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Application of ultrafiltration technology in drinking water industry of China: A comprehensive assessment of hybrid membrane processes

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ABSTRACT

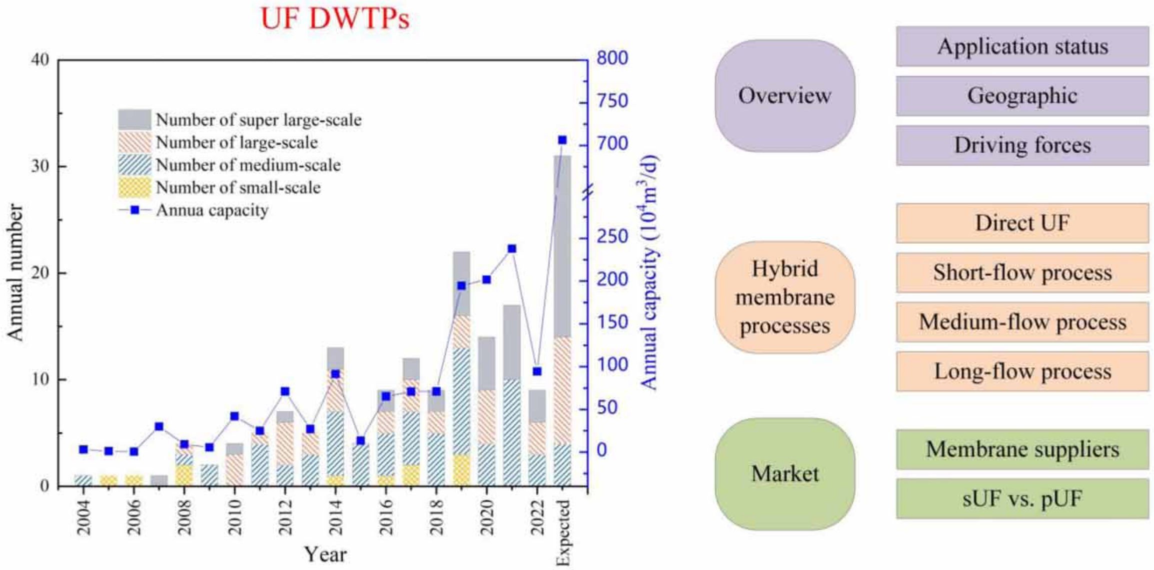
Over the last decades, ultrafiltration (UF) has been and will continue to play an important role in the Chinese drinking water industry. The hybrid membrane processes have been emerging as promising alternatives to traditional treatment processes. This review paper offers a thorough overview of the current status of UF technology in the drinking water industry in China, while also evaluating the landscape of different hybrid membrane processes. The paper conducts statistical analysis on the projects operational between 2004 and 2022; and those currently under construction. This analysis accentuates the evolution of scale and capacity, geographical distribution characteristics, and the driving forces. Furthermore, the characteristics and application scenarios of several hybrid membrane processes are emphatically described, including direct UF, gravity-driven membrane process, coagulation-UF, activated carbon-UF, medium-flow process, long-flow process, and double-membrane process. A granular dissection of UF membrane market distribution follows, including an incisive comparison between submerged and pressurized UF membrane systems. Finally, the potential trajectory of UF in the Chinese drinking water industry is prospected. UF applications have grown significantly in China's drinking water industry, with the dominance of medium- and long-flow membrane processes. UF technology will contribute to future decentralized water supply.

Key words: drinking water treatment, full-scale application, hybrid membrane processes, market distribution, ultrafiltration

HIGHLIGHTS

- The development of UF full-scale applications in drinking water treatment in China is revisited.
- The review provides the geographic distribution of UF DWTPs and driving forces.
- The characteristics and application scenarios of four hybrid membrane processes are described.
- The UF membrane market distribution is identified.
- The insights for the future application of UF technology are highlighted.

GRAPHICAL ABSTRACT



1. INTRODUCTION

In recent decades, the emergence of novel drinking water safety crises and the imposition of increasingly stringent water quality regulations have stimulated the innovation of traditional treatment processes (coagulation + sedimentation + filtration + disinfection) (Madaeni 1999). The latter faces challenges in effectively removing *Cyanobacteria* and protozoan parasites, especially *Cryptosporidium* and *Giardia* (Betancourt & Rose 2004). An alternative approach, utilizing biological granular activated carbon filters preceded by the ozonation process (O_3-GAC), also displays restricted ability in terms of removing these pathogens (Stoquart *et al.* 2012). Conventional disinfection methods can exterminate microorganisms but do not eliminate them, enabling their persistence in the water (Madaeni 1999). In contrast, ultrafiltration (UF) showcases the capability to completely remove particulate contaminants, encompassing protozoan parasites, thereby rendering it capable of replacing the disinfection step (Guo *et al.* 2010). Beyond addressing concerns regarding drinking water biosecurity, UF has been extensively applied worldwide in the drinking water industry due to its notable attributes, such as compactness, easy automation, and minimal staffing requisites (Yu *et al.* 2022).

Nevertheless, the inherent sieving retention mechanism of UF membranes dictates their limited removal of dissolved organic matter, particularly those of low molecular weight (Moreira *et al.* 2021a). Furthermore, there is a problem of membrane fouling during long-term operation. Consequently, UF is coupled with other pretreatment processes, encompassing coagulation, adsorption, and ozonation (Huang *et al.* 2009). Coagulation is so far the most efficacious pretreatment strategy for controlling UF membrane fouling. Coagulation for membrane filtration can be operated with or without sedimentation (Ma *et al.* 2020). For the coagulation-UF system, membrane fouling mainly depends on the removal of aqueous foulants and the characteristics of the cake layer, including porosity and thickness (Wang *et al.* 2019; Yu *et al.* 2019; Lu *et al.* 2020). Activated carbon has notably large specific surface areas, facilitating the adsorption of small substances that are difficult to remove by UF membrane from water (Huang *et al.* 2009). The impact of adding powdered activated carbon (PAC) to mitigate UF membrane fouling depends on the properties of organics, the dosage of PAC, and the membrane materials (Mozia *et al.* 2005; Lee & Walker 2006; Zhang *et al.* 2019). Generally, PAC has a limited ability to mitigate membrane fouling, and in certain instances, it may even have adverse effects. Oxidation pretreatment has been identified as modifying the physicochemical properties of effluent organic matter, including molecular weight, distribution, hydrophilicity, charges, etc., to enhance the removal of pollutants and mitigate membrane fouling (Lin *et al.* 2012, 2013; Lu *et al.* 2015; Wei *et al.* 2016; Winter *et al.* 2016; Huang *et al.* 2019). Distinct pretreatment technologies have varied impacts on membrane fouling. Thus, pretreatments employed in scaled UF applications frequently entail the integration of multiple processes, thereby amalgamating the advantages of each pretreatment technology. Corresponding hybrid membrane processes include PAC-UF, coagulation–sedimentation–UF, O_3-GAC-UF, etc. Numerous bench-scale and pilot-scale studies have demonstrated the role of these hybrid membrane processes in enhancing the removal of contaminants and mitigating membrane fouling (Siembida-Loesch *et al.* 2015; Huang *et al.* 2019; Zhang *et al.* 2019; Ma *et al.* 2020; Long *et al.* 2021).

The application of UF in China started in the 1990s. In 2004, the first drinking water treatment plant (DWTP) with a capacity of more than 5,000 m^3/day in China was constructed in Cixi City, becoming a milestone event in the development of UF applications in China (Fan *et al.* 2013). Since then, UF applications in China have been growing dramatically. This growth can be attributed, in part, to favorable socioeconomic trends and the reduced cost of membrane materials. The cumulative capacity of UF DWTPs (with individual capacities $\geq$ 5,000 m^3/day) reached 1.4 million m^3/day by 2011 (Zheng *et al.* 2012), and remarkably surged to 10 million m^3/day by 2020, constituting around 5.8% of China's overall urban water supply capacity (Chang *et al.* 2022). Against this backdrop, it is significant to undertake a comprehensive review of China's UF drinking water treatment industry's evolution from the point of process and engineering. While certain previous works have touched on the application and evolution of UF technology within China's drinking water industry (Xia *et al.* 2004; Zheng *et al.* 2012; Chang *et al.* 2022), a gap exists in the exploration of various hybrid membrane processes employed in China. An intensified analysis in this domain would be invaluable to advance our understanding of the continually evolving landscape of UF technology in China.

Therefore, a comprehensive survey of UF applications in China's drinking water treatment is conducted in this work. The data are sourced from municipal design institutes, operators, membrane technologies and water treatment websites, field surveys, and the literatures. Notably, only water plants with a capacity exceeding 5,000 m^3/day are considered in scope, as this sector essentially represents the market. The database included 171 UF DWTPs that are operational or under construction between 2004 and the conclusion of 2022 in China. It remains imperative to emphasize that the collection of UF applications in China herein presented may not be exhaustive. A comprehensive analysis is conducted regarding the evolution of capacity, geographic distribution, driving forces, hybrid membrane processes, and the membrane market. Finally, the future perspectives on UF application coupled with various types of hybrid membrane processes for China's drinking water treatment are critically outlined. Those insights are expected to provide valuable implications for the prospective deployment of UF drinking water treatment technology.

2. OVERVIEW OF UF DWTPS IN CHINA

2.1. Application status update

The UF drinking water treatment projects in China (with individual capacity $\geq$ 5,000 m^3/day) are statistically analyzed and drawn into a developmental history map (Figure 1). In recent decades, UF technology for drinking water treatment has

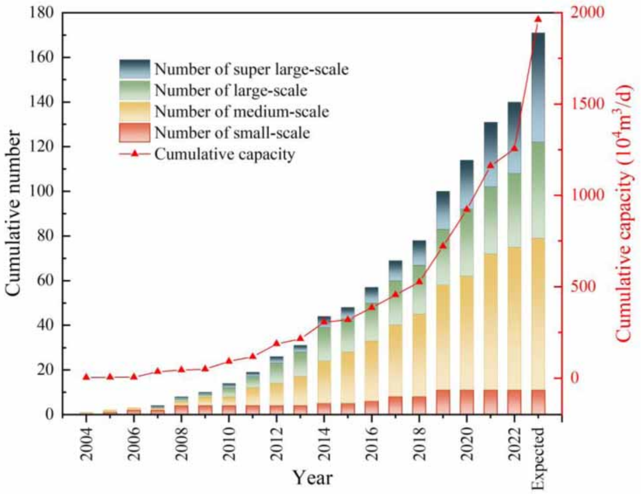


Figure 1 | Development of the treatment capacity and number of UF DWTPs for drinking water treatment in China. ($\geq$10,000 m^3/day refers to small-scale; $>$10,000 and $\leq$50,000 m^3/day are medium-scale; $>$50,000 m^3/day and $\leq$100,000 m^3/day is large-scale; $>$100,000 m^3/day is super large-scale; the data of 'expected' are according to the applications under construction.)

undergone rapid expansion and achieved wide and mature applications. Based on partial statistics, up to the end of 2022, 140 UF DWTPs have been installed with a total capacity of 12.5 million m^3/day in China. Taking into consideration the UF DWTPs presently under construction and planned initiatives, the total count of UF DWTPs (with individual capacity $>$5,000 m^3/day) has exceeded 171, with a cumulative capacity of 19.6 million m^3/day, accounting for over 7.8% of the total municipal water supply capacity in the nation (249.1 million m³/day) (National Bureau of Statistics of People's Republic of China 2022). Notably, China has evolved into a focal point of UF application. Furthermore, UF had begun to take a role in large-scale DWTPs since 2010 (the Shandong Dongying demonstration project with 100,000 m³/day is the first large-scale UF DWTP in mainland China). This development has offered a valuable experience for the application of UF in drinking water treatment. In 2012, the first super large-scale UF application with an individual capacity of 300,000 m³/day was commissioned (the Qingtai DWTP, Zhejiang), indicating that the application of UF in the context of drinking water treatment has transitioned into a phase of maturity. Nevertheless, medium-scale UF applications continue to dominate the market. Presently, 32 super large-scale UF DWTPs (individual capacities $>$ 100,000 m^3/day) have been installed with a total capacity of 7.58 million m^3/day in China. The individual treatment capacity of UF applications gradually enlarges from small- and medium-scale to large-scale even super large-scale, achieving mature applications. Consequently, it is foreseeable that large-scale and super large-scale UF applications will represent the market.

2.2. Geographic distribution

The geographic distribution of China's UF applications, including both operational and under-construction projects, is illustrated in Figure 2. Notably, the majority of the applications are located in Zhejiang, Hebei, Jiangsu, Beijing, and Shandong, with cumulative UF installed capacities of 2.06, 1.43, 1.42, 1.40, and 1.37 million m³/day, respectively. Collectively, these regions account for 61.3% of the nationwide total. Predominantly, UF plants are established in the East and North China regions. This distribution reflects variations in water quality, local policy, and economic statuses among different provinces. In 2007, an extensive cyanobacterial pollution outbreak occurred in Jiangsu's Taihu Lake, a catalyst for the accelerated adoption of UF technology within Jiangsu and Zhejiang provinces (Zheng *et al.* 2012). Furthermore, recent years have seen regions, such as Shanghai, Zhejiang, Shenzhen, Xiongan New Area, Haikou Jiangdong New Area, Wuhan, and Jiangsu, introduce or plan to implement local drinking water quality standards surpassing the existing national standards. The implementation of these localized standards has promoted the UF application. Additionally, the operation of the Dongying Nanjiao UF technology demonstration project in Shandong province provided valuable experience for the application of UF technology in Shandong province even in China, which is one of the factors in the pronounced deployment of UF technology in Shandong province.

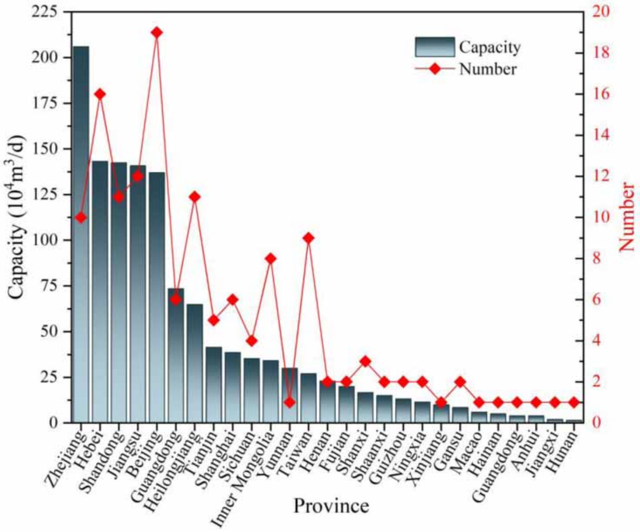


Figure 2 | The geographic distribution of UF DWTPs in China (with individual capacity $>$ 5,000 m³/day).

2.3. Driving forces

The increasingly strict drinking water hygiene standards and source water pollution play critical roles in favoring the application of UF for drinking water treatment in China. The latest Drinking Water Sanitation Standard (GB5749-2022) puts forward higher requirements for disinfection byproducts. To improve drinking water quality, regional authorities have introduced localized standards, surpassing national standards in terms of stringency. Those provided a great opportunity for UF application due to the high quality of produced water. Parallelly, the pollution and subsequent degradation of localized surface and groundwater that can be used to produce drinking water has prompted the development of advanced treatment technologies. The general driving force is the reduction of cost. Using the difference in elevation between the submerged membrane tanks and the downstream processes, the necessary vacuum for UF filtration is created, obviating the need for expensive and energy-consuming osmotic pumps. This strategy dramatically reduces capital and operating costs, such as the Jinan Nankang Water Plant (60,000 m^3/day, 2019), Ningbo Taoyuan Water Plant (500,000 m^3/day, 2020), Hangzhou Xianlin Water Plant (600,000 m^3/day, 2021), Nanjing Qiaolin Water Plant (200,000 m^3/day, 2022), and similar cases. Concurrently, benefiting from the development of the social economy and the cost reduction of membranes, compact UF technology is becoming more and more competitive in the renovation and expansion of ageing DWTPs. Especially when the area is limited. The strict standards and the pollution of source water have promoted the UF application number to increase exponentially, while the reduction of cost has increased the capacity of UF applications up to one more magnitude. The super large-scale UF DWTPs (with an individual capacity of more than 100,000 m^3/day) are shown in the Supplementary material, Table S1. The three driving forces interact with the advantages of UF to affect the UF application. With the accumulation of UF application experience and the gradual establishment of a comprehensive UF membrane-based drinking water treatment system, UF technology is poised to provide a more reliable water quality safeguard for regions (e.g., Anhui, Jiangxi, and Hunan) with less application of UF.

3. HYBRID MEMBRANE PROCESSES

3.1. Overview

The utility of UF membranes in the removal of suspended solids is well established. This capability inherently enables UF to replace the conventional steps of coagulation, flocculation, sedimentation, and granular media filtration (Jutaporn *et al.* 2021; Rho *et al.* 2022). This gives rise to four distinct UF membrane-based filtration technologies: direct UF, short-flow process, medium-flow process, and long-flow process. In the context of direct UF, the raw water directly enters the UF system without pretreatments and no or less chemical additives. The short-flow process refers to substitute UF for the conventional precipitation-filtration process. The medium-flow process involves the UF membrane replacing the sand filter in the traditional process. The long-flow process employs UF as an advanced treatment process and also includes a variety of advanced treatment combinations.

As depicted in Figure 3(a), long-flow and medium-flow processes have exhibited expansion in recent years, especially since 2014. These two processes have become the dominant choices for most large-scale UF DWTPs in China. Specifically, the adoption of long-flow and medium-flow applications accounted for nearly 94% of the cumulative capacity by 2019 (Figure 3(b)). The long-flow process presents an effective integration of multiple process components, creating a multi-level barrier strategy. The distinctive strengths of each process unit synergistically enhance overall operational flexibility and economic viability. Particularly well-suited for large-scale DWTPs, the long-flow process possesses an absolute advantage in water production scale. In terms of engineering numbers (Figure 3(b)), long-flow and medium-flow processes dominate the landscape of UF DWTPs in China, constituting 46.5 and 38.6%, respectively. The long-flow process is widespread adoption across varying scales in China, especially in large and super-large scales, due to its adaptability to seasonal fluctuations in raw water quality. On the other hand, the medium-term process is more competitive for ageing DWTPs requiring upgrades within spatial constraints. However, the applications of direct UF and short-term processes are limited due to the relatively low organic matter removal efficiency achieved by UF and the challenges with membrane fouling. As shown in Figure 3(c), direct UF is predominantly employed for treating high-hardness groundwater, often combined with nanofiltration or reverse osmosis, and there are few instances of direct UF for surface water treatment.

Currently, there are 14 UF DWTPs undergoing construction utilizing a long-flow process, with a total capacity of 4.1 million m^3/day (Figure 3(d)). It can be predicted that the primary focus of construction is persistently centered on super-large UF DWTPs that employ the long-flow filtration process. In contrast, medium-flow and short-flow processes demonstrate

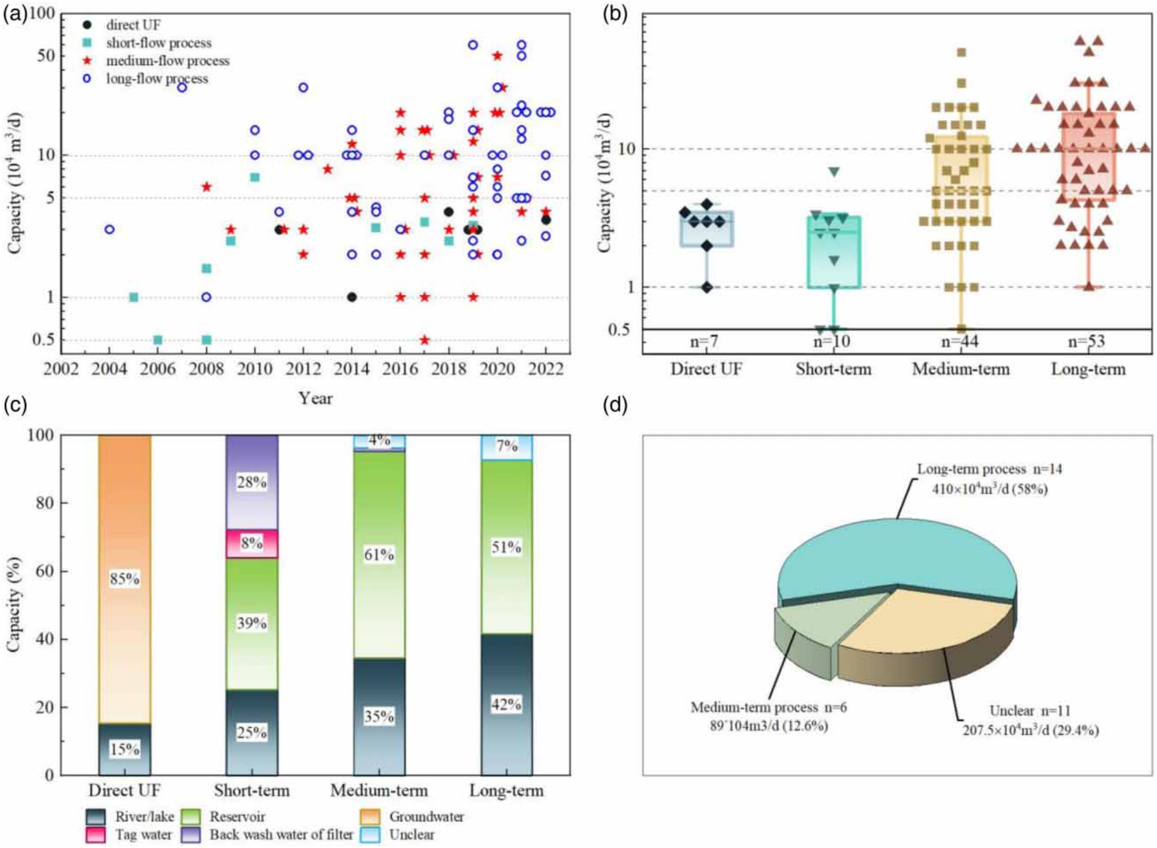


Figure 3 | The characteristics of four UF membrane-based processes in UF DWTPs in China (with individual capacity > 5,000 m³/day): (a) the developing roadmap, (b) capacity distribution, (c) source water types, and (d) capacity and number distribution of under construction projects.

favorable applicability, primarily targeted for upgrading water plants and addressing the demands of small or medium-scale plants. Despite the applications of direct UF being comparatively smaller scale, they bear considerable potential in rural drinking water supply and hold valuable prospects for widespread implementation. The characteristics and application status of the four processes are discussed in the following sections.

3.2. Direct UF

3.2.1. Decentralized water supply in rural regions

UF boasts a small footprint, flexible scale, and ease of installation, operation, and maintenance. This renders UF fitting for the demands of rural water supply, characterized by dispersion, limited scale, and operational challenges (Wu *et al.* 2022). Several studies have demonstrated the viability of a long-term direct UF process, even without pretreatment, in supplying clean water to rural regions (Mierzwa *et al.* 2008, 2012; Galvan *et al.* 2014; Ferrer *et al.* 2015; Wu *et al.* 2022). An on-site and online investigation is conducted on UF water supply stations situated in rural regions of Zhejiang province. Each station serves a village or several nearby villages, with capacities ranging from 50 to 900 m³/day. The main facilities include integrated UF water purification equipment, an automated control system, and a clear water tank. The integrated UF water purification equipment includes components such as the submerged UF system and backwashing system. The raw water is directly entered into the integrated submerged UF system for filtration, while the coagulant is added during rainstorms and flooding when the turbidity of the raw water is high. Besides, the system does not need a pump to obtain permeate, instead using the differential liquid levels between the immersion membrane tank and the clear water tank to achieve siphon-gravity water production, thereby greatly reducing energy consumption. This integrated UF water purification equipment offers rapid installation, a short construction cycle, and a small footprint. Additionally, it enables fully automated remote control and operation, truly unattended. Simultaneously, it has the advantages of greenness, energy efficiency, simplicity, and easy process control. These make direct UF have broad application prospects in rural water supply engineering.

3.2.2. GDM process

In recent years, researchers have developed a novel UF process, gravity-driven membrane (GDM), a dead-end operated UF system without any chemical or hydraulic fouling control at remarkably low and constant pressure (40–200 mbar) for decentralized treatment of surface water, stormwater, gray water, and household water (Peter-Varbanets *et al.* 2010; Peter-Varbanets *et al.* 2011; Ding *et al.* 2017), focusing around issues such as water quality assurance, energy saving, and simplifying operation and maintenance. The driving force is hydrostatic pressure. During the dead-end filtration, the microorganisms, organic matter, and inorganic material in the water accumulate on the membrane surface to gradually form a biofilm layer (Pronk *et al.* 2019), its thickness and resistance with the increase of filtration volume and foulants concentration increase (Peter-Varbanets *et al.* 2011; Chomiak *et al.* 2015). Additionally, the biodegradation process and predation activities induced structural changes in the biofilm layer, leading to the formation of a loose layer with stable hydraulic resistance (Peter-Varbanets *et al.* 2011; Klein *et al.* 2016; Chen *et al.* 2021). Consequently, the flux of the GDM system achieves stability after a long-term operation without any physical or chemical cleaning (Shi *et al.* 2020), and the stability level is influenced by the development of a permeable, heterogeneous biofilm layer. The biofilm layer developed on the GDM is considered a 'mini ecological system', enhancing the separation and biodegradation of natural organic matter (NOM) (Peter-Varbanets *et al.* 2011), assimilable organic carbon (Derlon *et al.* 2014), dissolved organic carbon (Lee *et al.* 2019), and micro-pollutants (Chen *et al.* 2022). Furthermore, research showed that the introduction of pro-coated/pro-added manganese oxides onto the membrane surface or within the system confers efficient manganese and iron performance to the GDM (Tang *et al.* 2020, 2021a, 2021b). The pro-coated/pro-added manganese oxides prove beneficial in improving the porosities and heterogeneities of the biofilm layer, leading to stabilized flux and improvements.

The GDM system offers a dual guarantee through the biofilm layer and UF membrane. As a result, GDM has better validity and universal applicability for purifying diverse types of surface and underground water when compared to direct UF. Moreover, GDM runs without any flushing or cleaning during long-term operation, endowing it with higher energy efficiency than direct UF. However, GDM usually operates under ultralow pressure with a stable flux of 4–10 L/(m^2·h) (Pronk *et al.* 2019). This is one of the main obstacles to the application of GDM within rural water supply projects (Chomiak *et al.* 2015). Overall, both direct UF and GDM exhibit distinct advantages and disadvantages. Each has confirmed its efficacy as a decentralized water supply solution in China's rural regions.

3.3. Short-flow process

3.3.1. Coagulation-UF process

The coagulation-UF process is an effective combination of improving the removal of contaminants such as large-size biopolymers (the fraction with high fouling potentials) (Kimura *et al.* 2018), extracellular organic matter of algal (Zhang *et al.* 2017), and humic acid (Liang *et al.* 2021), all contributors to UF membrane fouling. The deposition of coagulated flocs on the membrane surface enhances the removal of low molecular weight organic compounds by adsorption (Kimura & Kume 2020). The degree of membrane fouling in the system depends on the removal of aqueous foulants and the characteristics of the cake layer, including porosity and thickness (Wang *et al.* 2019). These characteristics are susceptible to various factors, including the quality of the feed water (Su *et al.* 2017), the coagulant type and dosage (Dong *et al.* 2014; Ma *et al.* 2014), and the membrane material (Huang *et al.* 2009). Studies have shown that aquatic contaminants, including sodium alginate molecules, biopolymers, and calcium ions, can change the cake layer structure (Su *et al.* 2017; Zhao *et al.* 2020; Long *et al.* 2021). These contaminants act as supportive skeletons within the cake layer, thereby averting compaction during operation. This dynamic, therefore, retards the decline in membrane resistance. Hence, the principal objective of pre-coagulation is to form an ideal cake layer, rather than the larger the flocs, the better.

The coagulation-UF process boasts a compact footprint and exhibits low energy consumption. The coagulation and UF units can be conveniently co-located, thereby optimizing land utilization. By directly introducing coagulated water into the membrane tank, the system efficiently capitalizes on raw water head, enabling gravity-driven water production in most instances. Furthermore, this process does not require sludge discharge operations. Sequential backwashing is applied to all membrane tanks, each undergoing variable flux filtration across the entire filtration cycle. This variable flux operation mode yields significant benefits in mitigating deep membrane fouling. The representative DWTPs employing this process are shown in Table 1. Presently, large-scale domestic UF applications primarily adopt long-flow and medium-flow processes, with fewer instances of short-flow UF applications. Notably, several foreign cases showcase large-scale utilization of short-flow process, including the Chestnut Avenue water plant in Singapore (273,000 m^3/day, 2003) (Janson *et al.* 2006), and the City of Kamloops water plant in Canada (160,000 m^3/day, 2013).

3.3.2. Activated carbon-UF process

The UF membrane has limited efficacy in removing small-molecule-weight contaminants. In contrast, activated carbon exhibits effectiveness in removing fractions with molecular weights ranging between 300 and 17,000 Da (Lin *et al.* 1999). Therefore, a modified UF process, integrating activated carbon adsorption, has demonstrated potency in enhancing permeate quality. This process is classified into two categories, the granular-activated carbon-UF process (GAC-UF) and the powder-activated carbon-UF (PAC-UF) process. Research has shown that PAC could enhance the removal of organic matter, including cyanotoxins, odor, taste, color, and microcystins (Tomaszewska & Mozia 2002; Stoquart *et al.* 2012). Many researchers believe that the PAC-UF process could replace the conventional water treatment process for mildly polluted raw water. However, PAC would inevitably deposit on the membrane surface during operation (Shao *et al.* 2017), requiring frequent backwashing or chemical cleaning. Thus, the current application of the PAC-UF process requires individual reactors and PAC separators, leading to additional costs and procedures, thereby limiting its comprehensive application (Yu *et al.* 2022). To this end, the utilization of GAC has emerged as a preferred strategy for mitigating membrane fouling. In addition, GAC facilitates recycling and reuse compared to PAC.

3.4. Medium-flow process

3.4.1. Upgrade of old water plants

The medium-flow process, denoted as the coagulation/sedimentation-UF process, holds significant relevance in drinking water treatment as a pivotal UF combination process. Compared with the short-flow process, the medium-flow process has a comprehensive flocculation and sedimentation stage after coagulation. This removes most of the flocs before the membrane, thereby improving the quality of effluent water and alleviating membrane fouling (Malkoske *et al.* 2020). Consequently, this process has been widely adopted in water plants encompassing diverse source water characteristics and production scales. The successful operation of several large-scale applications proves the viability of this process in large-scale UF DWTPs. For example, in Ningbo Taoyuan Water Plant (500,000 m^3/day, 2020), the raw water is taken from the Qincun reservoir, and the treatment process is coagulation/sedimentation-UF. Located on a hill, this contemporary plant astutely utilizes the elevation difference of the terrain to induce UF filtration via the siphoning effect. Subsequently, clean water is conveyed to the urban water distribution network through gravitational forces, obviating the necessity for secondary booster pumps. Comparative to the conventional pump-driven submerged UF systems, this configuration effectuates nearly 90% power savings. After three years of stable operation, the effluent turbidity remains below 0.1 NTU. Similar gravity-driven large-scale plants employing the medium-flow process include the Nanchang Xiuluoqiao Water Plant (20,000 m^3/day, 2017).

Table 1 | UF DWTPs with the short-flow process in China

Projects	Process	Capacity (10^4 m^3/day)	Raw water type	Year
Jinping County Xinhua Water Plant	Coagulation-UF	3.2	Reservoir	2019
Shahe Urban Area Water Plant	Coagulation-UF	2.5	Reservoir	2018
Greater Khingan Mountains Jiagedaqi Water Plant	Coagulation-UF	3.4	River	2017
Yongqing County Surface Water Plant	Coagulation-UF	3.1	Reservoir	2015
Beijing Ninth Water Plant	Coagulation-UF	7	Backwash water from the filter	2010
Nantong Lujing Water Plant	Coagulation-UF	2.5	River	2009
Yangliuqing Water Plant	Coagulation-UF	0.5	River	2008
Suzhou Ducun Water Plant	Coagulation-UF	1	Lake	2005
Yangshan Port Tongsheng Water Plant	GAC-UF	1.6	Municipal tap water	2008
High-quality water plant in Xincheng District, Foshan	GAC-UF	0.5	Municipal tap water	2006

Ageing water plants located in central urban areas confront multifaceted challenges, including the threat of biosecurity, algae contamination, bacterial viruses, and other problems in water. Additionally, these plants also face difficulties associated with stringent water quality requirements and spatial constraints, impeding the adoption of advanced treatment processes. In this context, the selection of an appropriate process is crucial for upgrading ageing water plants. The medium-flow process provides a feasible modification solution. By retaining the original coagulation and sedimentation facilities and integrating UF to replace conventional filters, the upgrade of the ageing water plant is realized. This strategy aligns with the principles of sustainable upgrading.

The Jiangdong Water Plant in Ningbo City was employed with the conventional treatment process before 2016. The raw water is taken from the Baixi and the Tingxia Reservoirs, where the turbidity is typically maintained below 15 NTU. However, inherent limitations of the siphon filter structure resulted in compromised interception capacity, frequent incomplete flushing, and escalated effluent turbidity. To improve water quality and safety, the existing coagulation and sedimentation processes were retained. The transformation involved converting two 50,000 m^3/day siphon filters into a single 200,000 m^3/day submerged UF tank. After upgrading, the effluent water quality surpassed the Sanitary Standard for Drinking Water (GB 5749-2006), turbidity consistently remained below 0.1 NTU, and oxygen consumption maintained below 1 mg/L. Other successful cases include Jinan Fenshuiling Water Plant (70,000 m^3/day, 2020), Tangshan Water Supply Company Water Plant (125,000 m^3/day, 2019), Jinan Xueshan Water Plant (30,000 m^3/day, 2018), Ningbo Jiangdong Water Plant (200,000 m^3/day, 2016), and Zhaoqing High-tech Zone Water Plant (2,000 m^3/day, 2012).

3.5. Long-flow process

3.5.1. Full-flow treatment process

Small flocs escaping from the sedimentation have been identified as a primary contributor to UF membrane fouling in the medium-flow process (Kimura & Kume 2020). The sand filter could effectively control microbial growth and reduce the release of extracellular polymeric substances by intercepting unseparated coagulation flocs, thus reducing the membrane fouling rate (Yu & Graham 2015). As a multi-tiered process, the long-flow process includes complete conventional treatment processes and advanced UF treatment, often combined with diverse advanced treatment technologies like O_3-GAC, NF, and reverse osmosis (RO). This combination endows the process with adaptable capabilities concerning source water quality and seasonal variations. Efficiently addressing source water challenges, the Guogongzhuang Water Plant (500,000 m^3/day, 2021), Shijingshan Water Plant (200,000 m^3/day, 2021), and Chengzi Water Plant (43,000 m^3/day, 2015) in Beijing employ the long-flow process. This process effectively mitigates issues related to high summer algae levels, winter low temperatures and turbidity, as well as challenges associated with organic matter, color, and odor.

The long-flow process is predominantly used in new water plant constructions and the upgrading of ageing water plants where space conditions permit. Process components are reasonably selected based on the source water quality, and the process can be flexibly matched to achieve process optimization. Remarkably, long-flow UF DWTPs generally have considerable scale. Among the super large-scale UF DWTPs either operational or in progress, 29 installations employ the long-flow process, with a total capacity of 8.685 million m^3/day. These large-scale long-flow UF DWTPs usually play primary roles in the local water supply. For example, the super large-scale UF DWTPs that are under construction include Dongguan Songshan Lake Water Plant (1,100,000 m^3/day), Shenzhen Changliupo Water Plant (550,000 m^3/day), Dongguan Luhuakeng Water Plant (500,000 m^3/day), Jiangmen Xinyuan Water Plant (300,000 m^3/day), and so on. Large-scale UF DWTPs based on long-flow processes will become the focus of future water plant development and renovation.

3.5.2. UF-NF/RO process

The dual-membrane process is a membrane technology that combines UF with NF or RO technology. This process is primarily tailored for water sources with excessive inorganic salts, such as brackish groundwater or surface water affected by seawater backflow. Several large-scale DWTPs exemplify the success of this process: The Xi'an Wanzi Water Plant (100,000 m^3/day, 2017) applies the UF + NF process for brackish groundwater treatment, the Yantai Gongjiadao Water Plant (72,000 m^3/day, 2022) adopts the UF + RO advanced treatment process to tackle excessive nitrate in the raw water, the Jinan Donghu Water Plant (200,000 m^3/day, 2021) employs the O_3-GAC + UF + RO process for targeted removal of organics, algae, taste, odors, and sulfates. The integration of NF or RO after UF further reduces the concentration of soluble inorganic salts, significantly improving issues related to water hardness and taste. On the other hand, the NF membrane could efficiently remove trace toxic and harmful organics while retaining essential mineral elements beneficial to human health.

This transition from providing 'qualified water' to supplying 'healthy water' aligns with the growing public demand for high-quality drinking water. Consequently, some economically developed regains have embraced the UF + NF process to elevate the supply of water quality beyond national standards. For example, the Zhangjiagang Third and Fourth Water Plants have implemented the UF + NF advanced process to treat Yangtze River water, thereby ensuring the supply of high-quality water to consumers.

4. MARKET

4.1. Membrane suppliers

Figure 4 illustrates the market distribution based on the suppliers of UF membranes in China. Only the main UF suppliers are indicated in the figure. The prominent manufacturers include Litree (China), Motimo (China), Inge (Germany), OriginWater (China), Meineng (China), Suez (America), and Asahi Kasei (Japan). Those overseas manufacturers are experienced in the earlier stage, providing 47.2% of the UF membranes for China's drinking water supply market before 2015 (Figure 5). In recent years, domestic suppliers in China have gradually expanded their market presence to become the major suppliers and expanded their influence internationally; 73.7% of the membranes of UF DWTPs in China were from domestic suppliers after 2015 (Figure 5).

4.2. Membrane modules

There exist two types of UF systems in water plants: the submerged UF membrane system (sUF) and the pressurized UF membrane system (pUF). The two types of UF systems are similar in terms of removal efficiencies of various contaminants

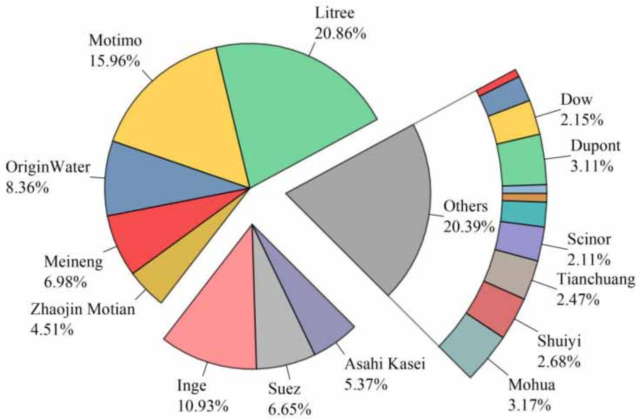


Figure 4 | Market repartition of membrane suppliers according to the installed capacity (the UF DWTPs of capacity ≥ 5,000 m³/day are considered).

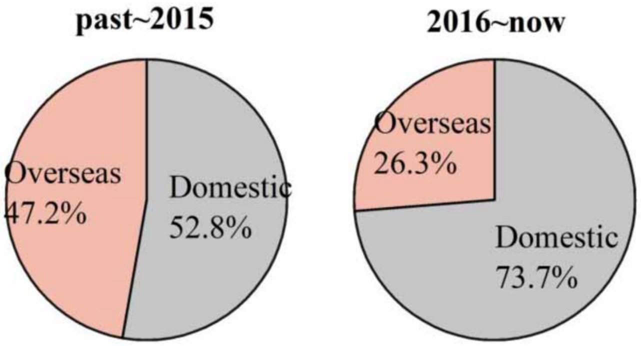


Figure 5 | Market repartition of the UF membrane modules according to the cumulative capacity.

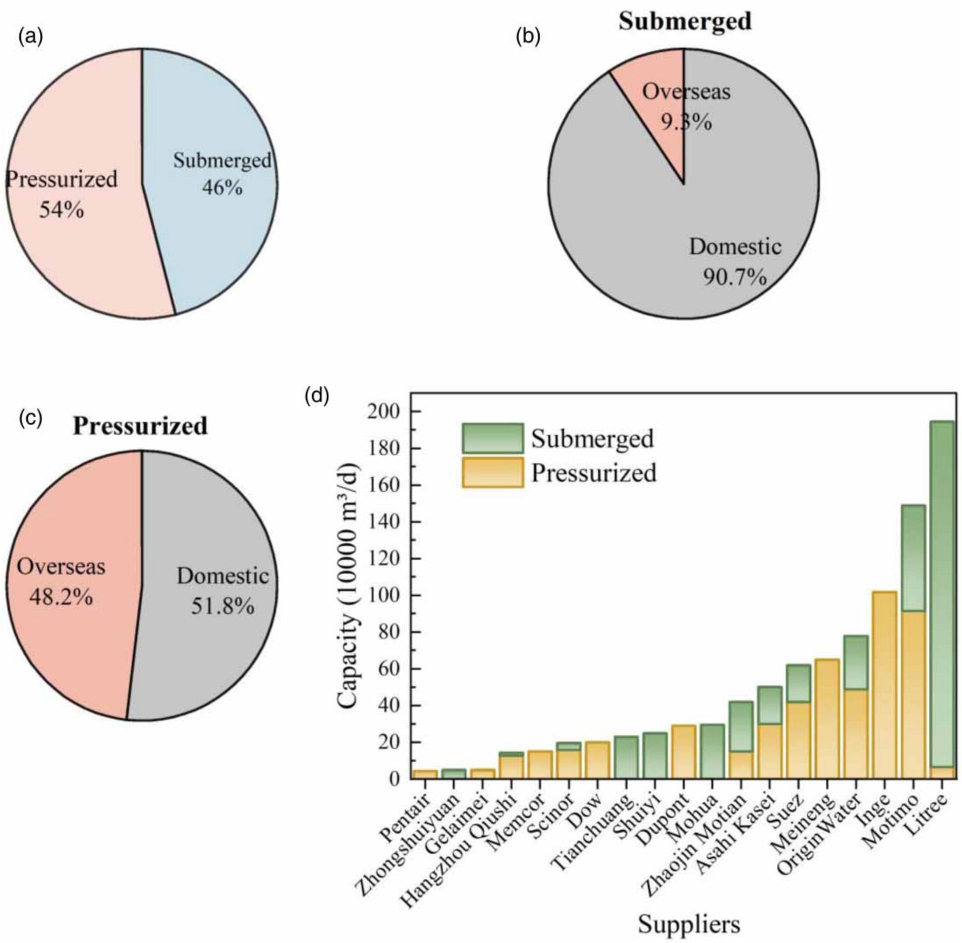


Figure 6 | The distributions of UF membrane modules in UF DWTPs in China: (a) capacity distribution of the two types of UF membrane systems, market share of (b) the pUF membrane system and (c) the sUF membrane system, and (d) membrane module distribution of suppliers.

(Chae *et al.* 2009; Lowenberg *et al.* 2014), but different in operation mode, permeate flux, fouling propensity, and costs. In general, the pUF system operates by depending on a high-pressure pump, whereas the conventional sUF system employs permeate pumps to create the vacuum essential for filtration, thereby limiting the transmembrane pressure (Akhondi *et al.* 2017). Consequently, the pUF system generally has a higher permeate flux compared to the sUF system. Based on existing domestic UF DWTPs, pUF system designs typically target permeate flux within the range of 50–80 L/(m^2·h), whereas the sUF system aims for 20–40 L/(m^2·h) (Zheng & Rui 2021). However, the higher permeate flux or higher external positive pressure corresponds to an accelerated fouling rate (Moreira *et al.* 2021b), thus endowing the sUF system with a longer operational lifespan. Economically speaking, the pUF system boasts a smaller land footprint due to its higher installed density. However, it comes with a higher energy consumption due to the utilization of pressure pumps. Conversely, the sUF system exhibits the opposite characteristics.

The percentage of installed capacity of sUF and pUF systems is, respectively, 46 and 54% (Figure 6(a)). The overwhelming majority of submerged UF membrane systems were domestic, according to 90.7% (Figure 6(b)). In addition, 51.8% of pressurized UF membrane systems were imported (Figure 6(c)), including Inge, Suez, Asahi Kasei, etc. (Figure 6(d)). Meanwhile, the application of domestic pressurized UF membrane systems is also widespread, mainly provided by Motimo, Meineng, and OriginWater.

5. CONCLUSIONS AND PERSPECTIVES

This paper provides a comprehensive overview of the advancements in UF applications, the current status of four distinct hydraulic membrane processes, and the distribution of the membrane market in the Chinese drinking water industry. The conclusions and perspectives drawn from the survey of UF DWTPs with an individual capacity of $\geq$5,000 m^3/day are as follows:

- China has emerged as a focal point for UF applications, with a total commissioned capacity of 12.54 million m^3/day in December 2022, poised to reach 19.61 million m^3/day with ongoing projects. Medium-scale UF DWTPs dominate, while the super large-scale UF DWTPs also contribute significantly, mainly in East and North China.
- Stringent standards and water pollution concerns drive UF application growth exponentially, while cost reduction significantly increases capacity.
- Within UF DWTPs, the long-flow and medium-flow processes are popular, with long-flow expected to maintain dominance. The medium-flow process gains prominence in small to medium-scale projects and plant upgrades. The short-flow process is effective for treating well-quality raw water, and direct UF is suitable for rural water supply. The GDM process is one of the effective solutions for decentralized water supply in rural areas.
- Major Chinese membrane manufacturers, including Litree (20.86%), Motimo (15.96%), OrigionWater (8.36%), Meineng (6.98%), and Zhaojin Motian (4.51%), collectively account for 56.67% of total capacity. Notably, 90.7% of the sUF systems utilize domestic membranes, while pUF systems rely on imported membranes (51.8%).
- With the boost of the sustainable policy stimulus and the domestic development of membrane materials and equipment, UF application in the Chinese drinking water industry is going to be one of the most promising world markets in the foreseeable future. It will contribute to decentralized water supply in economically challenged rural areas. Forecasts indicate a surge in the integration of UF technology into an increasing number of super large-scale DWTPs, and the UF DWTPs will develop toward modernization, intelligence, and energy-efficiency trends.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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