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Challenges and solutions for nanofiltration membranes in water treatment

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Nanofiltration (NF) membranes are a pressure-driven membrane separation technology that lies between reverse osmosis (RO) and ultrafiltration (UF), featuring selective separation of low-molecular-weight organic compounds, divalent ions, and some monovalent ions. Due to their low operating pressure, low energy consumption, and ability to efficiently desalinate while retaining some beneficial minerals, NF membranes have shown broad application prospects in drinking water purification, wastewater treatment, food and pharmaceutical industries, and resource recovery. This article systematically reviews the existing challenges (including trade-off effect between selectivity and flux, membrane fouling and insufficient chemical stability) and the corresponding countermeasures from the perspectives of material modification and structural design, etc., with the aim of providing references for further research and industrial application of NF membranes.

KEYWORDS

nanofiltration, water treatment, trade-off effect, membrane fouling, chemical stability

1 Introduction

With the increasingly severe global water shortage and environmental pollution problems, efficient and energy-saving water treatment technologies have become a research hotspot. Since its development in the 1980s, nanofiltration (NF) technology has been widely applied in several fields, thanks to its unique separation performance (molecular weight cut-off of 200–1,000 Da), relatively low operating pressure (0.5–1.5 MPa), and high selectivity in removing multivalent ions (Zhang et al., 2020; Wieczorek and Ulbricht, 2021; Di et al., 2024; Tan et al., 2025). Compared to reverse osmosis (RO) membranes, NF membranes require less energy for desalination and are capable of retaining certain monovalent ions (e.g., Na^+ and K^+). These properties make NF membranes particularly suitable for applications where high water quality is desired without the need for complete desalination (Zhang et al., 2020).

Interfacial polymerization (IP) is a commonly employed technique for the fabrication of NF membranes. It involves polymerization occurring at the interface between two immiscible solvents, resulting in the formation of an ultrathin and dense separation layer that exhibits highly efficient retention of small organic molecules and divalent ions (Chen J. et al., 2024; Ding et al., 2024). Despite significant progress in NF technology, the following bottlenecks still exist. 1) The trade-off between selectivity and flux: High rejection rates often come with low flux (Ni et al., 2024). 2) Membrane fouling: Adsorption of pollution leads to performance decline (Liu L. et al., 2025; Tan et al., 2025). 3) Insufficient chemical stability: Extreme pH or oxidative environments can cause membrane degradation (Miao et al., 2024; Wang et al., 2024).

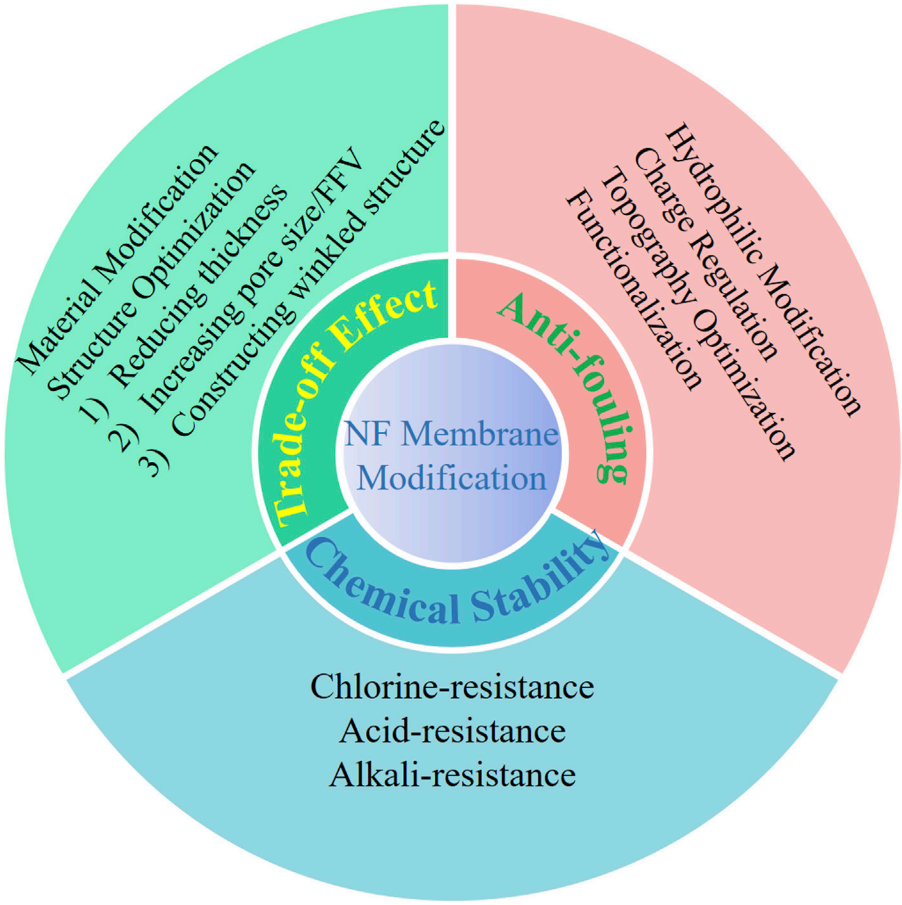

FIGURE 1
Limitations of NF membranes and corresponding countermeasures.

Based on these, this article aims to review the basic design principles of NF membrane and its current research progress in the field of water treatment. Specifically, it provides a comprehensive analysis of the aforementioned challenges associated with NF membranes, as well as their modification approaches from the perspectives of material composition and structural design. Finally, it looks forward to the future development directions of NF technology, providing a reference for related research.

2 Limitations of NF membranes and corresponding countermeasures

Up to now, the problems existing in NF membranes and the corresponding modification strategies are shown in Figure 1. The specific analysis is as follows.

2.1 The trade-off effect between selectivity and flux

2.1.1 Material modification

Introducing nanomaterials, such as metal-organic frameworks (MOFs) (Chen Q. et al., 2024), covalent organic frameworks (COFs) (Xiang et al., 2025), graphene oxide (GO) (Feng et al., 2025b), and carbon nanotubes (CNTs) (Ye et al., 2023), into the separation layer can effectively optimize the membrane's pore structure and surface properties. For example, MOFs (e.g., ZIF-8 (Xie et al., 2024) and UiO-66 (Huo et al., 2024; Yu et al., 2024) offer uniform channels and enhance molecular sieving capabilities. COFs, with their tunable pore sizes and excellent chemical stability, can improve membrane selectivity (Xiang et al., 2025). The interlayer nanochannels in GO regulate water transport pathways while maintaining a high rejection rate (Feng et al., 2025b). Additionally, incorporating CNTs with low-friction inner surfaces into the separation layer can accelerate water molecule transport and reduce osmotic resistance (Zhao et al., 2023). Inorganic nanoparticles such as SiO_2 and TiO_2 can also be added into the polyamide (PA) layer to simultaneously enhance mechanical strength and regulate pore size distribution (Yan et al., 2022; Feng et al., 2025a). However, large-scale production of new materials (such as MOFs, COFs, and GO) is challenging due to cost constraints. Besides the above-mentioned nanomaterials, adjusting the membrane surface wettability through block copolymers with hydrophilic/hydrophobic chain can reduce membrane fouling and optimize flux (Wieczorek and Ulbricht, 2021). Embedding artificial water channel proteins in the separation layer can achieve high selectivity and high flux (Song and Kumar, 2019).

2.1.2 Structure optimization

From the perspective of mass transfer, under the premise of ensuring excellent retention performance, reducing the thickness, increasing the pore size/free volume fraction (FFV), or enhancing the effective filtration area of the separation layer can also effectively break the trade-off effect. The IP process was optimized (such as adjusting the monomer concentration and changing the reaction interface) to prepare ultra-thin but dense PA layers, reducing mass transfer resistance (Liu G. et al., 2025). The incorporation of additives into the aqueous phase can also control the IP rate by regulating monomer diffusion, thus enabling the fabrication of a thinner separation layer (Zhang et al., 2022; Zhang et al., 2024; Wang et al., 2025a). In addition to directly controlling the separation layer thickness through aforementioned factors, the substrate can also be pre-modified by depositing a hydrophilic intermediate layer to improve control over the IP process and facilitate optimization of the separation layer structure (Wang et al., 2025b). The hydrophilic surface of the intermediate layer adsorbs amine solution, thereby increasing the local concentration of amine monomers near the reaction interface. This higher amine concentration, combined with the reduced surface pore size of the intermediate layer, helps suppress defect formation in the PA layer and enhances separation performance. Moreover, hydrogen bonding interactions between the intermediate layer and amine molecules can effectively slow down the diffusion of amine monomers, further limiting their supply in the reaction zone and promoting the formation of a thinner PA layer. Nevertheless, achieving a defect-free ultrathin separation layer remains challenging in practical applications.

By designing novel monomers for IP, the pore size distribution and FFV of the PA separation layer can be precisely controlled, thereby optimizing the permeability-selectivity balance of NF membranes. Specific strategies can be classified into the following types. 1) Introduction of rigid/distorted monomers: The use of monomers containing bulky groups or non-planar structures can increase the packing defects in the polymer chains, resulting in larger free volume and wider pore size distribution (Liu Y. et al., 2023; Peng et al., 2023; Tang et al., 2023). For instance, the PA network formed by the polymerization of a quaternized-spiro PIP and TMC has a 6% increase in FFV due to the enhanced rigidity of the designed monomer, leading to a higher permeance (~22 L m^{-2} h^{-1} bar^{-1}) (Peng et al., 2023). 2) Using macromolecule to react with TMC. Macromolecules have a relatively high steric hindrance and can react with TMC to increase the FFV of the PA layer (Wang et al., 2025a). For instance, ε-Polylysine/TMC system exhibits a larger FFV (from 15.64% to 38.85%) compared to Lysine/TMC system (Wang et al., 2025a). In addition to modulating the network structure by directly incorporating new monomers into the IP process, post-treatment methods can also be employed to dynamically adjust the network density through the reactive functional groups (e.g., hydroxyl, carboxyl, and amino groups) in monomers or additives (Yu et al., 2022; Mi et al., 2024).

By optimizing the kinetics of IP or introducing external control measures, wrinkled structures can be formed on PA layer surface, thereby significantly increasing the actual active area and simultaneously optimizing the mass transfer pathways. During the IP process, by adding surfactants (such as SDS) or polymers (such as PVA) to regulate the diffusion rate of amine monomers (such as PIP), interfacial instability is induced, resulting in the formation of nano-scale wrinkles or stripe patterns (Tan et al., 2018; Huo et al., 2022). By temporarily supporting the PA layer with removable templates such as $Cd(OH)_2$ nanowires during the IP process, a hollow wrinkled structure is formed after the removal, increasing the effective area (Karan et al., 2015).

2.2 Strategies for improving membrane anti-fouling performance

The improvement of the anti-fouling performance of NF membranes is one of the cores of its application. The key idea of the modification strategy is to change the properties of the membrane surface through physical or chemical methods, thereby weakening the interaction between pollutants and the membrane surface. Specific strategies need to be developed to direct the regulation of membrane surface properties in accordance with the composition of water.

2.2.1 Hydrophilic modification

The specific method involves immobilizing hydrophilic polymers or zwitterionic polymers on membrane surface through surface coating or surface grafting, forming a stable hydration layer on membrane surface as a physical barrier to effectively prevent the adhesion of hydrophobic organic substances (such as proteins, oils), colloids and other contaminants (You et al., 2017; Ding et al., 2021). Among them, zwitterionic polymers have positive and negative charge centers in their molecular structure, which can combine a large number of water molecules through strong ionic hydration to form a super-hydrated layer, and have excellent resistance to various pollutants (Ding et al., 2021). In addition to enhancing hydrophilicity through polymers, as mentioned in Section 3.1.1, some nanomaterials can also improve the hydrophilicity of the membrane surface and endow it with anti-fouling properties.

2.2.2 Surface charge regulation

By altering the charge nature of the membrane surface, electrostatic repulsion (Donnan effect) is utilized to repel contaminants with the same charge (Song et al., 2021; Liu H. et al., 2023; Hui et al., 2025). Most natural organic matter, colloidal particles and microorganisms in natural water bodies carry a negative charge. By sulfonating, carboxylating and other methods to make the membrane surface carry a strong negative charge, these pollutants can be effectively repelled, reducing organic and colloidal pollution. In specific scenarios (such as removing positively charged certain dyes), positively charged NF membranes are also designed. The key lies in the targeted design based on the charge characteristics of the target pollutants.

2.2.3 Surface morphology and roughness optimization

Altering the structure of the membrane surface can affect the way pollutants interact with the membrane and the hydrodynamic behavior. A smooth surface can reduce the anchor points for pollutant deposition, making it less likely for pollutants to adhere and easier for them to be washed away by water flow (Wang et al., 2023; Zhuang et al., 2024). The lotus leaf effect, which involves designing micro-scale patterns on the surface, can not only reduce the actual contact area between pollutants and the membrane surface but also alter the flow field on the membrane surface, generating local turbulence and enhancing shear force, thereby reducing concentration polarization and pollutant deposition.

2.2.4 Functionalization

Introducing specific chemical functional groups on membrane surface endows it with special properties (Liu L. et al., 2025). For instance, grafting quaternary ammonium salts, antimicrobial peptides or loading silver nanoparticles (AgNPs), copper nanoparticles can endow the membrane surface with antibacterial properties. However, it should be noted that all the above substances are based on killing bacteria, and secondary pollution caused by dead cells should be prevented. Therefore, preventing the initial adhesion of microorganisms through a highly hydrophilic or zwitterionic surface to avoid pollution caused by dead cells becomes an excellent strategy for enhancing the antibacterial properties of membranes.

2.3 Chemical stability improvement

The chemical stability of membrane materials is insufficient in extreme pH and oxidative environments, which can easily lead to performance degradation or structural damage, restricting their long-term application. In water treatment, the chemical degradation of NF membranes mainly includes hydrolysis reactions and oxidative erosion. The amide bonds within the PA layers are susceptible to hydrolysis under strongly acidic or alkaline conditions, which can lead to the disruption of the cross-linked network structure. Free chlorine (such as sodium hypochlorite) can attack the N-H bonds in the PA layer, forming chloramines or causing chain breaks. The chemical stability of nanofiltration membranes can be enhanced through novel membrane design. For example, developing polyester materials with chlorine-free attack sites (Li et al., 2024), acid-resistant polysulfonamides (Lai et al., 2022), and acid/alkali-resistant polyureas (Wang et al., 2024) not only ensures the long-term stable operation under harsh conditions, but also enables the membrane to withstand more extreme chemical cleaning conditions. However, the improvement of the stability of novel membrane is also only focused on a certain aspect. For instance, although polyester membranes have chlorine resistance, the ester bonds are prone to hydrolysis under alkaline conditions, leading to a sharp decline in performance. Therefore, the chemical stability of NF membranes should be determined by selecting materials and modification strategies based on specific application scenarios.

3 Summary

NF, as an efficient and energy-saving separation technology, holds broad application prospects in the field of water treatment. This paper reviews the main challenges faced by NF membranes and the corresponding improvement strategies. Despite numerous challenges, with the development of new materials and new processes, NF technology is expected to play a greater role in the field of water treatment. Future research should focus on the development of high-performance membrane materials, system optimization and intelligent operation to promote the wider application of NF technology. For example, from the perspective of membrane materials, more regular nanopores can be precisely constructed at atomic level to enable high-speed water molecule transport with near-zero friction and highly selective ion screening. Meanwhile, inorganic-organic hybrid membranes can employ "rigid-flexible integration" strategy by embedding rigid, well-defined channels within a flexible polymer matrix, thereby significantly improving the flux and chemical stability to withstand harsh environments.

Author contributions

MS: Conceptualization, Visualization, Writing – original draft. YZ: Conceptualization, Validation, Writing – original draft. SL: Conceptualization, Investigation, Writing – review and editing. YW: Conceptualization, Investigation, Writing – review and editing. TL: Conceptualization, Investigation, Project administration, Writing – review and editing.

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Conflict of interest

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