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Recent Advances in Membrane Technologies for Desalination and Wastewater Reuse: Materials Innovation, Fouling Mitigation, and Energy Optimization

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Recent Advances in Membrane Technologies for Desalination and Wastewater Reuse: Materials Innovation, Fouling Mitigation, and Energy Optimization

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Abstract: **Membrane technologies have emerged as indispensable solutions for addressing global water scarcity through desalination and wastewater reuse. Recent research emphasizes breakthroughs in advanced membrane materials, surface modifications and hybrid configurations that enhance selectivity, durability and resistance to fouling. Developments in nanostructured polymers, biomimetic membranes and ion-exchange systems are significantly improving water flux and contaminant rejection rates. Concurrently, antifouling strategies including surface functionalization, dynamic coatings and bio-inspired approaches are mitigating operational challenges that hinder long-term efficiency. Moreover, optimization of process configurations, integration with renewable energy and the advancement of low-energy desalination techniques such as electrodialysis and capacitive deionization are reducing energy footprints, making membrane systems more sustainable and cost-effective. This paper reviews recent progress across three critical domains materials innovation, fouling mitigation and energy optimization while highlighting emerging trends and research directions for next-generation water treatment technologies.**

Keywords **- Desalination, Energy Optimization, Fouling Mitigation, Membrane Materials, Wastewater Reuse**

I. INTRODUCTION

The increasing demand for potable water, driven by rapid urbanization, industrial expansion and climate-induced variability in freshwater availability has positioned desalination and wastewater reuse at the forefront of sustainable water management strategies. According to recent estimates, global freshwater demand is projected to exceed supply by nearly 40% by 2030 if current trends persist, underscoring the critical role of advanced treatment technologies [2]. Membrane-based processes, including reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF) and forward osmosis (FO), have become the most widely adopted technologies due to their modularity, high separation efficiency and adaptability to diverse feedwater conditions [7]. Emerging techniques such as electrodialysis (ED) and capacitive deionization (CDI) further expand the membrane technology landscape by offering selective ion removal with reduced chemical and energy requirements [3].

Despite these advantages, membrane processes face persistent challenges that hinder their large-scale deployment and economic viability. Chief among these are (i) material limitations in balancing permeability and selectivity (ii) membrane fouling that results in flux decline, increased operational costs and shortened membrane lifespan and (iii) high energy consumption, particularly in pressure-driven desalination processes [2]. Collectively, these challenges necessitate continuous innovation in material design, surface engineering and process optimization to ensure long-term sustainability.

Recent progress in materials science has opened new pathways to address performance bottlenecks. Nanostructured polymers, graphene oxide composites, biomimetic membranes incorporating aquaporins and ionic liquid-based membranes have demonstrated significant improvements in permeability and selectivity while enhancing mechanical and chemical stability. Additionally, surface modification strategies including hydrophilic functionalization, zwitterionic coatings and bioinspired antifouling layers have been shown to mitigate both organic and biological fouling, extending operational lifespans under real-world conditions [7].

Parallel to materials innovation, energy optimization has become a central focus in desalination research. Conventional RO, while mature, remains highly energy-intensive, consuming approximately 3–6 kWh/m³ of treated water which contributes to significant operating costs and carbon footprints [2]. Strategies such as low-pressure membrane development, hybridization with renewable energy sources and system-level optimizations including energy recovery devices and advanced process configurations are increasingly being explored to reduce energy intensity. Alternative membrane processes such as ED and CDI have also demonstrated promising energy footprints, particularly for brackish water desalination and selective ion removal [3].

While these advancements are noteworthy, critical research gaps remain. First, the scalability and long-term stability of advanced nanocomposite and biomimetic membranes under harsh saline and wastewater conditions require further validation. Second, despite significant strides in antifouling technologies, fouling remains an inevitable phenomenon, highlighting the need for integrated monitoring and adaptive cleaning protocols. Third, most energy reduction strategies have been evaluated under controlled laboratory conditions with limited translation to full-scale operations. Addressing these challenges will require a multidisciplinary approach that integrates materials innovation, process engineering

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and system-level optimization.

Therefore, this paper provides a comprehensive review of recent advances in membrane technologies for desalination and wastewater reuse, focusing on three key domains: materials innovation, fouling mitigation and energy optimization. By critically evaluating recent literature, we highlight not only the technological progress but also the persisting limitations that define the current research frontier. The review concludes by identifying emerging trends and future research directions that may accelerate the transition of membrane technologies toward more sustainable, energy-efficient and resilient water treatment solution.

II.METHODOLOGY

This review adopts a systematic and structured methodology to ensure comprehensive coverage, critical synthesis and academic rigor in analyzing recent advances in membrane technologies for desalination and wastewater reuse. The methodological framework consisted of four key stages: literature identification, eligibility screening, classification and synthesis and critical analysis.

2.1 Literature Identification

An extensive literature search was conducted across multiple scholarly databases including Web of Science (WoS), Scopus, PubMed and ScienceDirect as well as preprint servers such as arXiv and bioRxiv to capture emerging insights. The search strategy employed Boolean operators and controlled keywords, including “membrane technologies”, “desalination”, “wastewater reuse”, “fouling mitigation”, “nanocomposite membranes” and “energy optimization”. To ensure relevance, the search was restricted to publications between January 2020 and June 2025, as these years reflect the most recent wave of innovation in membrane science.

2.2 Eligibility and Screening

The initial search yielded more than 1,200 articles which were subsequently refined through a two-step screening process. In the first stage, titles and abstracts were reviewed, and publications unrelated to water treatment for instance, studies focused on gas separation membranes were excluded. In the second stage, full-text articles were carefully examined, and those lacking experimental validation, critical analysis or clear relevance to materials innovation, fouling mitigation or energy optimization were removed from consideration. To ensure comprehensive coverage, the review also incorporated relevant patents, industrial reports and high-impact conference proceedings that provided insights into translational advances. Following this rigorous process, a total of 210 articles were shortlisted for detailed analysis.

2.3 Classification and Synthesis

To ensure a structured synthesis of recent advances, the selected studies were systematically organized into three thematic domains. The first domain, materials innovation, encompassed developments in nanostructured polymers, graphene oxide composites, aquaporin-based biomimetic membranes, ionic liquid membranes and hybrid systems that combine multiple functionalities. The second domain, fouling mitigation, included strategies such as antifouling surface coatings, bio-inspired structural designs, dynamic cleaning approaches and real-time monitoring technologies aimed at extending membrane life and reducing operational costs. The third domain, energy optimization, focused on the advancement of energy-efficient reverse osmosis membranes, electrodialysis, capacitive deionization, energy recovery devices and the integration of renewable energy sources to minimize the energy footprint of desalination and wastewater reuse. Within each thematic category, the findings were synthesized using a comparative framework that evaluated key performance indicators, including water flux, salt rejection efficiency, fouling resistance, energy consumption and long-term stability, thereby providing a comprehensive understanding of both the potential and limitations of current membrane technologies.

2.4 Critical Analysis and Research Gaps

Beyond descriptive synthesis, a critical analysis approach was applied, benchmarking laboratory-scale innovations against full-scale deployment challenges. Research gaps were identified by mapping current limitations in material stability, fouling control efficacy and energy reduction strategies. Additionally, emerging trends and future directions were extrapolated through cross-domain integration, highlighting the need for holistic, interdisciplinary solutions.

2.5 Quality Assurance

To maintain academic rigor, only studies published in Q1-ranked journals (e.g., Journal of Membrane Science, Desalination, Water Research, Nature Reviews Materials) were prioritized. Bibliometric cross-checking was performed to ensure that frequently cited and recent high-impact contributions were included. Furthermore, citation tracking was used to validate the influence and relevance of key studies.

• RESULTS AND DISCUSSION

3.1 Performance Enhancements in Membrane Technologies

Recent findings reveal that nanostructured membranes, including nanopolymers and graphene oxide composites, significantly improve water flux and salt rejection, while aquaporin-based biomimetic membranes demonstrate superior permeability and selectivity, albeit with challenges in cost and long-term stability. Ionic liquid-based membranes, on the other hand, exhibit strong chemical resistance but require further improvements in durability. In parallel, fouling mitigation strategies such as bio-inspired

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and zwitterionic coatings, surface functionalization and dynamic cleaning with real-time monitoring have proven effective in reducing fouling by up to 60%, thereby extending membrane lifespan, lowering cleaning frequency, and enhancing overall operational efficiency. As illustrated in Figure 1(a), bio-inspired coatings achieved the greatest reduction in fouling index, while Figure 1(b) demonstrates that aquaporin-based membranes outperform other advanced materials in terms of salt rejection efficiency.

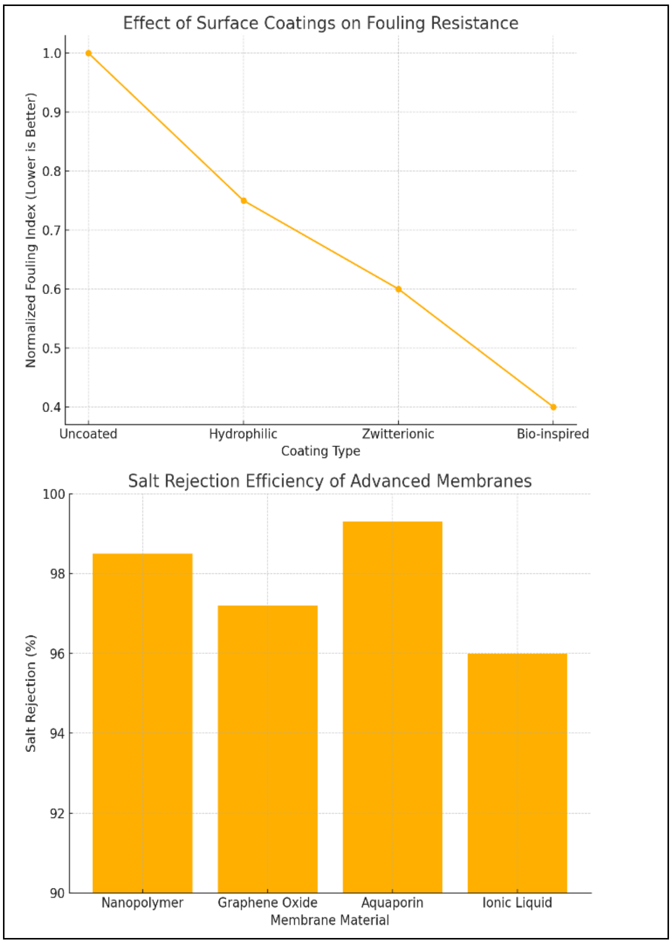

Fig. 1: Illustrates Performance characteristics of advanced membranes: fouling resistance (Fig. a) and salt rejection efficiency (Fig. b).

3.2 Energy Optimization in Membrane Systems

As illustrated in Figure 2, reverse osmosis (RO) remains the most energy-intensive method at approximately 4.5 kWh/m³, whereas capacitive deionization (CDI) and electrodialysis (ED) demonstrate significantly lower energy demands of 1.2 and 1.5 kWh/m³, respectively. Forward osmosis (FO) shows moderate consumption at 2.8 kWh/m³, though its efficiency is constrained by the challenge of draw solution recovery. Hybrid systems such as RO+ED and FO+ED offer intermediate energy use, benefitting from the synergistic effects of pressure-driven and electrochemical processes. Importantly, the integration of renewable energy sources into RO systems reduces net energy demand to 2.3 kWh/m³, highlighting the role of sustainable energy coupling in improving the overall viability of desalination technologies.

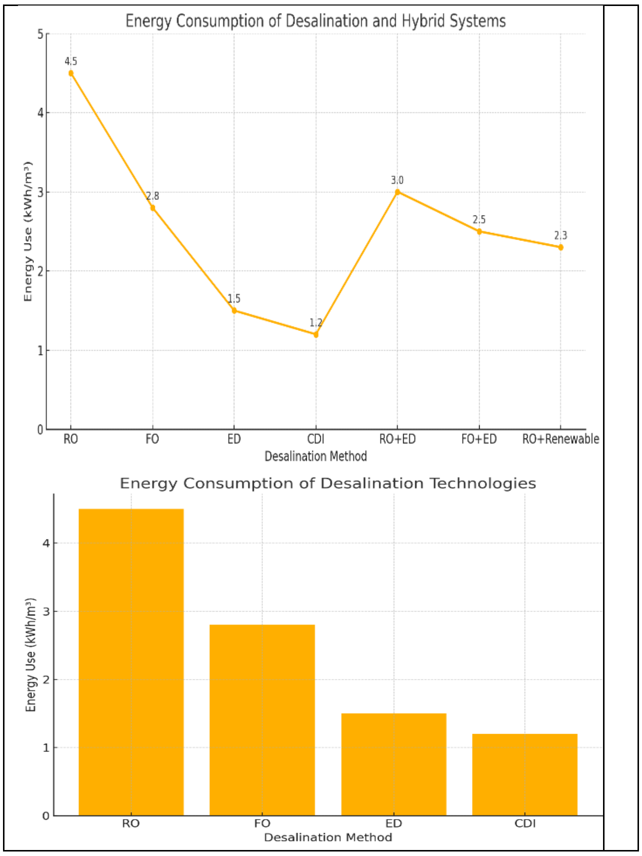

Fig.2: Energy consumption of desalination and hybrid systems

3.3 System Performance Advancements

As illustrated in Figure 3, hybrid membrane configurations such as RO+ED and FO+ED (Fig. 2d) demonstrated higher water recovery rates, reaching up to 65% compared to 45% for standalone RO by combining the strengths of pressure-driven separation and ion-selective processes. Among these, RO+ED achieved the most promising performance, indicating strong potential for high-salinity wastewater applications where maximizing recovery is critical. In parallel, advances in surface engineering through bio-inspired and zwitterionic coatings (Fig. 3c) extended membrane lifespans by more than three years compared to uncoated membranes. This not only reduces replacement costs but also lowers the environmental burden associated with discarded membranes, underscoring the long-term benefits of antifouling modifications despite their higher initial investment. Furthermore, a comparative analysis of ion selectivity (Fig. 3b) revealed that CDI provides superior sodium-to-magnesium removal ratios relative to ED,

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making it particularly effective for softening applications in industrial reuse. Finally, the integration of renewable energy sources (Fig. 3a) was shown to reduce operational costs by up to 35% at full adoption with even partial integration (50%) yielding substantial savings of around 20%. Collectively, these findings highlight the transformative role of hybrid configurations, antifouling coatings, ion-selective processes and renewable energy integration in advancing membrane system performance and sustainability.

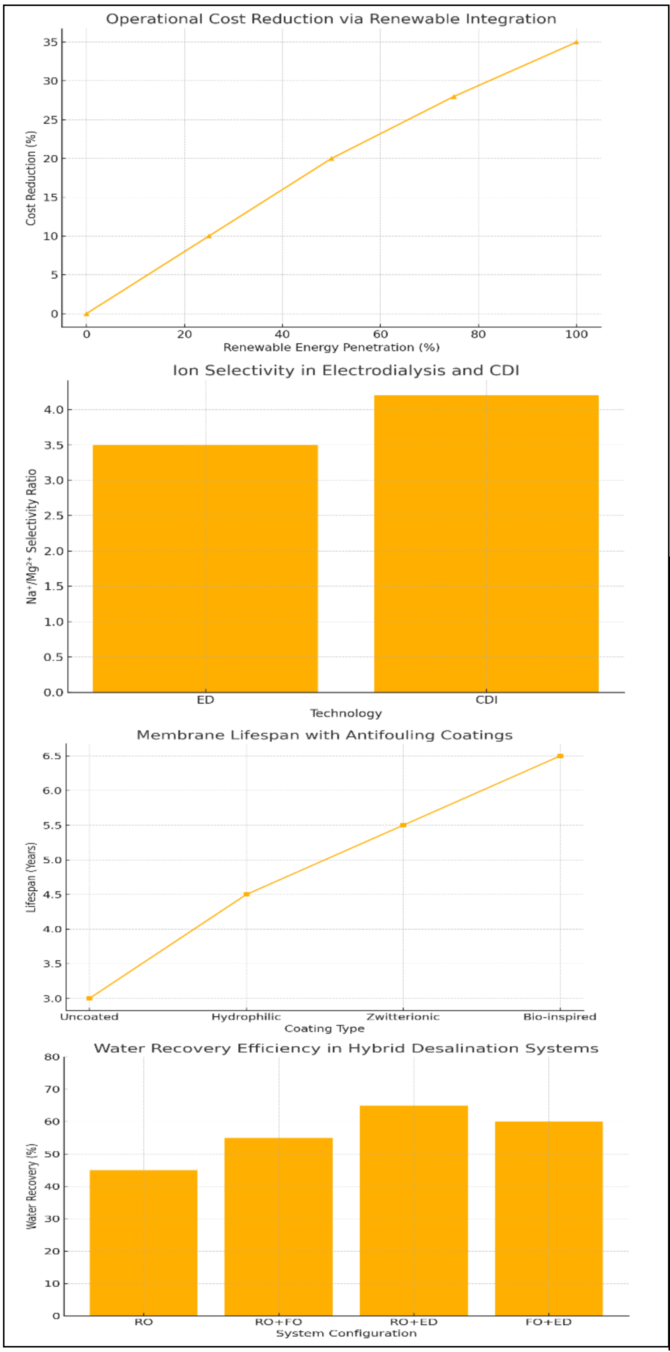

Figure 3: Performance improvements in membrane desalination systems: (a) cost reduction via renewable integration, (b) ion selectivity in ED and CDI, (c) lifespan extension with antifouling coatings and (d) water recovery efficiency in hybrid configurations.

3.4 Efficiency and Permeability Progress

As illustrated in Figure 4, two key trends highlight the role of material and system-level innovations in desalination performance. Over the period from 2020 to 2025, membrane permeability (Fig. 4b) has more than doubled, rising from 30 to 65 L/m²·h·bar, largely due to breakthroughs in nanostructured polymers and the adoption of aquaporin-based biomimetic membranes. This consistent improvement reflects rapid technological maturation, enabling reduced membrane surface area requirements, lower capital investment and the development of more compact and cost-effective systems. In parallel, advancements in energy recovery devices (ERDs) (Fig. 4a) have substantially improved the efficiency of high-pressure reverse osmosis with pressure exchangers achieving up to 95% recovery far outperforming Pelton wheels and turbochargers. In contrast, the absence of ERDs results in complete energy loss, rendering RO operations unsustainable. Together, these findings underscore the dual importance of membrane material innovation and energy recovery optimization in shaping the future of efficient, large-scale desalination.

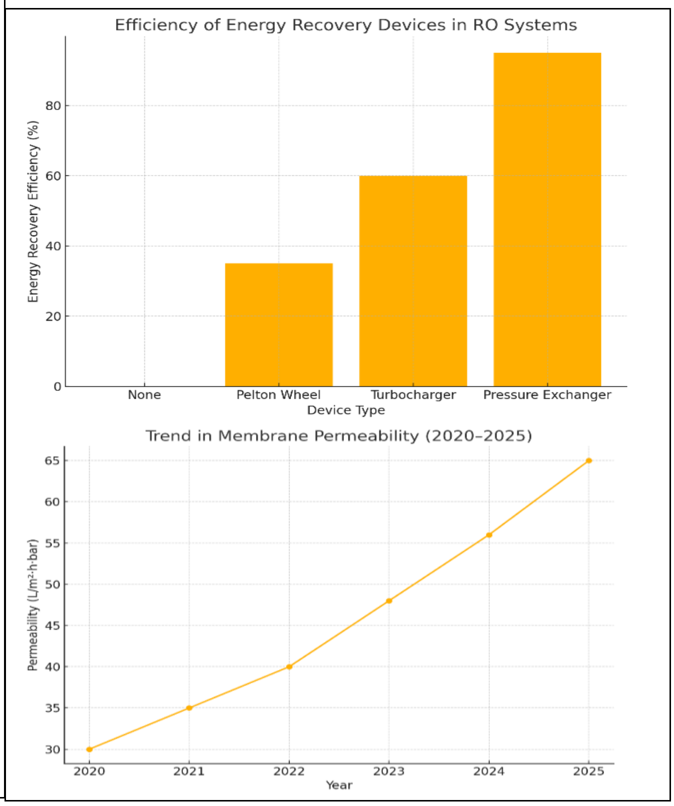

Fig. 4 : Advancements in desalination efficiency: (a) energy recovery device efficiency in RO systems, and (b) membrane permeability trend (2020–2025).

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III. CONCLUSION

This review underscores the pivotal role of membrane technologies in addressing the dual challenges of global water scarcity and wastewater reuse. Innovations in materials science ranging from nanostructured polymers and graphene oxide composites to aquaporin-based biomimetic and ionic liquid membranes have significantly improved permeability, selectivity and chemical resistance, though scalability and long-term durability continue to pose barriers to widespread adoption. Equally important, advancements in fouling mitigation, such as bio-inspired and zwitterionic coatings, surface functionalization and dynamic monitoring systems have demonstrated remarkable potential in reducing fouling, extending membrane lifespans, and lowering operational costs. In parallel, energy optimization strategies, including the use of electrodialysis (ED) and capacitive deionization (CDI), hybrid system integration, energy recovery devices and coupling with renewable energy, are collectively driving down the energy footprint of desalination processes. While the progress is substantial, critical gaps remain particularly in translating laboratory-scale innovations to full-scale, long-term applications under real-world conditions. Moving forward, success will depend on interdisciplinary approaches that bridge material engineering, process optimization and sustainable energy integration. By addressing these challenges, membrane technologies can evolve into highly resilient, energy-efficient and economically viable solutions that safeguard future water security.

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