. The two cases both applied ozone oxidation technology as pretreatment of membrane processing to remove COD, iron, and manganese oxides and inhibit microorganism. The detailed parameters of UF and RO membrane are shown in Table 6. The RO membrane replacement of FDWTP was used BDX8040B that was made in Hangzhou Beidouxing Membrane Products Co., Ltd. (HBMP) [48,52].

It is critical to clean membrane to maintain normal operation and thus the cost of membrane cleaning has to be considered. The UF processing of case A was designed with chemical cleaning every 6 months. The RO membrane of case A was cleaned mainly with chemical agents, once every 1.5 months. The UF membrane cleaning of case B is backwashing every 20–30 min and chemical cleaning (acid and alkali) every 2 months. When the UF operating pressure reached 0.1–0.15 MPa, the FDWTP used >300 $mg \cdot L^{-1}$ sodium hypochlorite to realize sterilization. The RO membrane of case B was cleaned by alkali every 1–2 months.

The advanced treatment systems were successful and stable after operated for 1 year of case A and 2 years of case B.

Table 5
The basic information of influent before advanced treatment of cases A and B

	Operation time	Wastewater source	Water flow ($m^3 \cdot d^{-1}$)	COD ($mg \cdot L^{-1}$)	BOD ($mg \cdot L^{-1}$)	SS ($mg \cdot L^{-1}$)	Conductivity ($\mu s \cdot cm^{-1}$)	pH	Chromaticity (DMM)
Case A	2012	Secondary effluent	13,000	150–180					
Case B	2014	Secondary effluent	30,000	90	20	30	2,130	6–9	≤70

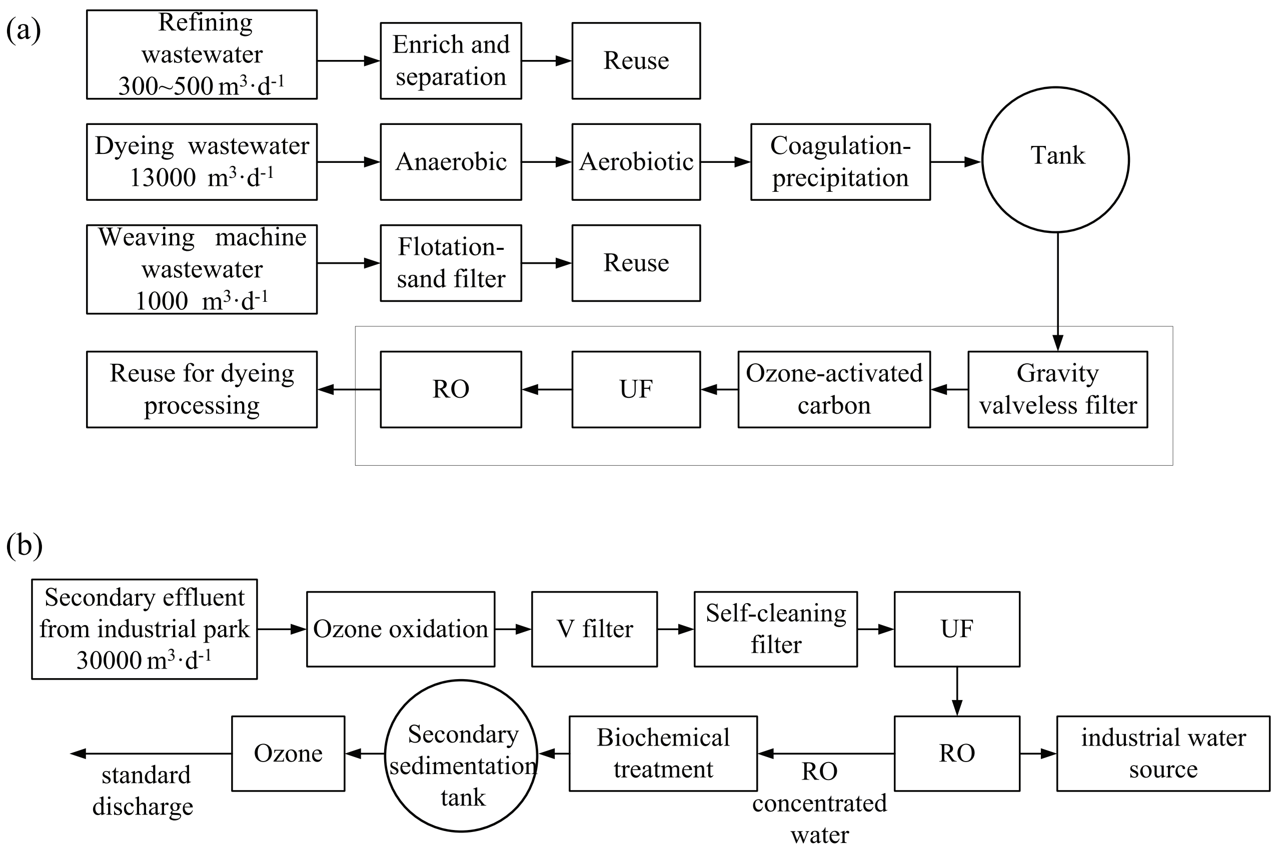

Fig. 7. The wastewater treatment processes of cases A and B.

The effluent water quality is shown in Table 7. The effluent was reused for dyeing processing and the direct operational cost (including electricity and agent cost) of the advanced treatment was 1.8 RMB per ton of water of case A. The effluent of case B was reused. The detailed economic analysis is shown in section 6.3. and Table 4. Both the cases A and B provided much economic and environmental benefit.

8. Conclusions

This study comprehensively examined the membrane technology research and applications to treat wastewater from the dyeing industry in China via literature metrology analysis and a national survey of membrane applications. The study is aimed to provide scientific overview of membrane applications in the dyeing industry in China and analyze its features. Based on the results, the following conclusions could be reached.

Three research stages are identified: the slow progress stage (1998), the rapid growth stage (1999–2008), and the steady progress stage (2009 to present). China has published the largest number of SCI papers focused in membrane technology applied in dyeing wastewater. For CNKI papers, Donghua University leads the publications in this filed.

Table 6
The parameters of UF and RO

Contents		Case A		Case B	
		UF	RO	UF	RO
Basic parameters	Membrane supplier	Bluestar Toray	Bluestar Toray	Hangzhou Water Treatment Technology Development Center Co., Ltd. (HWTTDC)	Toray, HBMP
	Membrane type	HFU2020N	TML20D-400		TML20-370 (Toray) BDX8040B (HBMP)
	Membrane material	Polyvinylidene fluoride (PVDF)	Aromatic polyamide	Modified PVDF	
	Pore size (nm)	10	–	30	–
	Membrane form	External pressure hollow fiber	–	External pressure hollow fiber	–
	Membrane area of one module (m^2)	72	37	80	34.37
Operating parameters	Operating mode	Dead-end filtration	–	Crossflow filtration	–
	Operating pressure (MPa)	0.1	0.5	0.06–0.1	0.25
	Net flux ($L\cdot m^{-2}\cdot h^{-1}$)	35.7		22	
	Total membrane modules	68	192	682	
	Net water yield ($m^3\cdot h^{-1}$)	175	100	1,200	840
	Standard desalination ratio	–	99.8%		≥90%
	Chemical cleaning frequency (month)	6	1.5	2	1–2
	Water recovery rate	>94%	65%		

Table 7
The water quality of each unit

Contents		Turbidity (NTU)	COD ($mg\cdot L^{-1}$)	BOD ($mg\cdot L^{-1}$)	SS ($mg\cdot L^{-1}$)	Conductivity ($\mu s\cdot cm^{-1}$)	pH	Chromaticity (DMM)
Case A	Settling tank effluent	20.9	140			1,129		
	UF effluent	0.08	15			1,170		
	RO effluent	<0.05	<5	0.05		20.5		
Case B	Pretreatment		84	19	24	1,774	7.70	60
	UF effluent		55	6.9	0–1	595	7.56	50
	RO effluent		2–10	0	0	20–35	7.55	0

The membrane technology was initially applied in recycling dyes then it was gradually expanded to treat and reuse wastewater.

Based on the national survey of membrane technology applications, the total capacity of the membrane technology in dyeing wastewater treatment was 662,000 $m^3 \cdot d^{-1}$ and the number of applications was 128 with treatment capacity of 500 $m^3 \cdot d^{-1}$ or more by the end of 2015. Most of the membrane applications are clustered in the five eastern coastal provinces including Zhejiang, Jiangsu, Guangdong, Fujian, and Shandong. "UF + RO" technology was the most widely applied processes of membrane technology application in dyeing wastewater treatment, and the "MBR + RO"and "CMF + RO" were closely behind it. RO technology dominates the membrane applications.

The total operation cost is often lower than local water price when membrane technology is applied to treat dyeing wastewater, which provides both economic and environmental benefits by treating dyeing wastewater with membrane technology. It is noted that the cost of membrane technology applications is higher than conventional technology applications. However, it is still a promising and important technology in dyeing wastewater treatment and reuse in near future because of environmental stress, stricter water management, and higher water price, decreasing membrane cost, and increasing life span of membranes.

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