STM JOURNALS

International Journal of
Membranes

Volume 1, Issue 1, 2024
January—June
DOI (Journal): 10.37591/IJM

https://journals.stmjournals.com/ijm

Review IJM

Advancements in Nanostructured Membranes for Gas Separation: A Comprehensive Review

Shweta Tomar*

Abstract

Gas separation is vital in petrochemical, pharmaceutical, and environmental industries, yet traditional methods like distillation and cryogenic separation are energy-intensive and inefficient. Nanostructured membranes present a promising alternative, utilizing nanomaterials such as titanium dioxide, silica, carbon nanotubes, zeolite, and metal-organic frameworks to enhance separation efficiency and selectivity while reducing energy consumption. These membranes fall into various categories: polymeric nanostructured membranes, including mixed matrix and thin-film composites; inorganic membranes, such as those made from ceramics or carbon; hybrid membranes combining organic and inorganic elements; bio-inspired membranes that mimic natural processes; and advanced membranes utilizing precise nanoscale engineering. Fabrication techniques like template-assisted methods, layer-by-layer assembly, electrospinning, and self-assembly enable tailored membrane properties. Performance evaluation of these membranes focuses on selectivity, permeability, stability, and scalability. Applications are diverse, ranging from natural gas purification and hydrogen production to carbon dioxide capture and air separation, providing energy-efficient and cost-effective solutions. Challenges such as membrane fouling, scalability, and cost-effectiveness remain, necessitating further research into novel materials, optimized fabrication processes, and integration with other technologies. In order to improve gas separation systems' sustainability and efficiency and open the door for wider industrial usage, these problems must be resolved.

Keywords: Gas separation, nanostructured membranes, polymeric membranes, inorganic membranes, advanced membranes

INTRODUCTION

Gas separation is a critical process across a spectrum of industries, including petrochemical, pharmaceutical, and environmental sectors. In petrochemical industries, separating various hydrocarbons and gases is crucial for producing high-quality fuels and chemicals. Similarly, in pharmaceutical manufacturing, gas separation is essential for purifying gases used in drug synthesis and packaging. Moreover, in environmental applications, gas separation plays a vital role in removing pollutants from industrial emissions and mitigating greenhouse gas emissions [1].

Recent years have seen the views provided by the shift from our linear, fossil fuel-based economy to a sustainable, circular economy. This change is an exciting technological challenge as well as a major social change. The circular economy considers the "take-make-waste" industrial model and seeks to redefine growth. In order to do this, it emphasizes the benefits to society, stresses the significance of renewable resources, embraces new technology, and reconstructs an industrial infrastructure that can replace the extraction of fossil fuels. Additionally, it diverts attention from

*Author for Correspondence
Shweta Tomar
E-mail: swetatomer2001@gmail.com

Student, Department of Biochemistry, Chaudhary Charan Singh University, Ramgarhi, Meerut, Uttar Pradesh, India.

Received Date: May 21, 2024
Accepted Date: May 23, 2024
Published Date: May 29, 2024

Citation: Shweta Tomar. Advancements in Nanostructured Membranes for Gas Separation: A Comprehensive Review. International Journal of Membranes. 2024; 1(1): 31–36.

the urgent environmental and climate change challenges of the day by recycling waste into items with added value [2].

However, conventional gas separation techniques such as distillation, adsorption, and cryogenic separation have inherent limitations. These methods often require high energy inputs, have large physical footprints, and exhibit limited selectivity and efficiency. More effective and sustainable gas separation methods are required as the world's energy needs expand and environmental issues become more urgent.

The limitations of conventional gas separation methods have been addressed by the development of nanostructured membranes, which show great promise in this regard [3]. Various nanomaterial have been incorporated into polymer matrixes to prepare nanostructured membranes for gas separations, including titanium dioxide (TiO2), silica (SiO2), carbon nanotubes, zeolite, and metal organic frameworks (MOF). The selection of the nanomaterial and polymer matrix has been the subject of extensive research recently [4]. By harnessing the unique properties of nanomaterial, such as high surface area, precise pore size control, and molecular selectivity, nanostructured membranes offer the potential to revolutionize gas separation processes. These membranes enable highly efficient and selective separation of gas mixtures while minimizing energy consumption and process complexity. Figure 1 Typical examples of nanoparticles with varying dimensions used in gas and liquid separation nanocomposite membranes [5].

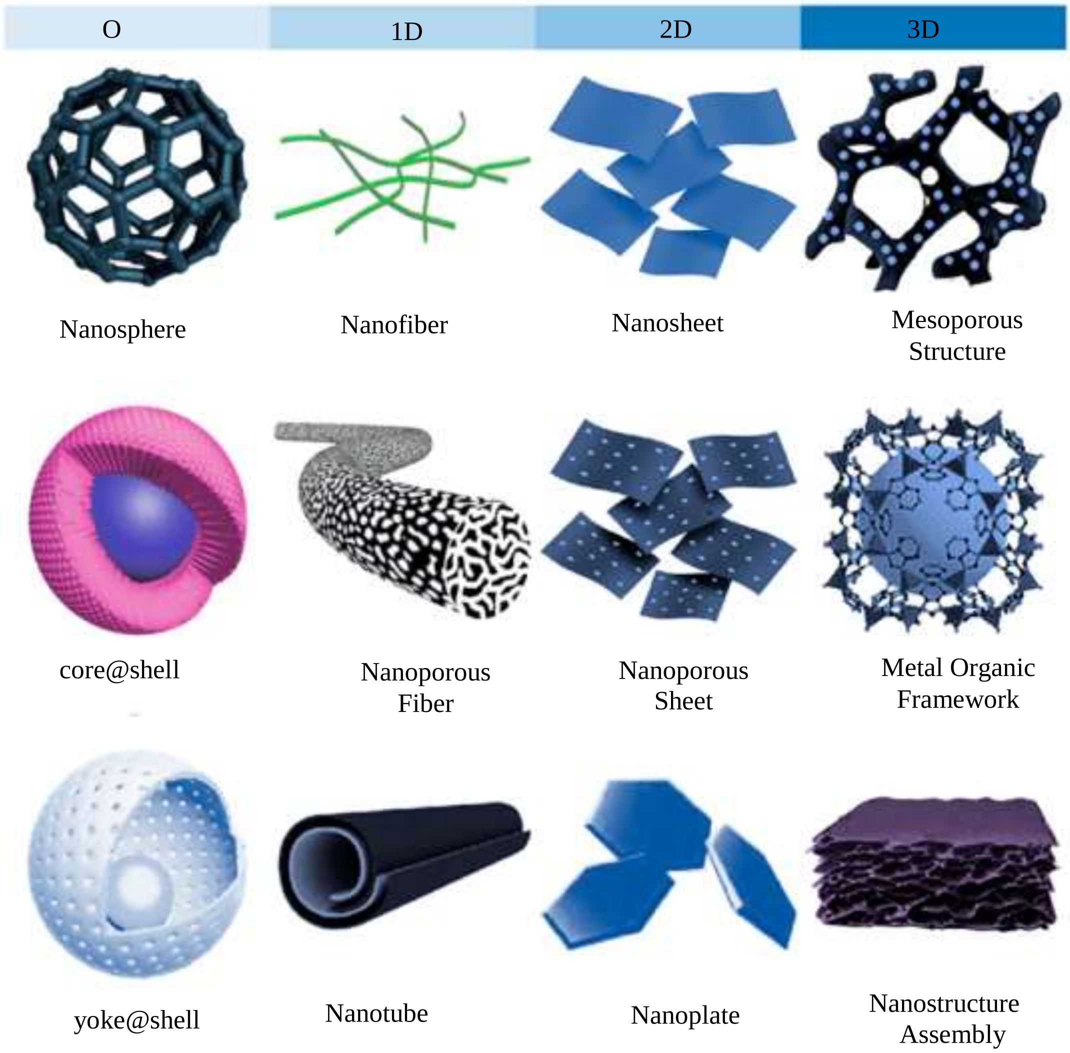

Figure 1. Typical examples of nanoparticles with varying dimensions used in gas and liquid separation nanocomposite membranes [5].

TYPES OF NANOSTRUCTURED MEMBRANES

Diverse materials and shapes are included in nanostructured membranes, and each has unique benefits for applications involving gas separation. Size-based gas molecule separation is possible with nanoporous membranes because of their tiny pores. The permeability and selectivity of nanocomposite membranes are increased by combining nanoparticles with polymeric or inorganic matrix. Depending on their material composition, structure, and mode of separation, nanostructured gas separation membranes can be categorized [6]. Here are the main types:

Polymeric Nanostructured Membranes

These membranes are made from various polymers and can include nanofillers to enhance their properties.

- *Mixed Matrix Membranes (MMMs):* Incorporate inorganic nanoparticles into a polymer matrix to combine the advantages of both materials.
- *Thin Film Composite Membranes (TFC):* Have a nanometer-scale selective layer on top of a porous support, improving separation efficiency and permeability.
- *Block Copolymer Membranes:* Utilize the self-assembly of block copolymers to create nanostructured domains that enhance selectivity.

In recent years, significant research efforts have been devoted towards the development of high-performance membranes through surface modification of polymers and nanoparticles, nanotubes, etc. to achieve appreciable salt rejection, water flux and antifouling properties [7].

Inorganic Nanostructured Membranes

Inorganic membranes have outstanding thermal, chemical, and mechanical robustness over polymeric counterparts, and are playing increasingly important roles across a broad spectrum of applications, particularly gas separations that can be further combined with diverse catalytic reactions [8].

These are composed of inorganic materials like ceramics, metals, or carbon.

- *Zeolite Membranes:* Utilize the uniform pore structure of zeolites to achieve high selectivity for certain gases.
- *Carbon Molecular Sieve (CMS) Membranes:* Derived from polymer precursors and offer high selectivity and permeability due to their fine-tuned pore sizes.
- *Metal-Organic Framework (MOF) Membranes:* Composed of metal ions coordinated to organic ligands, providing tunable pore sizes and high surface areas for gas separation.

Hybrid Nanostructured Membranes

In the chemical industry, hydrocarbons must be separated from permanent gases of great relevance. PTMSP, or poly(1-trimethylsilyl-1-propyne), has a strong hydrocarbon/permanent gas selectivity and is incredibly permeable to hydrocarbons.PMP was modified by adding several non-porous, nano-sized, fumed silica fillers to control the molecular polymer chain packing. The PMP/silica hybrid membranes' pure and mixed gas permeation characteristics were examined. The gas permeability and the hydrocarbon/permanent-gas selectivity increased simultaneously with increasing filler content [9]. These combine organic and inorganic materials to leverage the benefits of both.

- *Organic-Inorganic Hybrid Membranes:* Integrate materials like silica with polymers to enhance thermal stability and mechanical strength while maintaining good separation performance.
- *Graphene-based Membranes:* Utilize graphene or graphene oxide layers to create ultrathin membranes with high permeability and selectivity due to their nanometer-scale channels.

Bio-inspired and Biomimetic Membranes

In recent years, there has been a resurgence of interest in biomimetic approaches to membrane development for separations. Biomimetic membranes are composed of biological components or take cues, ideas, or models from biological systems. These membranes have the ability to leverage the mechanisms that nature has developed over billions of years to enhance the efficiency and specificity of transportation. After reviewing biological paradigms pertinent to membranes for separations, this article provides an overview of techniques motivated by these paradigms. It also poses practical and fundamental obstacles to using these tactics at scales relevant to their intended applications [10]. These mimic natural processes and structures to achieve efficient gas separation.

- *Aquaporin-based Membranes:* Use protein channels to selectively allow gases through, inspired by natural gas transport mechanisms in biological systems.
- *Peptide-based Membranes:* Employ peptides that self-assemble into nanostructures with specific gas separation properties.

Advanced Nanostructured Membranes

These include emerging technologies that leverage nanoscale engineering.

- *Nanoporous Membranes:* Utilize materials with nanopores, such as silica or alumina, which provide precise control over pore size and distribution.
- *2D Material Membranes:* Employ materials like molybdenum disulfide (MoS_2) or MXenes to create atomically thin layers with high gas separation efficiency [11].

FABRICATION TECHNIQUES

Several fabrication techniques are employed to synthesize nanostructured membranes with tailored properties and structures. Template-assisted methods utilize templates or molds to create precise nanostructures with controlled pore sizes. In layer-by-layer assembly, thin material layers are sequentially deposited to construct membrane structures [12]. Electrospinning produces nanofibrous membranes through the electrostatic spinning of polymer solutions, offering high surface area and porosity. Self-assembly techniques rely on the spontaneous organization of molecules or nanoparticles to form ordered membrane structures.

PERFORMANCE EVALUATION

The performance of nanostructured membranes in gas separation is assessed based on various parameters, including selectivity, permeability, stability, and scalability [13]. The ability of the membrane to separate some gas molecules preferentially over others is referred to as selectivity. Permeability measures the rate of gas permeation through the membrane. Stability assesses the membrane's durability and resistance to degradation under operating conditions. Scalability evaluates the feasibility of mass production and commercialization of membrane technologies.

Advancements in material modification, surface functionalization, and structural optimization have led to significant improvements in membrane performance. These enhancements enable nanostructured membranes to achieve higher selectivity, permeability, and stability, making them increasingly competitive with traditional gas separation methods There is little doubt that using polymeric nanocomposite membranes (PNM) can help limit the harmful environmental effects of gaseous contaminants and lessen their leakage into the environment [14].

Applications

Nanostructured membranes find applications across a wide range of gas separation processes, including natural gas purification, hydrogen purification, carbon dioxide capture, and air separation. In natural gas purification, nanostructured membranes offer a cost-effective and energy-efficient alternative to conventional methods for removing impurities such as CO_2, H_2S, and water vapor. Hydrogen purification membranes enable the production of high-purity hydrogen for fuel cell applications, enhancing the efficiency and sustainability of hydrogen-based energy systems. Carbon dioxide capture membranes facilitate the separation and capture of CO_2 from flue gases and industrial emissions, helping mitigate greenhouse gas emissions and combat climate change. Air separation membranes provide a reliable and energy-efficient means of producing oxygen and nitrogen gases for various industrial and medical applications [15].

Challenges and Future Perspectives

Despite their potential benefits, nanostructured membranes face several challenges that hinder their widespread adoption in gas separation applications. Membrane fouling, caused by the accumulation of contaminants on the membrane surface, can reduce separation efficiency and increase maintenance costs. Scalability remains a key concern, as large-scale production of nanostructured membranes requires scalable fabrication processes and cost-effective materials. Additionally, the cost-effectiveness of nanostructured membranes compared to traditional separation methods is an ongoing consideration for industrial implementation [16].

Addressing these challenges requires interdisciplinary efforts spanning materials science, engineering, and chemistry. Future research directions may focus on developing novel membrane materials, optimizing fabrication techniques, and exploring innovative membrane configurations to enhance performance and reduce costs. Integration with other technologies, such as membrane reactors and hybrid separation processes, could further improve the efficiency and sustainability of gas separation systems [17].

CONCLUSION

Gas separation is crucial in industries like petrochemical, pharmaceutical, and environmental sectors for producing fuels, purifying gases, and removing pollutants. Traditional methods, such as distillation and adsorption, are energy-intensive and inefficient. To address these issues, nanostructured membranes have emerged as a promising solution. Comprising materials like titanium dioxide, silica, and metal-organic frameworks, these membranes offer high surface area, precise pore size control, and molecular selectivity, enhancing efficiency and sustainability. Various types of nanostructured membranes exist, including polymeric, inorganic, hybrid, and bio-inspired membranes. Improved stability, permeability, and selectivity are just a few of the distinct advantages offered by each variety. Fabrication techniques like template-assisted methods, layer-by-layer assembly, and electrospinning create tailored membrane structures. Recent advancements in material modification have significantly improved their performance, making them competitive with traditional methods. Applications of nanostructured membranes include natural gas purification, hydrogen production, carbon dioxide capture, and air separation. Despite their potential, challenges like membrane fouling, scalability, and cost remain. Future research should focus on developing novel materials, optimizing fabrication techniques, and exploring innovative configurations to overcome these challenges and enhance the adoption of nanostructured membranes in gas separation processes. This will support the shift towards a sustainable and circular economy

REFERENCES

1. Bernardo P, Drioli E. Membrane gas separation progresses for process intensification strategy in the petrochemical industry. Petroleum Chemistry. 2010 Jul;50: 271-82.
2. Iulianelli A, Drioli E. Membrane engineering: Latest advancements in gas separation and pre-treatment processes, petrochemical industry and refinery, and future perspectives in emerging applications. Fuel Processing Technology. 2020 Sep 1;206: 106464.
3. Yuan H, Liu J, Zhang X, Chen L, Zhang Q, Ma L. Recent advances in membrane-based materials for desalination and gas separation. Journal of Cleaner Production. 2023 Feb 10;387: 135845.
4. Salim W, Ho WW. Recent developments on nanostructured polymer-based membranes. Current Opinion in Chemical Engineering. 2015 May 1;8: 76-82.
5. Goh PS, Wong KC, Ismail AF. Nanocomposite membranes for liquid and gas separations from the perspective of nanostructure dimensions. Membranes. 2020 Oct 21;10(10):297.
6. Salim W, Ho WW. Recent developments on nanostructured polymer-based membranes. Current Opinion in Chemical Engineering. 2015 May 1;8: 76-82.

7. Mehwish N, Kausar A, Siddiq M. Advances in polymer-based nanostructured membranes for water treatment. Polymer-Plastics Technology and Engineering. 2014 Aug 26;53(12):1290-316.
8. Wu Z. Inorganic membranes for gas separations. InMembrane separation principles and applications 2019 Jan 1 (pp. 147-179). Elsevier.
9. He Z, Pinnau I, Morisato A. Nanostructured poly (4-methyl-2-pentyne)/silica hybrid membranes for gas separation. Desalination. 2002 Sep 10;146(1-3):11-5.
10. Shen YX, Saboe PO, Sines IT, Erbakan M, Kumar M. Biomimetic membranes: A review. Journal of Membrane Science. 2014 Mar 15;454: 359-81.
11. Smith BD. A novel approach to the scalable production of nanoporous silicon membranes for applications in water and energy (Doctoral dissertation, Massachusetts Institute of Technology).
12. Ismail AF, Chandra Khulbe K, Matsuura T, Ismail AF, Khulbe KC, Matsuura T. Membrane fabrication/manufacturing techniques. Gas Separation Membranes: Polymeric and Inorganic. 2015:193-220.
13. Zeng H, He S, Hosseini SS, Zhu B, Shao L. Emerging nanomaterial incorporated membranes for gas separation and pervaporation towards energetic-efficient applications. Advanced Membranes. 2022 Jan 1;2: 100015.
14. Zhao C, Hussain W, Alkaaby HH, AL-Khafaji RM, Alghazali T, Izzat SE, Shams MA, Abood ES, Anisimova EY, Ehab M. Polymeric nanocomposite membranes for gas separation: Performance, applications, restrictions and future perspectives. Case Studies in Thermal Engineering. 2022 Oct 1;38: 102323.
15. Ersoz TT, Ersoz M. Nanostructured Material and its Application in Membrane Separation Technology. Micro and Nanosystems. 2023 Mar 1;15(1):16-27.
16. Imtiaz A, Othman MH, Jilani A, Khan IU, Kamaludin R, Iqbal J, Al-Sehemi AG. Challenges, opportunities and future directions of membrane technology for natural gas purification: a critical review. Membranes. 2022 Jun 23;12(7):646.
17. Favre E. The future of membrane separation processes: A prospective analysis. Frontiers in Chemical Engineering. 2022 May 17;4: 916054.

