STM JOURNALS

International Journal of
Membranes

https://journals.stmjournals.com/ijm

ISSN: 3049-4427
Volume 2, Issue 2, 2025
July—December
DOI (Journal): 10.37591/IJM

Review IJM

Advances in Membrane Technology: A Comprehensive Review of Materials, Processes, and Applications

Kulsum Jamal*

Abstract

Membrane technology has become a critical platform for sustainable separation processes across water treatment, energy generation, chemical processing, and healthcare. Over recent decades, advances in materials, fabrication methods, and process design have dramatically expanded the performance, efficiency, and applications of membrane-based systems. Polymeric membranes dominate the industry due to cost-effectiveness and scalability, while ceramic, metallic, and composite membranes offer enhanced thermal and chemical resistance for specialized environments. Nanostructured and bio-inspired membranes, incorporating materials, such as graphene oxide, carbon nanotubes, and functionalized polymers, are transforming the landscape with improved selectivity, permeability, and fouling resistance. Innovations in fabrication techniques, including phase inversion, interfacial polymerization, electrospinning, and additive manufacturing, have enabled membranes with finely tuned properties. Simultaneously, processes, such as reverse osmosis, nanofiltration, forward osmosis, membrane distillation, and membrane bioreactors, have achieved greater efficiency and broader industrial uptake. Applications span water and wastewater treatment, carbon capture, fuel cells, pharmaceuticals, and food processing. Despite these achievements, challenges including fouling, cost, material stability, and energy consumption persist. This review provides a comprehensive overview of recent advances in membrane technology, focusing on materials, processes, and applications. It highlights current challenges and future opportunities in sustainable design, smart membrane development, and integration with emerging technologies such as nanotechnology and artificial intelligence.

Keywords: Membrane technology, nanostructured membranes, separation processes, sustainable design, water treatment

INTRODUCTION

Membranes, as semi-permeable barriers, play a fundamental role in selective separation processes in both natural and engineered systems. Biological membranes, such as cell walls, have long inspired scientists due to their precise control over molecular transport. Industrial adoption of membrane technology began in the mid-20th century, particularly with the development of reverse osmosis (RO) membranes for desalination. Since then, membranes have become indispensable tools in a wide range of industries, from water purification and chemical processing to food, pharmaceuticals, and clean energy [1].

The global challenges of water scarcity, environmental pollution, energy demand, and carbon emissions have accelerated innovation in this field. Membrane technology provides unique advantages compared to conventional separation methods: high efficiency, modular design, lower energy consumption, and the potential for environmentally sustainable operations. The scope of research has expanded from simple pressure-

***Author for Correspondence**
Kulsum Jamal
E-mail: kulsumjamal31@gmail.com

Researcher, Department of Biomedical Science, Jamia Hamdard University, New Delhi, Delhi, India

Received Date: September 14, 2025
Accepted Date: October 15, 2025
Published Date: November 05, 2025

Citation: Kulsum Jamal. Advances in Membrane Technology: A Comprehensive Review of Materials, Processes, and Applications. International Journal of Membranes. 2025; 2(2): 1–6p.

driven membranes to sophisticated hybrid systems, membrane reactors, and smart membranes with stimuli-responsive properties.

This article reviews the advances in membrane technology, structured around materials, fabrication processes, applications, and future perspectives. It provides insights into how membranes have evolved to address complex global issues and the challenges that remain.

FUNDAMENTALS OF MEMBRANE TECHNOLOGY

Definition and Principles

A membrane is a selective barrier that separates two phases and regulates the transport of substances between them. Transport mechanisms may involve size exclusion, diffusion, charge interactions, or affinity-based selectivity.

Classification of Membranes

Membranes can be classified based on structure, material, and driving force:

- *By Structure:* Symmetric, asymmetric, and composite membranes.
- *By Material:* Polymeric, ceramic, metallic, and hybrid membranes.
- *By Driving Force:* Pressure-driven (RO, NF, UF, and MF), concentration-driven (FO), thermal-driven (membrane distillation), and electrically driven (electrodialysis).

Advantages of Membrane Processes

Membranes offer modularity, compact design, scalability, and reduced chemical requirements. Unlike distillation or chemical treatments, membranes operate at lower temperatures and with fewer hazardous by-products [2].

MATERIALS IN MEMBRANE TECHNOLOGY

Polymeric Membranes

Polymeric membranes dominate industrial use due to low cost, ease of fabrication, and flexibility. Common polymers include polysulfone (PSf), polyethersulfone (PES), cellulose acetate, and polyvinylidene fluoride (PVDF). They are widely used in water treatment, ultrafiltration (UF), and nanofiltration (NF) systems [3].

Ceramic Membranes

Ceramic membranes, made from alumina, zirconia, or silica, offer excellent thermal, chemical, and mechanical stability. They are suited for harsh industrial environments such as petrochemical processes or hot wastewater treatment. However, high production costs limit widespread adoption [4].

Metallic Membranes

Metals, like palladium, are used in hydrogen separation and catalytic membrane reactors. They offer high selectivity but are costly and prone to embrittlement [5].

Composite and Hybrid Membranes

Recent years have seen growth in mixed matrix membranes (MMMs), which combine polymers with nanoparticles such as zeolites, graphene oxide, or carbon nanotubes. These enhance permeability, selectivity, and antifouling capacity [6].

Bio-Inspired and Nanostructured Membranes

Aquaporin-based biomimetic membranes replicate natural water channels, achieving exceptional selectivity. Nanomaterials, such as graphene and MOFs (metal–organic frameworks), are revolutionizing design by enabling ultrathin, high-flux membranes [7].

MEMBRANE FABRICATION TECHNIQUES

The performance and functionality of membranes are heavily influenced by the fabrication method employed. Various techniques have been developed to control membrane structure, porosity, surface characteristics, and overall performance to meet specific application requirements.

Phase Inversion

Phase inversion is a foundational method for creating porous polymer membranes. It involves the transformation of a polymer solution into a solid membrane through solvent exchange. Depending on the conditions, such as temperature and nonsolvent type, the pore structure can be finely tuned. Common approaches include immersion precipitation and vapor-induced phase separation, each offering different control over morphology and performance [8].

Interfacial Polymerization

Used extensively in thin-film composite membrane production, interfacial polymerization involves a reaction between two immiscible monomers – typically in aqueous and organic phases. This process creates an ultrathin, dense selective layer ideal for applications like RO and NF [9].

Electrospinning

Electrospinning uses high-voltage electric fields to produce nanofibers with adjustable diameters. These membranes exhibit high surface area and interconnected pores, making them suitable for high-efficiency filtration and biomedical uses [10].

Additive Manufacturing (3D Printing)

3D printing introduces a new era in membrane design by enabling precise control over geometry and structure. It supports rapid prototyping and the development of complex membrane architectures [11].

Surface Modification

To enhance membrane performance, surface treatments, such as plasma activation, grafting, and nanoparticle coating, are applied. These modifications improve antifouling properties, hydrophilicity, and resistance to harsh chemical environments [12].

ADVANCES IN MEMBRANE PROCESSES

Membrane processes have evolved significantly, enabling more efficient, sustainable, and versatile separation technologies across various sectors. Innovations in materials and system design are pushing performance boundaries while addressing energy and environmental challenges.

Pressure-Driven Processes

Pressure-driven processes remain central in membrane technology. RO is the benchmark for desalination, with recent developments focusing on energy reduction, chlorine resistance, and improved membrane longevity. NF, targeting divalent ions and organic molecules, is being increasingly used in pharmaceutical purification and water softening. UF and microfiltration (MF) offer reliable separation of macromolecules and particulates, making them indispensable in food, wastewater, and bioprocessing industries [13].

Osmotic Processes

Forward osmosis (FO) exploits osmotic pressure gradients rather than hydraulic pressure, offering lower energy consumption. It is increasingly explored in industrial wastewater recovery and brine management. Pressure-retarded osmosis (PRO), although still under development, shows promise for generating renewable energy from salinity gradients.

Membrane Distillation (MD)

MD uses thermal gradients to drive vapor transport through hydrophobic membranes. It is particularly appealing for desalination where low-grade or waste heat is available [14].

Gas Separation Membranes

Gas separation membranes are critical in the energy and environmental sectors. Advances in polymer blends and hybrid materials are enhancing both permeability and selectivity [15].

Membrane Bioreactors (MBRs)

MBRs integrate biological treatment with membrane filtration, offering high effluent quality. Innovations focus on reducing energy demand and controlling membrane fouling, making them a robust choice for wastewater treatment.

APPLICATIONS OF MEMBRANE TECHNOLOGY

Water and Wastewater Treatment

Desalination, industrial effluent treatment, and potable water reuse are among the largest applications. Advanced RO and NF membranes are making water security more achievable in arid regions.

Gas Separation and Carbon Capture

Membranes are being developed for CO_2 separation from flue gases, hydrogen purification, and natural gas processing. With the global push for decarbonization, this area is rapidly expanding [15].

Food and Beverage Industry

Applications include whey protein concentration, fruit juice clarification, and beer sterilization. Membranes improve product quality while reducing chemical use.

Biomedical and Pharmaceutical Applications

Membranes are used in hemodialysis, controlled drug delivery, and sterile filtration. Advances in nanofibrous and bio-inspired membranes are opening new opportunities in regenerative medicine [10].

Energy and Fuel Cells

Proton exchange membranes (PEMs) are critical in fuel cells for clean energy. Research is focused on improving durability and conductivity while lowering costs.

CHALLENGES AND LIMITATIONS

Despite significant progress, several challenges persist:

- *Fouling and Scaling:* Biofouling and inorganic scaling reduce membrane performance and lifespan.
- *Cost:* High-performance membranes, especially ceramic and biomimetic, remain expensive.
- *Trade-Off Between Selectivity and Permeability:* Improving one often reduces the other.
- *Environmental Impact:* Disposal of used membranes and energy demand raises sustainability concerns.

FUTURE PERSPECTIVES

Future Directions Include

- The future of membrane technology lies in the convergence of smart design, advanced materials, and digital innovation. Smart membranes, capable of responding to environmental stimuli, such as pH, temperature, or pressure, are emerging as promising tools for dynamic and adaptive separation systems. These membranes can self-regulate their permeability or selectivity, offering enhanced control in real-time applications.
- The integration of nanotechnology is set to revolutionize membrane performance. Materials, like MOFs, carbon nanotubes, graphene, and electrospun nanofibers, are being incorporated into membrane structures to improve mechanical strength, chemical resistance, and transport efficiency. Such nanostructured components also offer opportunities to reduce fouling and extend operational lifespan.
- Artificial intelligence (AI) and digital twin technologies are poised to play a transformative role in process monitoring and optimization. By enabling predictive analytics, these tools can anticipate membrane fouling, recommend operational adjustments, and support proactive maintenance strategies, significantly reducing downtime and operational costs.

- From a sustainability perspective, future membrane development will focus on biodegradable polymers, solvent-free fabrication, and designs that align with circular economy principles. Emphasis on eco-friendly manufacturing and recyclability will reduce environmental impacts across the membrane life cycle.
- By embracing interdisciplinary innovation, membrane technologies will continue to address global challenges in clean water, renewable energy, and environmental stewardship.

CONCLUSION

Membrane technology continues to evolve as a versatile and vital platform for sustainable separation processes across diverse industries. Its role in water purification, environmental remediation, and clean energy solutions has become more pronounced, especially in the face of increasing global resource challenges. Innovations in membrane materials, such as graphene oxide, MOFs, and bio-inspired polymers, are leading to improved selectivity, permeability, and resistance to fouling. These advances are further supported by new fabrication methods that allow for precise control over membrane architecture and function. Beyond material improvements, the integration of membranes with emerging technologies, like AI, machine learning, and real-time sensing, is enabling smarter, adaptive systems capable of predictive maintenance and performance optimization. Additionally, circular economy principles are encouraging the development of recyclable and biodegradable membrane materials to reduce environmental footprints. Despite these advancements, challenges, such as energy-intensive operations, membrane degradation, and high production costs, must still be addressed. Overcoming these limitations will require a multidisciplinary approach, combining expertise from chemistry, materials science, environmental engineering, and data analytics. Looking forward, the convergence of technological innovation and sustainable design will define the next era of membrane development. By prioritizing performance, affordability, and ecological responsibility, membrane technology is well-positioned to support a cleaner, more resilient future across both developed and developing regions.

REFERENCES

1. Baker RW. Membrane technology and applications. 3rd ed. Chichester (UK): Wiley; 2012.
2. Strathmann H. Introduction to membrane science and technology. Weinheim (Germany): Wiley-VCH; 2011.
3. Mulder M. Basic principles of membrane technology. Dordrecht (The Netherlands): Springer; 1996.
4. Leiknes T, Ødegaard H. Ceramic membranes for water treatment: Applications and future outlook. Water Sci Technol. 2018;78(1):1–11.
5. Paglieri SN, Way JD. Innovations in palladium membranes for hydrogen separation. Sep Purif Rev. 2002;31(1):1–169.
6. Lau CH, Li P, Chung TS, Paul DR. Mixed matrix membranes for gas separation: An overview. J Membr Sci. 2013;451:1–80.
7. Zhao Y, Qiu C, Li X, Vararattanavech A, Shen W, Torres J, et al. Synthesis of aquaporin-based biomimetic membranes for desalination. J Membr Sci. 2012;423–424:422–8.
8. Smolders CA, Reuvers AJ, Boom RM, Wienk IM. Formation of asymmetric membranes by phase inversion. J Membr Sci. 1992;73(2–3):259–75.
9. Petersen RJ. Composite reverse osmosis and nanofiltration membranes. J Membr Sci. 1993;83(1):81–150.
10. Li D, Xia Y. Electrospinning of nanofibers: Reinventing the wheel? Adv Mater. 2004;16(14):1151–70.
11. Lee A, Elam JW, Darling SB. Membrane materials for water purification: Design, development, and application. Environ Sci Water Res Technol. 2016;2(1):17–42.
12. Wang Z, Ma J, Tang CY, Kimura K, Wang Q, Han X. Membrane surface modification for fouling control: Status and future directions. Chem Soc Rev. 2015;44(10):3813–37.
13. Madaeni SS. The application of membrane technology for water disinfection. Water Res. 1999;33(2):301–8.

14. Alkhudhiri A, Darwish N, Hilal N. Membrane distillation: A comprehensive review. Desalination. 2012;287:2–18.
15. Bernardo P, Drioli E, Golemme G. Membrane gas separation: A review/state of the art. Ind Eng Chem Res. 2009;48(10):4638–63.