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REVIEW ARTICLE

Advances In Reverse Osmosis and Nanofiltration Membrane Technologies for Sustainable Water Treatment and Desalination

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ABSTRACT: Worldwide water scarcity and contamination are increasing problems because of population growth, industrialization, and agriculture. Traditional water treatment processes are unable to remove the large quantities of emerging pollutants, and thus, there is a trend toward using membrane technology. In this paper, we review the development, performance, and applications of reverse osmosis (RO) and nanofiltration (NF) membranes. RO modules such as plate-and-frame, tubular, spiral-wound, and hollow fiber RO modules are compared in terms of their flux, salt rejection, energy requirements, and fouling resistance. The applications of RO and NF membranes for desalination and wastewater treatment are highlighted. NF operates between ultrafiltration and RO and has lower energy consumption than RO, and it can remove certain selective ions. NF can remove divalent ions and is effective at removing organic pollutants and heavy metals. Integrated cascading systems, Ultrafiltration (UF)-NF system or Powdered activated carbon (PAC)-NF system, were investigated, and the integrated system was found to improve NF performance by reducing fouling and extending the lifetime of the membrane. Case studies show that in two coastal villages in South China, membrane technology has provided the coastal villagers with a means of obtaining freshwater from seawater. We conclude that RO and NF have indispensable roles to play in the future of water management. However, NF coupled with appropriate pretreatment may provide more cost-effective and more environmentally sustainable solutions. Policy recommendations include investment in decentralized membrane systems fueled by renewable energy and training of local technicians to ensure long-term safe water supplies and sustainable resource use.

KEYWORDS: Engineering, Environmental Engineering, Water Resources Management, Recycling and Waste Management.

Introduction

With the vast development of industrial and agricultural demands and the booming global population, water source shortages and wastewater contaminants are no longer problems in a specific area but have become global problems.[1] We have an urgent need for sustainable water management, emphasizing technological solutions such as wastewater contaminants reuse, desalination, and improved water infrastructure. However, conventional water treatment methods cannot satisfy the emerging contaminant removal, so the advanced treatment technology, such as membrane filtration, has been developed.[2] In a case study in South China, many less-developed coastal fishing villages were found to be in short supply of fresh water. Due to their exceptional geographical advantages, they can filter seawater to obtain sufficient freshwater resources. This review aims to provide a comprehensive overview of reverse osmosis membranes and nanofiltration membranes technologies, discussing their recent development, key performance parameters, applications, and future perspectives. Local people and governments can use the information and suggestions provided by this paper to take some corresponding measures. Additionally, real-world case studies are included to illustrate practical applications.

Discussion

Reverse osmosis (RO) membrane:

Reverse osmosis (RO) is a membrane-based separation process used to remove dissolved salts, contaminants, and other impurities from water. It pushes water under a semi-permeable membrane under pressure and separates ions, molecules, and impurities in water by taking advantage of the selective permeability of specific membranes. Water is divided into two streams: one with low solubility and the other with high solubility.[3] Low-solubility streams are called osmotic water or product water, while high-solubility streams are called concentrated water, brine, or waste liquid. Osmosis is a natural process that allows a highly concentrated solution to flow into a compartment with a weaker concentration of dissolved solids. If the concentration changes on either side of the membrane, the direction in which the water flows will not change[4] (Figure 1).

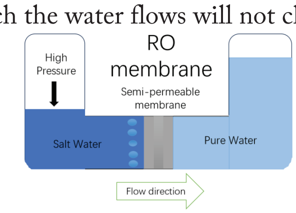

Figure 1: The process of the reverse osmosis membrane, which shows how the RO membrane works. In the schematic diagram, High pressure is applied to feed water, forcing pure water through a semi-permeable membrane while dissolved salts are retained. The blue dots represent sodium ions and chloride ions that are blocked by the membrane.

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Before using the RO membrane, sewage needs to undergo pretreatment. There are four kinds of common pretreatments. The first one is the sand filter. It can remove colloidal particles and silt to reduce raw water's turbidity. The second treatment is using liquid chlorine or sodium hypochlorite to kill the bacteria in the raw water. Next, activated carbon is used to absorb organic substances and residual chlorine in the raw water. The final method is the secondary filter. The filtration accuracy is 1μ, 3μ, or 5μ. RO membranes have four different types of modules: Plate-and-Frame Module, Tubular Module, Spiral-Wound Module, and Hollow Fiber Module. The paper is going to talk about their definition, characteristics, functions, and operation. First, the plate-and-frame Module uses flat membranes arranged between supporting layers, similar to the setup of a plate heat exchanger. The layers are stacked inside a rigid frame. There are key performance parameters of the Plate-and-Frame Module.[5] Parameters, as seen in Table 1, depend on feedwater quality and operating conditions.

Table 1: Typical operating parameters and performance characteristics of a Plate-and-Frame Reverse Osmosis Module for brackish water treatment.[5-7]

Parameters	Description
Flux	10–20 L/m²·h
NaCl Removal Efficiency	95–98%
Operating Pressure	4–10 bar
Operating temperature	45°C.
Recovery Rate	30–50%
NaCl Concentration in Feed Water	2,000 ppm
SDI	5
Electrical Conductivity	3,000 μS/cm
packing density	45–150 ft²/ft³

The module operates at low to moderate pressure. It has low recovery rates due to design limitations. The Plate-and-Frame Module can handle higher SDI values due to the ease of cleaning.[6] Simple and accessible design makes the plate-and-frame module easy to open for cleaning or membrane replacement.[7] However, it not only has a low packing density but also has a higher manufacturing cost and is easily prone to creating dead zones, which increases the risk of fouling. So, the plate-and-frame module is ideal for small-scale or specialized applications like leachate or sludge filtration. The operation mechanism is that when water flows across the membrane surface, clean water passes through, and the remaining concentrate is drained off.

Second, the Tubular Module is composed of some tubes with membranes inside a pressure casing. Water flows through the inside of these tubes. The Tubular Module can handle feedwater with high solids because of its wide flow channels. There are key performance (Table 2) parameters for the Tubular Module.

Table 2: Operating parameters for a Tubular Reverse Osmosis Module, demonstrating its suitability for higher-salinity or fouling-prone feed waters.[7,8]

Parameters	Description
Flux	15–30 L/m²·h
NaCl Removal Efficiency	95–99%
Operating Pressure	4–30 bar
Operating temperature	45°C
Recovery Rate	50–70%
NaCl Concentration in Feed Water	5,000 ppm
SDI	5
Electrical Conductivity	5,000 μS/cm
packing density	6–120 ft²/ft³

The Tubular Module has strong resistance to fouling and is easy to clean using mechanical or chemical methods, so it's suitable for industrial and food wastewater. But it has low packing density, so it is expensive.[8] The Tubular Module is best for purifying wastewater streams. Water runs through the tubes, permeates the filters, and exits through the membrane wall, and the remaining solution exits separately.

Moreover, the Spiral-Wound Module has a compact design where sheets of membrane and spacer material are wrapped around a central collection pipe, forming a spiral pattern.[9] There are several parameter indices (Table 3).

Table 3: The table of the Spiral-Wound Module's parameters[9-11]

Parameters	description
Flux	12-18 L/m²·h
NaCl Removal Efficiency	99.40%
Operating Pressure	69 bar
Operating temperature	45°C
Recovery Rate	50–75%
NaCl Concentration in Feed Water	32000 ppm
SDI	< 3
Electrical Conductivity	64000 μS/cm
packing density	150-1500 ft²/ft³

It offers a good balance between cost, efficiency, and space use. It is commonly used in salty water and seawater desalination. Membrane replacement and scaling are manageable due to standardized sizes. But it is more vulnerable to fouling, especially without proper pretreatment.[10] Spiral-Wound Module is popular in municipal and industrial RO systems. The operation mechanism is that water spirals along the membrane surface, with clean water flowing into the center tube and concentrate leaving at the module's end.[11]

Finally, the Hollow Fiber Module is composed of thousands of small, hair-like hollow fiber membranes, which are put in a vessel.[12] It has the highest packing density-150-1500 ft^2/ft^3, so it is very small and lightweight.[13] But it is easiest to foul and clog, so it is common in ultrafiltration and microfiltration rather than reverse osmosis. The parameters are shown in Graph [14] (Table 4).

Table 4: High-pressure performance parameters of a Spiral-Wound Reverse Osmosis Module, indicative of configurations used in seawater desalination.[12-14]

Parameters	description
Flux	40-80 L/m²·h
NaCl Removal Efficiency	/
Operating Pressure	≤1.2 bar
Operating temperature	5-45°C
Recovery Rate	90%
NaCl Concentration in Feed Water	/
SDI	≤3
Electrical Conductivity	2000 μS/cm
packing density	90-305 ft²/ft³

Certain parameters vary widely depending on membrane material and operational configuration. Therefore, representative ranges are not consistently reported across the literature. The Hollow Fiber Module is well-suited for low-pressure operations or as a pretreatment step. The mechanism is that water flows either through the inside or around the outside of the fibers, with clean water collected from the opposite side.

The reverse osmosis membrane is applied in seawater and wastewater contaminant removal and deep treatment. Although reverse osmosis membrane modules differ in structure and performance, their operational trade-offs become clearer when their parameters are compared. Plate-and-frame modules are relatively easy to clean but have lower packing density, making them suitable for small-scale applications. Tubular modules tolerate feedwater with higher suspended solids but require more space due to their lower packing density. Spiral-wound modules offer a balance between efficiency, compact design, and cost, which explains their widespread use in desalination plants. Hollow fiber modules provide extremely high packing density but are more susceptible to fouling because of their narrow flow channels. These differences indicate that module selection should consider operating conditions, maintenance requirements, and economic constraints. For instance, in situations where electricity costs are high or unstable, compared to methods with lower pressure, such as nanofiltration, reverse osmosis may not be the most sustainable solution.

Nanofiltration (NF):

Nanofiltration is a separation process driven by pressure that operates between ultrafiltration and reverse osmosis. NF membranes have pore sizes less than 2 nanometers and a molecular weight cut-off (MWCO) ranging from 150 to 800 Daltons.[15] They are effective in removing divalent and larger monovalent ions, organic molecules, and certain salts, so they are suitable for various water treatment applications (Figure 2). Compared with RO systems, nanofiltration typically operates at lower pressures and therefore consumes less energy. While RO removes nearly all dissolved salts, NF selectively removes divalent ions and organic molecules, making it particularly suitable for water softening and wastewater treatment.

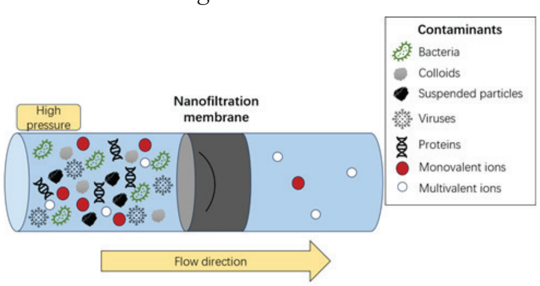

Figure 2: The processes of nanofiltration. High pressure is applied to feed water, forcing pure water through a semi-permeable membrane while dissolved salts are retained.

Nanofiltration has four modules: Spiral-Wound modules, Tubular Modules, Hollow Fiber Modules, and Plate-and-Frame Modules. They have different characteristics and applications because of their parameters, as depicted in Figure 6. Spiral-Wound Modules are commonly used and ideal for municipal and industrial water treatment because of their compact design and high surface area.[9] Tubular Modules are suitable for high-sticking or high-fouling feedwaters,[16] so they are often used in the food and beverage industries. Hollow Fiber Modules offer high packing density and are used in applications that require low-pressure operations.[17] Plate-and-Frame Modules can be cleaned and replaced easily,[18] so they are used in niche applications. The key parameter is 20-80% NaCl Removal.

Table 5: Comparison of key characteristics for the four main nanofiltration module types, illustrating trade-offs in packing density, operating pressure, flux, NaCl rejection, cleaning, and typical applications.[16-18]

Module Type	Packing Density (m^2/m^3)	Pressure (bar)	Flux ($L/m^2 \cdot h$)	NaCl Rejection (%)	Applications	Cleaning
Spiral-wound	~300–800	4–10	12–18	46–97	Groundwater, heavy metals	Chemical cleaning
Tubular	~60–200	4–10	Varies	50–90+	Wastewater, dyes, leachate	Physical/manual
Plate-frame	~60–300	4–10	Varies	Similar to tubular	High-fouling industrial streams	Manual cleaning
Hollow-fiber	~6,000	2–4	Similar-higher	Divalent ions high	Fouling feed, reclamation	Hydraulic methods

Case studies of integrated cascading systems:

There are seven integrated cascading systems. The first one is an integrated cascading coagulation-flocculation-sedimentation (CFS)-NF system. (Figure 3) By adding coagulants in a rapid mixing chamber, suspended particles and colloids in water can aggregate to form larger flocs, which is convenient for subsequent removal.[19] This method can effectively reduce the turbidity and organic matter content of water, so the practice reduces membrane fouling. The second practice is an integrated cascading powdered activated carbon (PAC)-NF system (Figure 3). 10-50mg/L PAC mixes with water for 10-30 minutes.[20] PAC has a larger surface area so that it can absorb organic and micro pollutants in the water.[21] PAC can not only prevent organic fouling, but also improve the water's taste and odor. The third way is an integrated cascading Ultrafiltration (UF)-NF system (Figure 3). 0.5-4 bar water flows across UF membranes with pore sizes of 0.01 μm.[22] Clean water passes; large particles and microbes are retained. UF can remove colloids, microorganisms, and large organic molecules, so periodic backwashing or chemical cleaning is required. Fouling and SDI are reduced. The next system, ozone, is an integrated cascading biological Activated Carbon (O_3–BAC)-NF system (Figure 3). The process is that ozone gas is bubbled into water for 10-30 minutes. Then, the water flows through the BAC filter, and the microorganisms on the carbon break down the residual organic matter.[19] O_3-BAC degrades organic and biological pollutants, controls biofouling, and removes micropollutants. The fifth integrated cascading system is UV Irradiation (UV)-NF (Figure 3). The operation is that water flows through UV chambers equipped with mercury or LED lamps emitting 254nm wavelength.[23] The exposure time is 10-60 seconds, depending on intensity. However, UV inactivates microorganisms and degrades certain organic compounds, but it does not remove solids. The sixth system is microfiltration (MF)-NF (Figure 3). MF removes large particulates and microorganisms.[24] By reducing turbidity and contaminant loads, MF contributes to higher-quality feed water for NF processes, leading to better overall treatment outcomes. The following integrated cascading system is chemical dosing-NF (Figure 3), including pH adjustment, Antiscalants, and Biocides.

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By adjusting the pH of the influent water, the precipitation of metal ions is promoted, and membrane fouling is reduced. Antiscalants prevent inorganic salts (such as calcium carbonate, calcium sulfate, and barium sulfate) from scaling on the membrane surface, thereby extending the service life of the membrane. Inhibit the growth of microorganisms, prevent the formation of biofilms, and reduce biological contamination. The wide range of pretreatment strategies used before nanofiltration highlights the importance of controlling different fouling mechanisms. Physical pretreatments such as ultrafiltration or microfiltration primarily remove suspended solids and microorganisms, reducing particulate fouling. In contrast, adsorption and advanced oxidation processes target dissolved organic contaminants responsible for organic fouling. Because these methods address different contamination pathways, integrated treatment systems generally outperform single-stage nanofiltration processes by improving membrane stability and extending operational lifespan. Unlike reverse osmosis (RO), which highly relies on high-pressure tolerance and strict inlet conditions, if the nanofiltration system is combined with a well-designed pre-treatment strategy, it will be more cost-effective in the long run.

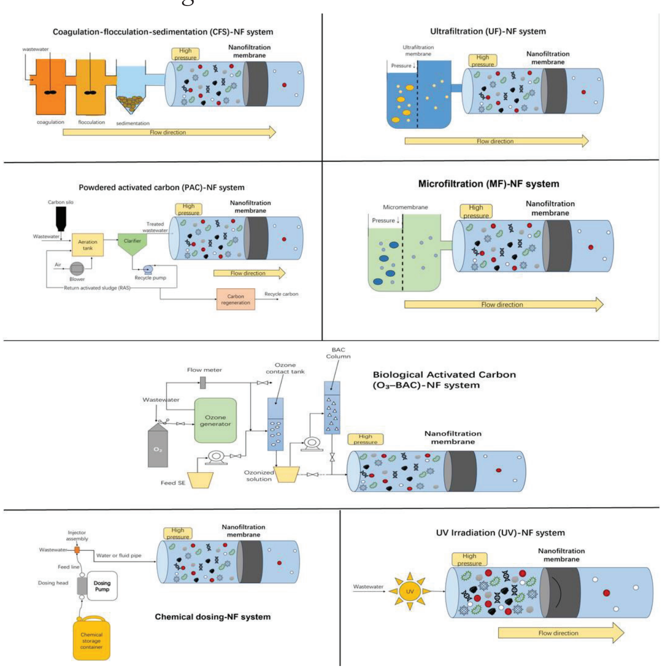

Figure 3: Case studies of integrated cascading systems demonstrate a decrease in economic cost and an increase in water quality after filtration.

Conclusion

In conclusion, both reverse osmosis and nanofiltration technologies play a crucial role in addressing the global water shortage and pollution problems. Although many studies reflect membrane performance under laboratory conditions, more long-term evaluations in real operational environments are needed to better understand fouling behavior and system durability. A reverse osmosis membrane has a high purification performance, while nanofiltration, when combined with appropriate pre-treatment, can provide more energy-efficient and sustainable solutions. Each membrane module has its own advantages, and the choice should be based on the specific application scenario. Based on the technical comparisons discussed in this review, decentralized nanofiltration systems combined with appropriate pretreatment may be particularly suitable for resource-limited regions due to their lower pressure and energy requirements. In addition, establishing training programs for local technicians and encouraging research on low-pollution membrane materials can ensure their long-term effectiveness. By taking these policy measures, the government can enhance the community's ability to access safe water while protecting environmental resources.

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