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Review of Ultrafiltration Membrane Applications in Wastewater Treatment

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Abstract. Water scarcity and the challenge of wastewater reuse have become increasingly pressing issues. Developing efficient and sustainable water treatment technologies is now an urgent priority. Ultrafiltration membrane technology, with its outstanding performance, plays an increasingly vital role in water treatment and represents a processing technique with broad prospects. Ultrafiltration membranes are microporous membranes with pore sizes ranging from 0.01 to 0.1 μm. Utilising pressure difference as the driving force, they achieve efficient retention of microorganisms, viruses, and particulate matter while permitting the passage of water molecules and small dissolved solutes. This paper systematically outlines the principal types of ultrafiltration membranes, detailing the characteristics of hollow fibre, flat sheet, and tubular membranes. It focuses on combined processes integrating ultrafiltration with advanced oxidation and reverse osmosis technologies, analysing the significant advantages of synergistic effects in enhancing pollutant removal rates and mitigating membrane fouling. Findings indicate removal rates exceeding 90% for both chemical oxygen demand (COD) and ammonia nitrogen. Subsequently, the paper briefly introduces ultrafiltration membrane applications in short-process water purification systems centred on submerged ultrafiltration. Finally, addressing the primary challenges hindering ultrafiltration technology adoption—namely membrane fouling and cost concerns—it briefly prospects future development trends towards high-performance novel materials and intelligent control systems.

Keywords: Ultrafiltration Membrane, Wastewater Treatment, Membrane Fouling, Combined Processes

1. Introduction

With the expansion of industrial scale, the volume of industrial wastewater continues to increase. Concurrently, the global issue of water scarcity grows ever more acute. How to efficiently and sustainably treat and reuse wastewater has become a critical problem requiring urgent resolution. Traditional wastewater treatment processes often exhibit low treatment efficiency, high operational costs, and unstable effluent quality when confronted with complex water bodies [1]. Therefore, developing highly efficient, easily scalable advanced treatment technologies represents a key direction in contemporary water treatment.

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Among pressure-driven membrane separation technologies, microfiltration membranes represent one of the earliest and most fundamental membrane processes. Utilising the 'sieving' action of homogeneous porous membranes, they separate water using static pressure differentials as the driving force. Typically featuring pore sizes ranging from 0.1 to 10 μm, microfiltration membranes efficiently retain suspended solids (SS), turbidity, bacteria, and even certain large viruses from water, while permitting the passage of water, dissolved salts, and small organic molecules. Consequently, microfiltration technology finds extensive application in solution clarification, sterilisation, and pre-filtration. Owing to their relatively large pore size and lower operating pressure, microfiltration membranes offer advantages including reduced energy consumption, higher flux rates, and lower operational costs. However, the limitations of microfiltration technology are equally pronounced. Its retention capability primarily targets particulates and microorganisms, with negligible removal efficiency for small-molecule contaminants and dissolved substances. Consequently, when treating complex wastewater streams, the effluent quality often falls short of meeting standard reuse or discharge criteria.

Building upon microfiltration membranes, a membrane technology with similar positioning yet superior performance has emerged and rapidly advanced: ultrafiltration membrane technology, characterised by its finer separation capabilities. Leveraging its highly efficient solid-liquid separation, excellent microbial retention properties, and low operational energy consumption, ultrafiltration membrane technology demonstrates broad application prospects in drinking water purification, industrial wastewater reuse, and pretreatment processes [2]. Since its mid-20th-century development, ultrafiltration membrane materials have evolved from early cellulose acetate to contemporary high-performance polymers such as polyvinylidene fluoride (PVDF) and polyethersulfone (PES), alongside ceramic composite materials [3]. Membrane structures have expanded beyond flat sheets to include hollow fibres, tubular configurations, and other forms, adapting to diverse water qualities and operational conditions. With continuous advancements in materials science and membrane processing, ultrafiltration membrane technology is progressively evolving towards higher performance, enhanced fouling resistance, and intelligent operation.

This paper aims to systematically review the technical principles, typical classifications, and research progress of ultrafiltration membranes within combined processes. It focuses on exploring synergistic effects between ultrafiltration and various technologies, analysing the application advantages of ultrafiltration membranes in processes, and summarising key challenges currently faced by ultrafiltration membrane technology in practical engineering applications.

2. Principles and classification of ultrafiltration membranes

2.1. Technical principles of ultrafiltration membranes

Ultrafiltration membranes are microporous membranes with pore sizes ranging from 0.01 to 0.1 μm. They permit the passage of water molecules and dissolved substances while efficiently retaining minute particles such as microorganisms and viruses within water, thereby achieving filtration and separation that meets higher water quality requirements [4]. As one of numerous membrane treatment technologies, ultrafiltration membrane technology utilises the pressure differential between fluids on either side of the membrane as its driving force. This pressure-driven mechanism propels liquids through the membrane, thereby achieving filtration, separation, and purification of substances [5].

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2.2. Types of ultrafiltration membranes

Ultrafiltration membranes are primarily categorised into three types: hollow fibre, flat sheet, and tubular. These differ in structure and suitability for specific applications. Hollow fibre membranes exhibit low energy consumption and high throughput. Comprising numerous fine tubular membrane filaments bundled together, they feature an extremely high packing density, providing an extensive filtration area per unit volume. This confers significant advantages when treating large volumes of relatively well-quality wastewater, such as domestic sewage. Plate ultrafiltration membranes comprise multiple membrane sheets assembled within a frame. This design enables precise control over inter-sheet spacing and facilitates membrane surface cleaning through disassembly. Consequently, plate ultrafiltration membranes exhibit outstanding fouling resistance, finding extensive application in industrial wastewater treatment [6]. Tubular membranes typically feature a membrane layer coated onto the inner surface of a rigid, porous support tube. This structure offers high mechanical strength and ease of cleaning, enabling treatment of extremely complex wastewater containing substantial suspended solids. However, this configuration results in low packing density and reduced operational flux. Furthermore, tubular membranes carry a high cost [7].

3. Research on combined ultrafiltration membrane processes

3.1. Ultrafiltration + advanced oxidation processes

The combined application of ultrafiltration (UF) and advanced oxidation processes (AOP) represents a significant integrated technology within water treatment. This synergy effectively leverages the strengths of both techniques, not only enhancing the treatment capacity for recalcitrant pollutants but also mitigating UF membrane fouling to a certain extent.

In research on high-concentration brine treatment, Wang et al. employed advanced oxidation processes as a pre-treatment stage prior to ultrafiltration, establishing a 'chemical softening-advanced oxidation-ultrafiltration' process flow. Results demonstrated that the O_3/H_2O_2 advanced oxidation combination significantly reduced wastewater COD concentrations, substantially alleviating ultrafiltration membrane loading and ensuring stable, reliable operation of the membrane system [8]. In the field of industrial wastewater treatment, Luo et al. combined ultrafiltration membranes with advanced oxidation technology for advanced treatment of mixed industrial effluents. Results demonstrated average removal rates of 92% for suspended solids, 90% for COD, 70% for ammonia nitrogen, 63% for total phosphorus, and 90% for colour. Total coliform removal approached 100%, with effluent fully meeting urban reclaimed water standards [9]. In the paper 'Research Progress on Mitigating Ultrafiltration Membrane Fouling via Ultraviolet Advanced Oxidation Processes,' Lu et al. emphasised that the core of ultraviolet advanced oxidation coupled with ultrafiltration membrane technology lies in combining ultraviolet radiation with oxidants (such as ozone (O_3), hydrogen peroxide (H_2O_2), chlorine (Cl), or persulfate (PS)) to generate highly reactive free radicals (e.g., ·OH or $SO_4^{\cdot-}$). These radicals decompose high-molecular-weight organic compounds into smaller, more readily biodegradable substances, thereby reducing fouling burdens on ultrafiltration membranes. This ultimately enhances overall water purification efficiency and extends the service life of ultrafiltration membranes [10].

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3.2. Ultrafiltration + reverse osmosis technology (UF+RO)

The dual-membrane process integrating ultrafiltration and reverse osmosis technology has now become the core integrated solution for achieving water resource recycling and zero liquid discharge in industrial water treatment. This technological system establishes a scientific pathway of 'tiered treatment progressively enhancing purification efficacy': serving as the critical pre-treatment stage, ultrafiltration effectively removes suspended particles, colloidal substances, bacteria, and high-molecular-weight organic compounds from water through its efficient physical sieving action. This significantly reduces water turbidity and pollution indicators, thereby effectively safeguarding the feedwater quality for subsequent reverse osmosis processes [11]. Reverse osmosis, as the core desalination process, leverages the selective separation properties of semi-permeable membranes to efficiently remove the vast majority of dissolved salts, ions, and small-molecule organic compounds from water, ensuring the final effluent meets water quality standards. The synergistic combination of ultrafiltration and reverse osmosis membranes fully integrates the advantages of both membrane technologies, creating a pronounced synergistic effect. In practical operation, this combination not only achieves a comprehensive removal rate exceeding 90% for COD, ammonia nitrogen, and total dissolved solids, but also demonstrates robust resistance to shock loads, ensuring stable operation under complex conditions [12].

This technology represents a crucial pathway for wastewater resource recovery within the chemical industry. Liu's research demonstrates that employing a dual ultrafiltration-reverse osmosis membrane system in advanced petrochemical wastewater treatment stabilises reverse osmosis permeate conductivity below 150 μS/cm. This approach not only fully meets high-pressure boiler feedwater quality standards but also elevates wastewater reuse rates to over 80%, substantially reducing effluent discharge volumes. Similarly, this technology has yielded notable achievements in the power generation sector [13]. Yang's practical data from a power plant's reclaimed water reuse project demonstrated that the combined ultrafiltration and reverse osmosis process achieved removal rates of 91.67% for organic matter, 93.22% for ammonia nitrogen, and 98.49% for inorganic salts, with effluent fully complying with standards for recirculating cooling system return water [14]. Furthermore, in the Shangdu Thermal Power Plant case study, a full-membrane process employing 'ultrafiltration + two-stage reverse osmosis + electrodialysis' successfully produced ultrapure water, replacing conventional ion exchange processes. This approach not only eliminated secondary pollution from acid-base regeneration but also enhanced system automation.

3.3. Short-flow water purification technology

Short-flow water purification technology denotes a compact water treatment process centred on submerged ultrafiltration membranes, coupled with pretreatment steps such as coagulation, pneumatic flocculation, and powdered activated carbon dosing, while simplifying conventional sedimentation stages [15]. With its notable advantages of compact footprint, rapid construction, and low effluent turbidity, short-process purification technology serves as an efficient, intensive alternative to conventional long-process systems in specific scenarios. It demonstrates strong applicability in upgrading ageing waterworks, emergency water supply expansions, and rural/remote water provision [16]. For instance, during the refurbishment of a surface water treatment plant in Hebei Province, the adoption of an ultra-short process combining 'high-density sedimentation + ultrafiltration' increased production capacity by over 25% while reducing effluent turbidity to below 0.1 NTU. Operating costs rose only marginally, achieving dual improvements in water quality and quantity within constrained land availability.Moreover, the chemical-free, short-process modular

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water treatment plant centred on 'electrocoagulation-ultrafiltration' offers a solution for remote areas featuring low maintenance costs and strong adaptability to raw water sources.

4. Conclusion

As a pivotal technology within modern membrane separation science, ultrafiltration membrane technology plays a crucial role in drinking water purification, industrial wastewater reuse, and pretreatment applications. It efficiently removes suspended solids, colloids, bacteria, and viruses from water, thereby significantly enhancing effluent quality. However, two core challenges persist in the widespread adoption of ultrafiltration membrane technology: membrane fouling remains the foremost issue. As ultrafiltration membranes operate, contaminants adsorb and accumulate on the membrane surface, leading to reduced water production and increased energy consumption. Although regular physical and chemical cleaning can maintain stability, irreversible fouling during operation remains unavoidable. Moreover, frequent chemical cleaning can cause irreversible damage to the membranes. Cost issues remain prominent, with high initial investment, reliance on imported key membrane materials, and ongoing operational energy consumption and cleaning chemical expenses constituting persistent problems. Reducing costs and enhancing efficiency are therefore paramount.

In response to these challenges, ultrafiltration membrane technology is advancing towards high performance and intelligent operation. Firstly, the development and application of new materials, such as hydrophilic modified polymer membranes, nanocomposites like graphene and carbon nanotubes, and ceramic ultrafiltration membranes with enhanced fouling resistance and extended lifespan, aim to improve membrane performance and longevity at the source. Secondly, deep integration with intelligent control systems enables real-time monitoring and maintenance of critical parameters like transmembrane pressure difference and water flux through big data and sensors. This facilitates precise membrane backwashing and chemical cleaning, thereby improving operational efficiency.

References

[1] Lu Xinyu. Current Status and Key Technologies in Urban Domestic Sewage Treatment [J]. Leather Manufacturing and Environmental Protection Technology, 2024, 5(18): 116-118.
[2] Yue Xiaoxia, Yang Fan, Sheng Liang. Application of Ultrafiltration Membrane Technology in Environmental Engineering Water Treatment [J]. Resource Conservation and Environmental Protection, 2020, (03): 93.
[3] Xue Zhen. Preparation and Performance Study of Zinc Oxide Microsphere/Polysulfone Hybrid Matrix Ultrafiltration Membranes [D]. Zhejiang University of Technology, 2017.
[4] Feng Yehui. Application Research of Ultrafiltration Membrane Water Treatment Technology in Industrial Wastewater Treatment [J]. Resource Conservation and Environmental Protection, 2025, (01): 70-73.
[5] Cao Chunna. Current Status of Modified Ultrafiltration Membrane Research [J]. Liaoning Chemical Industry, 2024, 53(08): 1272-1274+1278.
[6] Wang Shungang, Chen Xiaodong, Li Xiaochuan. Application and Operation of Flat Sheet Ultrafiltration Membranes in Wastewater Treatment [J]. Resource Conservation and Environmental Protection, 2025, (08): 24-28.
[7] Tao Zhengxing. Application of Tubular Ultrafiltration Membranes in Reverse Osmosis Concentrate Treatment [J]. Chemical Industry Management, 2021, (36): 39-40.
[8] Wang Qiang, Wei Fengmi, Li Ya, et al. Advanced Treatment of Concentrated Brine and Resource Recovery in Zero Liquid Discharge Systems [J]. Water Purification Technology, 2023, 42(03): 127-135.
[9] Luo Minghan, Chen Qiwen, Hou Guohua. Research on Advanced Treatment of Comprehensive Industrial Wastewater Using Ultrafiltration Membrane Combined with Advanced Oxidation Technology [J]. Environmental Engineering, 2015, 33(02): 32-37.
[10] Lu Xiaoyu, Gao Zhimin, Zhu Zhaoliang, et al. Research progress on mitigating ultrafiltration membrane fouling based on ultraviolet advanced oxidation processes [J]. Water Purification Technology, 2023, 42(10): 46-53.

DOI: 10.54254/2755-2721/2026.KA29869

[11] Liu Qiang, Zhang Liguo. A Brief Discussion on the Application of Ultrafiltration Membrane Technology in Environmental Engineering Water Treatment [J]. Leather Manufacturing and Environmental Protection Technology, 2024, 5(15): 14-16.
[12] Peng Qiaoling, Cao Shunan, Zheng Guanwen. Application of Ultrafiltration and Reverse Osmosis Technologies in Reclaimed Water Reuse at Power Plants [J]. Applied Chemistry, 2017, 46(01): 199-202. DOI: 10.16581/j.cnki.issn1671-3206.2017.01.027.
[13] Liu Juan. Application of Combined Ultrafiltration and Reverse Osmosis Process in Petrochemical Wastewater Reuse [J]. Petroleum & Petrochemical Green & Low Carbon, 2016, 1(05): 43-48.
[14] Yang Fan. Pilot Study on Ultrafiltration Treatment and Reuse of Cooling System Effluent from Power Plants [D]. Huazhong University of Science and Technology, 2004.
[15] Li Qiong. Experimental Research on Pretreatment Technology for Short-Process Water Purification Using Static Pressure Outflow Flat Sheet Membranes [D]. Yangzhou University, 2013.
[16] Cong Xuezhi, Jiao Wenhai, Yang Honghong, et al. Application of Immersed Ultrafiltration in the Retrofit Project of a Short-Process Water Purification Plant [J]. China Water Supply and Drainage, 2023, 39(10): 111-114.