



# Journal of Frontiers in Multidisciplinary Research

## Challenges and Innovations in Polymeric Membrane Technology for Industrial Gas Separation and Carbon Dioxide Capture with Focus on Air Separation

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### Article Info

**E-ISSN:** 3050-9726

**P-ISSN:** 3050-9718

**Volume:** 04

**Issue:** 02

**July-December 2023**

**Received:** 06-09-2023

**Accepted:** 03-10-2023

**Published:** 01-11-2023

**Page No:** 17-26

### Abstract

Polymeric membrane technology has emerged as a promising approach for industrial gas separation and carbon dioxide capture, offering energy efficiency, operational simplicity, and environmental benefits compared to conventional separation methods. This review examines recent advances in polymeric membrane materials, structures, and processes for gas separation applications with a particular focus on air separation and CO<sub>2</sub> capture. We discuss fundamental challenges including the permeability-selectivity trade-off, physical aging, and plasticization, alongside innovative strategies to overcome these limitations through material design, mixed-matrix formulations, and membrane fabrication techniques. Special attention is given to emerging applications in air separation (oxygen/nitrogen), which represents a significant industrial market. The review concludes by identifying promising research directions and discussing the practical considerations for industrial implementation of these technologies, highlighting the continued importance of polymeric membranes in addressing global energy and environmental challenges.

**DOI:** <https://doi.org/10.54660/IJFMR.2023.4.2.17-26>

**Keywords:** polymeric membranes; gas separation; carbon dioxide capture; air separation; mixed-matrix membranes; physical aging; plasticization; membrane fabrication

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### 1. Introduction

Gas separation represents one of the most energy-intensive processes in the chemical and petrochemical industries, accounting for approximately 10-15% of global energy consumption (Bernardo, Drioli and Golemme, 2009). Conventional separation technologies such as cryogenic distillation, pressure swing adsorption, and amine absorption processes are not only energy-intensive but also capital-intensive and often environmentally problematic (Gin and Noble, 2011). In this context, membrane-based separation has emerged as an attractive alternative due to its lower energy requirements, operational simplicity, and reduced environmental impact (Baker, 2002).

Among various membrane materials, polymeric membranes have garnered significant attention due to their processability, mechanical stability, and relatively low production costs (Park *et al.*, 2017). These membranes are particularly promising for applications in natural gas sweetening, hydrogen recovery, air separation, and carbon dioxide capture from flue gases and other industrial sources (Galizia *et al.*, 2017). The global drive toward reducing greenhouse gas emissions has further accelerated research into membrane technologies for CO<sub>2</sub> separation, with polymeric membranes at the forefront of these developments (Brunetti *et al.*, 2010).

This review examines the challenges and innovations in polymeric membrane technology for gas separation, with a particular focus on air separation and CO<sub>2</sub> capture. We discuss the fundamental principles of gas transport in polymeric membranes, the persistent trade-off between permeability and selectivity, and the various strategies employed to overcome this limitation.

Special attention is given to recent advances in material design, membrane fabrication, and process optimization that have enabled enhanced performance in targeted applications.

## 2. Fundamentals of gas transport in polymeric membranes

### 2.1 Membrane transport mechanisms

Gas transport through dense polymeric membranes primarily occurs via the solution-diffusion mechanism, which involves three key steps: (1) gas sorption at the upstream membrane surface, (2) diffusion through the polymer matrix, and (3) desorption from the downstream surface (Wijmans and Baker, 1995). Figure 1 demonstrates these steps.

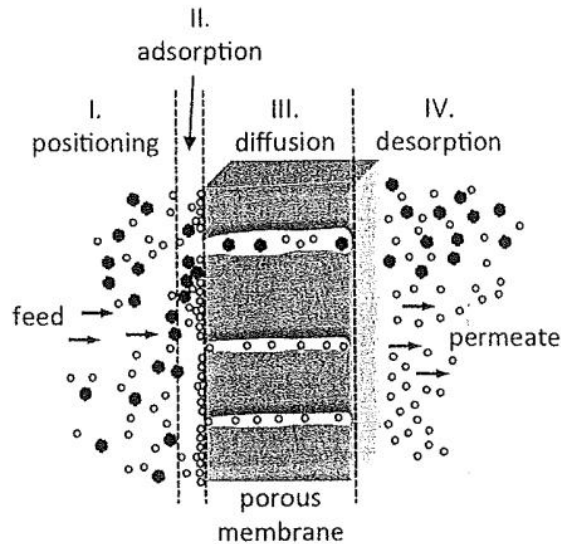


Fig 1: Membrane transport mechanism (Gitis and Rothenberg, 2016)

The overall performance of a membrane is typically characterized by two parameters: permeability, which describes the productivity of the membrane, and selectivity, which indicates its separation efficiency (Freeman, 1999). The permeability coefficient ( $P$ ) is defined as:

$$P = D \times S \quad (1)$$

Where  $D$  is the diffusion coefficient reflecting the mobility of gas molecules through the polymer matrix, and  $S$  is the solubility coefficient representing the amount of gas that can be accommodated in the polymer (Matteucci *et al.*, 2006).

Both factors are influenced by the physicochemical properties of the polymer and the penetrant gas. Selectivity ( $\alpha$ ) is typically expressed as the ratio of the permeabilities of two gases ( $A$  and  $B$ ):

$$\alpha_{A/B} = \frac{P_A}{P_B} = \left[ \frac{D_A}{D_B} \right] \left[ \frac{S_A}{S_B} \right] \quad (2)$$

Equation (2) illustrates that selectivity has both diffusivity and solubility components, offering multiple pathways for membrane performance enhancement (Koros and Zhang, 2017).

### 2.2 Permeability-selectivity trade-off

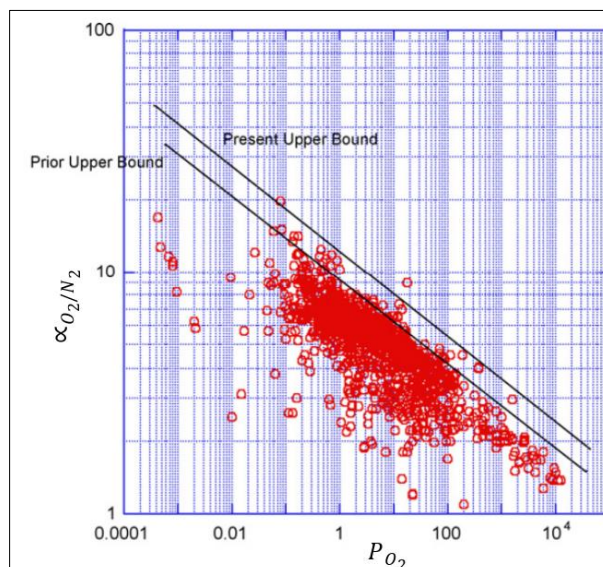


Fig 2: Robeson upper bound for O<sub>2</sub>/N<sub>2</sub> pair (Robeson, 2008).

One of the most significant challenges in polymeric membrane development is the inherent trade-off between permeability and selectivity, first empirically demonstrated by Robeson in 1991 and updated in 2008 (Robeson, 2008) as shown in figure 2. This relationship, known as the Robeson upper bound, shows that as permeability increases, selectivity typically decreases, and vice versa. This trade-off fundamentally limits membrane performance and has been the focus of extensive research aimed at developing materials that can exceed this upper bound (Sanders *et al.*, 2013).

The physical basis for this trade-off lies in the free volume distribution within the polymer matrix. Polymers with high free volume generally exhibit high permeability but low selectivity due to less discriminative molecular sieving, while tightly packed polymers with low free volume show the opposite behavior (Freeman and Pinnau, 1997).

### 3. Material challenges and innovations in polymeric membranes

#### 3.1 Physical Aging

Physical aging, characterized by the gradual densification of polymer chains over time, represents a significant challenge for polymeric membranes, particularly those based on high free volume glassy polymers (Huang and Paul, 2004). This phenomenon results in decreased permeability and sometimes altered selectivity, potentially compromising the long-term performance stability of the membrane (Tiwari *et al.*, 2017).

Several strategies have been developed to mitigate physical aging. Cross-linking the polymer chains can restrict their mobility and reduce aging rates, as demonstrated by Park *et al.* using thermal and chemical cross-linking methods (Park *et al.*, 2014). Incorporation of nanofillers into the polymer matrix has also been shown to effectively inhibit chain rearrangement, with Fu *et al.* reporting significantly reduced aging rates in ZIF-8/polymer composites (Fu *et al.*, 2015).

#### 3.2 Plasticization

Plasticization occurs when highly soluble gases, particularly CO<sub>2</sub>, dissolve into the polymer matrix, increasing chain mobility and free volume (Ismail and Lorna, 2002). This phenomenon typically leads to increased permeability of all gases and decreased selectivity, and can lead to unpredictable membrane performance under varying feed compositions (Horn and Paul, 2011).

Cross-linking has proven effective in suppressing plasticization, as shown by Wind *et al.* in polyimide membranes (Wind *et al.*, 2002). Thermal treatment to induce chain rearrangement and densification has also been employed, though this approach often comes at the cost of reduced permeability (Tin *et al.*, 2004). Recently, blending with rigid, plasticization-resistant polymers has emerged as a promising strategy, as demonstrated by Kraftschik *et al.* using polyimide blends (Kraftschik *et al.*, 2013).

#### 3.3 Fouling and Scalability

Fouling is a significant challenge in membrane technology, primarily arising from the accumulation of various contaminants on the surface of the membrane. This phenomenon not only hinders the flow of permeate but also drastically reduces the membrane's separation efficiency,

leading to increased operational costs and reduced lifespan of the membrane (Gkotsis *et al.*, 2014). The contaminants can include organic matter, biological organisms, and inorganic salts, each contributing to the fouling process in distinct ways (Speight, 2015). Effective management strategies, such as pre-treatment of feed streams, regular cleaning protocols, and the development of antifouling membrane materials, are essential to mitigate these adverse effects and enhance the overall performance of membrane systems (Bucs *et al.*, 2018). In addition to the issues posed by fouling, scalability presents another formidable challenge in the field of membrane production. As industries seek to expand their operations and utilize polymeric membranes for large-scale applications, ensuring consistent quality and performance becomes increasingly complex. The scalability of membrane production involves not only the replication of laboratory-scale processes to industrial scales but also the maintenance of the physical and chemical properties that define the membrane's functionality (Kadir Khan *et al.*, 2019). Factors such as material selection, fabrication techniques, and quality control measures must be meticulously optimized to achieve reliable and high-performance membranes in larger quantities. Addressing the dual challenges of fouling and scalability is crucial for the commercial viability of polymeric membranes (Mondal, Griffiths and Ramon, 2019).

#### 3.4 Polymer design strategies

Recent years have seen significant advances in the design of new polymers with enhanced gas separation properties. High free volume polymers of intrinsic microporosity (PIMs) have attracted considerable attention due to their rigid, contorted molecular structures that prevent efficient chain packing (Budd *et al.*, 2004). These materials, pioneered by Budd and McKeown, have demonstrated permeabilities that approach those of inorganic membranes while maintaining reasonable selectivities (McKeown and Budd, 2006).

Thermally rearranged (TR) polymers represent another important development, involving the thermal conversion of functionalized polyimides to polybenzoxazoles or polybenzothiazoles (Park *et al.*, 2007). Park *et al.* demonstrated that this rearrangement creates microporosity and enhances both permeability and selectivity, positioning many TR polymers above the Robeson upper bound (Park *et al.*, 2010).

The incorporation of bulky substituents and rigid functional groups into conventional polymers has also proven effective in enhancing gas separation performance. For instance, Wang *et al.* reported that the introduction of triptycene units into polyimides significantly increased both permeability and selectivity for various gas pairs (Wang *et al.*, 2014).

#### 4. Mixed-matrix membranes: Combining polymers with inorganic materials

Mixed-matrix membranes (MMMs), which incorporate inorganic fillers into a polymer matrix, have emerged as a promising approach to overcome the limitations of pure polymeric membranes (Aroon *et al.*, 2010). These hybrid materials aim to combine the processability and mechanical properties of polymers with the superior separation performance of inorganic materials (Dong, Li and Chen, 2013).

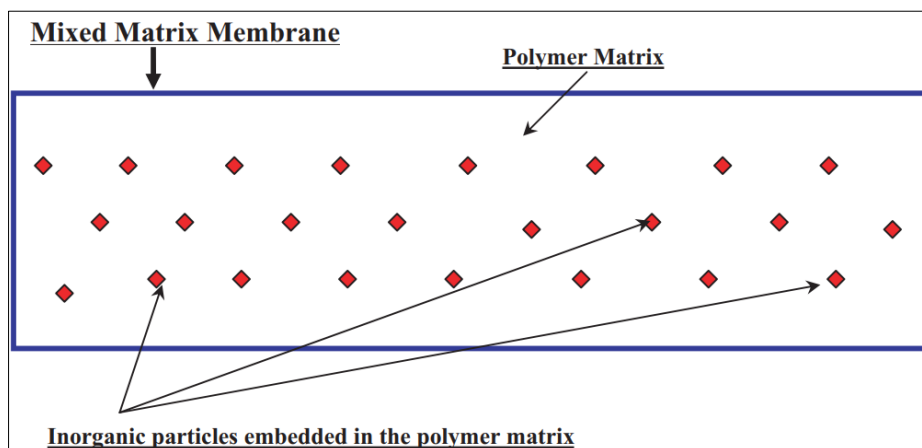


Fig 3: Mixed matrix membrane representation (Aroon *et al.*, 2010).

#### 4.1 Types of fillers and their impact

Various types of fillers have been investigated for MMMs, including:

**Traditional inorganic materials:** Zeolites and silica have been widely studied as fillers in MMMs. Mahajan and Koros demonstrated that incorporation of zeolite 4A into polysulfone improved O<sub>2</sub>/N<sub>2</sub> selectivity (Mahajan and Koros, 2000), while Kim *et al.* reported enhanced CO<sub>2</sub>/CH<sub>4</sub> separation performance using mesoporous silica in polyimide membranes (Kim *et al.*, 2006).

**Metal-organic frameworks (MOFs):** The highly porous nature and tunable pore size of MOFs make them attractive fillers for gas separation membranes. Basu *et al.* showed that ZIF-8 incorporation into Matrimid® enhanced both CO<sub>2</sub> permeability and CO<sub>2</sub>/N<sub>2</sub> selectivity (Basu, Cano-Odena and Vankelecom, 2011), while Rodenas *et al.* demonstrated that 2D MOF nanosheets could significantly improve the performance of polyimide membranes for CO<sub>2</sub>/CH<sub>4</sub> separation (Rodenas *et al.*, 2015).

**Carbon-based materials:** Graphene oxide (GO) and carbon nanotubes (CNTs) have garnered attention due to their unique transport properties. Shen *et al.* reported that GO incorporation into polyethersulfone membranes enhanced gas permeability while maintaining selectivity (J. Shen *et al.*, 2015), and Cong *et al.* demonstrated improved O<sub>2</sub>/N<sub>2</sub> separation performance in CNT-polyimide composites (Cong *et al.*, 2007).

#### 4.2 Interface challenges and solutions

The polymer-filler interface represents a critical factor in MMM performance, with poor compatibility often leading to non-selective voids or rigidified polymer regions (Moore and Koros, 2005). Several strategies have been developed to enhance this compatibility:

**Surface modification of fillers:** Chemical functionalization of filler surfaces can improve their interaction with the polymer matrix. Nik *et al.* demonstrated that amine-functionalized MOFs showed better compatibility with polyimides, leading to enhanced gas separation performance (Nik, Chen and Kaliaguine, 2012).

**Polymer chain engineering:** Designing polymers with functional groups that can interact favorably with fillers

represents another approach. Zhang *et al.* reported improved interfacial adhesion and gas separation performance in MMMs based on carboxyl-functionalized polyimides and amino-functionalized MOFs (Zhang *et al.*, 2016).

**Priming techniques:** Introducing a thin layer of compatible material at the interface can mitigate interfacial defects. Moore *et al.* developed a "priming" technique using low molecular weight additives that significantly improved the performance of zeolite-polymer MMMs (Moore *et al.*, 2004).

### 5. Advanced membrane fabrication techniques

#### 5.1 Thin film composite membranes

Thin film composite (TFC) membranes, consisting of an ultrathin selective layer on a porous support, have emerged as a promising configuration for high-performance gas separation (Karan, Jiang and Livingston, 2015). The thin selective layer (typically <1 μm) minimizes transport resistance, while the porous support provides mechanical strength (Xie *et al.*, 2012).

Interfacial polymerization has been widely used to fabricate TFC membranes for gas separation. Li *et al.* developed high-performance TFC membranes via interfacial polymerization of polyamines and trimesoyl chloride, achieving excellent CO<sub>2</sub>/N<sub>2</sub> separation properties (Li *et al.*, 2014). Rawtani and Agrawal's work highlights layer-by-layer (LbL) assembly's ability to create precisely controlled thin films by sequentially depositing oppositely charged materials, enabling fine-tuning of membrane properties for applications like gas separation. Their research emphasizes the technique's versatility in tailoring film thickness and composition through careful selection of deposition parameters and materials (Rawtani and Agrawal, 2014).

#### 5.2 Hollow fiber membranes

Hollow fiber configurations provide high surface area-to-volume ratios, making them attractive for industrial applications (Peng *et al.*, 2012). Recent advances in hollow fiber spinning have focused on optimizing spinneret design, dope formulation, and spinning conditions to enhance membrane performance and reproducibility (Feng *et al.*, 2013).

Dual-layer spinning, which allows for the simultaneous extrusion of different polymer solutions, has enabled the development of composite hollow fibers with tailored properties. Chung *et al.* demonstrated high-performance dual-layer hollow fibers with a thin selective layer of a high-

performance polymer supported by a more economical material (Chung *et al.*, 2007). Post-spinning modifications, such as chemical cross-linking or thermal treatment, have also been employed to enhance the performance of hollow fiber membranes, as shown by Shao *et al.* in their work on cross-linked polyimide hollow fibers for CO<sub>2</sub>/CH<sub>4</sub> separation (Shao *et al.*, 2009).

### 5.3 3D printing and other emerging fabrication methods

Additive manufacturing (3D printing) technologies have recently been explored for membrane fabrication, offering unprecedented control over membrane architecture (Guessasma, Belhabib and Nouri, 2015). Wessling's group demonstrated the feasibility of 3D printing complex membrane structures with controlled porosity and channel geometry, opening new possibilities for membrane module design (Femmer, Kuehne and Wessling, 2014).

Electrospinning has gained attention for producing nanofibrous membranes with interconnected pore structures, adjustable thickness and pore size distribution ranging from several nanometers to numerous microns, and extensive surface area with enhanced gas permeation properties (Liao *et al.*, 2017).

## 6. Air Separation: Challenges and recent advances

Air separation for the production of nitrogen and oxygen represents one of the largest industrial gas separation markets, traditionally dominated by cryogenic distillation and pressure swing adsorption (Castle, 2002). Membrane-based air separation offers potential advantages in terms of energy efficiency, operational simplicity, and scalability, particularly for small to medium-scale applications (Caro *et al.*, 2000).

### 6.1 Current status and limitations

The key challenge in membrane-based air separation is the similar molecular sizes of oxygen (3.46 Å) and nitrogen (3.64 Å), resulting in inherently low O<sub>2</sub>/N<sub>2</sub> selectivity in most polymeric membranes (Baker, 2012). Commercial membranes typically exhibit O<sub>2</sub>/N<sub>2</sub> selectivity in the range of 3-6, which is insufficient for many high-purity applications (Baker and Low, 2014).

Additionally, membrane-based air separation faces economic challenges when competing with established technologies, particularly for large-scale, high-purity applications (Smith and Klosek, 2001). Current membrane systems are most competitive for moderate-purity nitrogen production (<99%) and small to medium-scale applications (Belaissaoui, Willson and Favre, 2012).

### 6.2 Material innovations for enhanced O<sub>2</sub>/N<sub>2</sub> separation

Recent research has focused on developing polymeric materials with enhanced O<sub>2</sub>/N<sub>2</sub> separation performance:

**Size-sieving polymers:** Polymers with rigid structures and precisely controlled free volume distributions have shown improved O<sub>2</sub>/N<sub>2</sub> selectivity. Ghanem *et al.* reported spirobisindane-based PIMs with O<sub>2</sub>/N<sub>2</sub> selectivity exceeding 5.0 while maintaining high O<sub>2</sub> permeability (Ghanem *et al.*, 2014). Wang *et al.* demonstrated that thermally rearranged polymers based on ortho-hydroxyl polyimides exhibited remarkable O<sub>2</sub>/N<sub>2</sub> selectivity (up to 6.8) with good permeability (Wang *et al.*, 2016).

**Facilitated transport membranes:** Incorporation of oxygen carriers, such as cobalt complexes, into polymer matrices can enhance oxygen transport via a reversible chemical reaction mechanism. Yampol'skii *et al.* reviewed various facilitated transport membranes, highlighting their potential for achieving significantly higher O<sub>2</sub>/N<sub>2</sub> selectivity compared to conventional polymeric membranes (Yampol'skii and Volkov, 1991).

**Composite approaches:** Wang *et al.* developed carbon molecular sieve (CMS)/polymer composite membranes that exhibited O<sub>2</sub>/N<sub>2</sub> selectivity up to 7.5 with good O<sub>2</sub> permeability (Tian *et al.*, 2016). Similarly, Shen *et al.* reported that graphene oxide incorporation into specific polymers enhanced O<sub>2</sub>/N<sub>2</sub> selectivity through molecular sieving effects and pore blocking of non-selective defects (Y. Shen *et al.*, 2015).

### 6.3 Process innovations and system integration

Process design innovations have complemented material developments to enhance the overall performance of membrane-based air separation:

**Multistage configurations:** Sanders *et al.* demonstrated that multistage membrane systems with recycle streams could significantly improve nitrogen purity and recovery compared to single-stage systems (Sanders *et al.*, 2012).

**Hybrid processes:** Combining membranes with other separation technologies can leverage the strengths of each. Xu *et al.* investigated a hybrid membrane-PSA process for oxygen production, showing improved energy efficiency compared to either technology alone (Xu, Rungta and Koros, 2011).

**Module design optimization:** Advances in module design, particularly for hollow fiber configurations, have improved flow distribution and reduced concentration polarization. Feng *et al.* reported that optimized module designs could significantly enhance the effective separation performance of air separation membranes (Yang, 2001).

## 7. Carbon dioxide capture: Polymeric membrane solutions

Carbon capture and storage (CCS) has emerged as a critical technology for mitigating climate change, with membrane-based separation offering potential advantages for CO<sub>2</sub> capture from various sources (Merkel *et al.*, 2010). Key applications include post-combustion capture from power plants, pre-combustion capture from syngas, and CO<sub>2</sub> removal from natural gas (D'Alessandro, Smit and Long, 2010).

### 7.1 Post-Combustion CO<sub>2</sub> Capture

Post-combustion CO<sub>2</sub> capture presents significant challenges for membrane technology, including low CO<sub>2</sub> partial pressure, high temperature, and the presence of contaminants (Kenarsari *et al.*, 2013). Several membrane materials have shown promise for this application:

**CO<sub>2</sub>-philic polymers:** Polymers containing polar groups that interact favorably with CO<sub>2</sub> have demonstrated enhanced CO<sub>2</sub>/N<sub>2</sub> selectivity. Lin *et al.* developed poly

(ethylene oxide)-based membranes with high CO<sub>2</sub>/N<sub>2</sub> selectivity due to favorable CO<sub>2</sub> solubility (Lin *et al.*, 2006), while Tena *et al.* reported polyimides with fluorinated side chains exhibiting excellent CO<sub>2</sub>/N<sub>2</sub> separation performance (Tena *et al.*, 2013).

**Fixed-carrier membranes:** Incorporation of amine groups that can reversibly react with CO<sub>2</sub> has been explored to enhance selectivity. Zhao *et al.* demonstrated that polyvinylamine-based membranes exhibited CO<sub>2</sub>/N<sub>2</sub> selectivity exceeding 500 under humid conditions due to facilitated transport mechanisms (Zhao and Ho, 2013).

**Thermally rearranged polymers:** Gleason *et al.* reported that thermally rearranged polymers showed enhanced resistance to contaminants typical in flue gas streams while maintaining good CO<sub>2</sub>/N<sub>2</sub> separation performance (Gleason *et al.*, 2015).

## 7.2 Process Considerations for CO<sub>2</sub> Capture

The implementation of membrane technology for CO<sub>2</sub> capture requires careful consideration of process design and operating conditions:

**Pressure ratio optimization:** Merkel *et al.* conducted a comprehensive analysis of membrane processes for post-combustion CO<sub>2</sub> capture, highlighting the importance of pressure ratio optimization for energy-efficient separation (Merkel, Zhou and Baker, 2012).

**Feed conditioning:** Pretreatment to remove particulates and adjust temperature and humidity can significantly impact membrane performance and longevity, as discussed by Roussanaly *et al.* in their techno-economic analysis of membrane-based CO<sub>2</sub> capture (Roussanaly *et al.*, 2016).

**Integration with existing infrastructure:** Belaïssaoui *et al.* explored various configurations for integrating membrane systems into power plants, identifying opportunities for heat integration and process optimization to reduce the overall energy penalty (Belaïssaoui *et al.*, 2012).

## 8. Future perspectives and conclusions

### 8.1 Emerging research directions

Several promising research directions are likely to shape the future of polymeric membranes for gas separation:

**Bio-inspired membrane materials:** Learning from biological systems such as cell membranes could lead to the development of membranes with unprecedented selectivity and transport properties. Kumar *et al.* reviewed bio-inspired approaches to membrane design, highlighting the potential of aquaporin-based and other biomimetic membranes (Kumar *et al.*, 2007).

**Responsive and adaptive membranes:** Membranes that can dynamically adjust their properties in response to external stimuli (temperature, pressure, or chemical environment) could enable more efficient and flexible separation processes. Zhang *et al.* demonstrated temperature-responsive membranes that exhibited switchable gas transport properties (Zhang *et al.*, 2013).

**Advanced computational design:** Molecular simulation and machine learning approaches are increasingly being employed to accelerate the discovery and optimization of membrane materials. Farmahini and Bhatia utilized molecular dynamics simulations to predict gas transport properties in novel polymeric materials, demonstrating good agreement with experimental results (Farmahini and Bhatia, 2015).

### 8.2 Scaling and Manufacturing Challenges

The translation of laboratory innovations to commercial products remains a significant challenge. Key areas requiring attention include:

**Scalable synthesis routes:** Developing cost-effective, environmentally friendly synthesis methods for high-performance polymers is crucial for commercial viability. Pinnau's group has focused on simplifying the synthesis of PIMs to facilitate their commercial production (Pinnau and Toy, 1996).

**Quality control and reproducibility:** Establishing robust quality control methods and improving manufacturing reproducibility are essential for membrane commercialization, as discussed by Koros and Zhang in their review of membrane manufacturing considerations (Koros and Zhang, 2017).

**Module and system integration:** Innovative module designs that maximize membrane area while minimizing pressure drop and concentration polarization are needed for efficient large-scale systems. Caro reviewed advances in module design, highlighting their impact on overall system performance (Caro, 2011).

### 8.3 Economic and environmental considerations

The economic competitiveness of membrane-based separation processes compared to conventional technologies depends on several factors:

**Capital costs vs. operating costs:** Membrane systems typically feature lower capital costs but potentially higher operating costs (due to compression energy) compared to traditional technologies. Zhai and Rubin conducted a comprehensive economic analysis of membrane processes for CO<sub>2</sub> capture, identifying key economic drivers and performance targets (Zhai and Rubin, 2013).

**Life cycle assessment:** Environmental impact evaluations have shown that membrane-based separations can offer significant reductions in greenhouse gas emissions and energy consumption compared to conventional processes. Giordano *et al.* performed a life cycle assessment of membrane-based CO<sub>2</sub> capture, demonstrating potential environmental benefits (Giordano, Roizard and Favre, 2018).

**Energy integration:** Optimizing energy integration between membrane systems and other process units can significantly improve overall efficiency. Belaïssaoui and Favre explored various heat and energy integration strategies for membrane-based gas separation, highlighting opportunities for efficiency enhancement (Belaïssaoui and Favre, 2014).

## 9. Conclusion

Polymeric membrane technology has made significant strides in addressing the challenges of industrial gas separation and CO<sub>2</sub> capture. Innovations in material design, membrane fabrication, and process engineering have pushed performance boundaries, with many systems now exceeding the traditional permeability-selectivity trade-off constraints. For air separation specifically, recent advances in size-sieving polymers and facilitated transport membranes have improved O<sub>2</sub>/N<sub>2</sub> selectivity while maintaining reasonable permeability, enhancing the competitiveness of membrane technology in this important industrial application. Similarly, for CO<sub>2</sub> capture, the development of CO<sub>2</sub>-philic polymers and fixed-carrier membranes has significantly enhanced separation performance under practically relevant conditions. Despite these advances, challenges remain in scaling up production, ensuring long-term stability, and optimizing system integration. Addressing these challenges will require continued interdisciplinary collaboration between polymer chemists, material scientists, and chemical engineers.

As global energy demands and environmental concerns continue to grow, the role of advanced membrane technologies in enabling more efficient and sustainable industrial processes becomes increasingly critical. With continued research and development, polymeric membranes are poised to make significant contributions to addressing these global challenges in the coming decades.

## 10. References

1. Aroon MA, Ismail AF, Matsuura T, Montazer-Rahmati MM. Performance studies of mixed matrix membranes for gas separation: A review. *Separation and Purification Technology*. 2010;75(3):229–242. Available from: <https://www.sciencedirect.com/science/article/pii/S1383586610003461>
2. Baker RW. Future directions of membrane gas separation technology. *Industrial & Engineering Chemistry Research*. 2002;41(6):1393–1411.
3. Baker RW. Membrane Technology and Applications [Internet]. 2012. Available from: <https://cir.nii.ac.jp/crid/136001144127019136>
4. Baker RW, Low BT. Gas separation membrane materials: A perspective. *Macromolecules*. 2014;47(20):6999–7013. Available from: <https://doi.org/10.1021/ma501488s>
5. Basu S, Cano-Odena A, Vankelecom IF. MOF-containing mixed-matrix membranes for CO<sub>2</sub>/CH<sub>4</sub> and CO<sub>2</sub>/N<sub>2</sub> binary gas mixture separations. *Separation and Purification Technology*. 2011;81(1):31–40. Available from: <https://www.sciencedirect.com/science/article/pii/S138358661100387X>
6. Belaïssaoui B, Favre E. Membrane separation processes for post-combustion carbon dioxide capture: State of the art and critical overview. *Oil & Gas Science and Technology – Revue d'IFP Energies Nouvelles*. 2014;69(6):1005–1020. Available from: <https://ogst.ifpenergiesnouvelles.fr/articles/ogst/abs/2014/06/ogst130021/ogst130021.html>
7. Belaïssaoui B, Le Moullec Y, Willson D, Favre E. Hybrid membrane cryogenic process for post-combustion CO<sub>2</sub> capture. *Journal of Membrane Science*. 2012;415:424–434. Available from: <https://www.sciencedirect.com/science/article/pii/S0376738812004139>
8. Belaïssaoui B, Willson D, Favre E. Membrane gas separations and post-combustion carbon dioxide capture: Parametric sensitivity and process integration strategies. *Chemical Engineering Journal*. 2012;211:122–132. Available from: <https://www.sciencedirect.com/science/article/pii/S1385894712012004>
9. Bernardo P, Drioli E, Golemme G. Membrane gas separation: A review/state of the art. *Industrial & Engineering Chemistry Research*. 2009;48(10):4638–4663.
10. Brunetti A, Scura F, Barbieri G, Drioli E. Membrane technologies for CO<sub>2</sub> separation. *Journal of Membrane Science*. 2010;359(1–2):115–125.
11. Bucs SS, Farhat N, Kruithof JC, Picioreanu C, van Loosdrecht MC, Vrouwenvelder JS. Review on strategies for biofouling mitigation in spiral wound membrane systems. *Desalination*. 2018;434:189–197. Available from: <https://www.sciencedirect.com/science/article/pii/S001916417320830>
12. Budd PM, Ghanem BS, Makhseed S, McKeown NB, Msayib KJ, Tattershall CE. Polymers of intrinsic microporosity (PIMs): Robust, solution-processable, organic nanoporous materials. *Chemical Communications*. 2004;(2):230–231. Available from: <https://pubs.rsc.org/en/content/articlehtml/2004/cc/b311764b>
13. Caro J. Are MOF membranes better in gas separation than those made of zeolites? *Current Opinion in Chemical Engineering*. 2011;1(1):77–83. Available from: <https://www.sciencedirect.com/science/article/pii/S2211339811000128>
14. Caro J, Noack M, Kölsch P, Schäfer R. Zeolite membranes—State of their development and perspective. *Microporous and Mesoporous Materials*. 2000;38(1):3–24. Available from: <https://www.sciencedirect.com/science/article/pii/S1387181199002954>
15. Castle WF. Air separation and liquefaction: Recent developments and prospects for the beginning of the new millennium. *International Journal of Refrigeration*. 2002;25(1):158–172. Available from: <https://www.sciencedirect.com/science/article/pii/S0140700701000032>
16. Chung TS, Jiang LY, Li Y, Kulprathipanja S. Mixed matrix membranes (MMMs) comprising organic polymers with dispersed inorganic fillers for gas separation. *Progress in Polymer Science*. 2007;32(4):483–507. Available from: <https://www.sciencedirect.com/science/article/pii/S0079670007000081>
17. Cong H, Zhang J, Radosz M, Shen Y. Carbon nanotube composite membranes of brominated poly(2,6-diphenyl-1,4-phenylene oxide) for gas separation. *Journal of Membrane Science*. 2007;294(1–2):178–185. Available from: <https://www.sciencedirect.com/science/article/pii/S0376738807001354>
18. D'Alessandro DM, Smit B, Long JR. Carbon dioxide capture: Prospects for new materials. *Angewandte Chemie International Edition*. 2010;49(35):6058–6082.

- Available from: <https://doi.org/10.1002/anie.201000431>
19. Dong G, Li H, Chen V. Challenges and opportunities for mixed-matrix membranes for gas separation. *Journal of Materials Chemistry A*. 2013;1(15):4610–4630. Available from: <https://pubs.rsc.org/en/content/articlehtml/2013/ta/c3ta00927k>
  20. Farmahini AH, Bhatia SK. Differences in the adsorption and diffusion behaviour of water and non-polar gases in nanoporous carbon: Role of cooperative effects of pore confinement and hydrogen bonding. *Molecular Simulation*. 2015;41(5–6):432–445. Available from: <https://doi.org/10.1080/08927022.2014.976640>
  21. Femmer T, Kuehne AJ, Wessling M. Print your own membrane: Direct rapid prototyping of polydimethylsiloxane. *Lab on a Chip*. 2014;14(15):2610–2613. Available from: <https://pubs.rsc.org/en/content/articlehtml/2014/lc/c4lc00320a>
  22. Feng CY, Khulbe KC, Matsuura T, Ismail AF. Recent progresses in polymeric hollow fiber membrane preparation, characterization and applications. *Separation and Purification Technology*. 2013;111:43–71. Available from: <https://www.sciencedirect.com/science/article/pii/S138358661300155X>
  23. Freeman B, Pinnau I. Separation of gases using solubility-selective polymers. *Trends in Polymer Science (Regular Ed.)*. 1997;5(5):167–173.
  24. Freeman BD. Basis of permeability/selectivity tradeoff relations in polymeric gas separation membranes. *Macromolecules*. 1999;32(2):375–380.
  25. Fu S, Sanders ES, Kulkarni SS, Koros WJ. Carbon molecular sieve membrane structure–property relationships for four novel 6FDA-based polyimide precursors. *Journal of Membrane Science*. 2015;487:60–73.
  26. Galizia M, Chi WS, Smith ZP, Merkel TC, Baker RW, Freeman BD. 50th anniversary perspective: polymers and mixed matrix membranes for gas and vapor separation: a review and prospective opportunities. *Macromolecules*. 2017;50(20):7809–43.
  27. Ghanem BS, Swaidan R, Ma X, Litwiller E, Pinnau I. Energy-efficient hydrogen separation by AB-type ladder-polymer molecular sieves. *Advanced Materials*. 2014;26(39):6696–700. Available from: <https://doi.org/10.1002/adma.201401328>
  28. Gin DL, Noble RD. Designing the next generation of chemical separation membranes. *Science*. 2011;332(6030):674–6.
  29. Giordano L, Roizard D, Favre E. Life cycle assessment of post-combustion CO<sub>2</sub> capture: a comparison between membrane separation and chemical absorption processes. *International Journal of Greenhouse Gas Control*. 2018;68:146–63. Available from: <https://www.sciencedirect.com/science/article/pii/S1750583617304875>
  30. Gitis V, Rothenberg G. *Ceramic membranes: new opportunities and practical applications*. Hoboken, NJ: John Wiley & Sons; 2016.
  31. Gkotsis PK, Banti DC, Peleka EN, Zouboulis AI, Samaras PE. Fouling issues in membrane bioreactors (MBRs) for wastewater treatment: major mechanisms, prevention and control strategies. *Processes*. 2014;2(4):795–866. Available from: <https://www.mdpi.com/2227-9717/2/4/795>
  32. Gleason KL, Smith ZP, Liu Q, Paul DR, Freeman BD. Pure- and mixed-gas permeation of CO<sub>2</sub> and CH<sub>4</sub> in thermally rearranged polymers based on 3,3'-dihydroxy-4,4'-diamino-biphenyl (HAB) and 2,2'-bis-(3,4-dicarboxyphenyl) hexafluoropropane dianhydride (6FDA). *Journal of Membrane Science*. 2015;475:204–14. Available from: <https://www.sciencedirect.com/science/article/pii/S0376738814007753>
  33. Guessasma S, Belhabib S, Nouri H. Significance of pore percolation to drive anisotropic effects of 3D printed polymers revealed with X-ray  $\mu$ -tomography and finite element computation. *Polymer*. 2015;81:29–36. Available from: <https://www.sciencedirect.com/science/article/pii/S003238611530327X>
  34. Horn NR, Paul DR. Carbon dioxide plasticization of thin glassy polymer films. *Polymer*. 2011;52(24):5587–94.
  35. Huang Y, Paul DR. Physical aging of thin glassy polymer films monitored by gas permeability. *Polymer*. 2004;45(25):8377–93.
  36. Ismail AF, Lorna W. Penetrant-induced plasticization phenomenon in glassy polymers for gas separation membrane. *Separation and Purification Technology*. 2002;27(3):173–94.
  37. Kadirkhan F, Mustapa WNF, Halim MHM, Kian SW, Yean YS. Towards commercialization: challenges in scaling up lab-scale membrane for field performance evaluation. *Malaysian Journal of Fundamental and Applied Sciences*. 2019;15(6):857–61. Available from: <https://www.academia.edu/download/109679928/pdf.pdf>
  38. Karan S, Jiang Z, Livingston AG. Sub-10 nm polyamide nanofilms with ultrafast solvent transport for molecular separation. *Science*. 2015;348(6241):1347–51. Available from: <https://doi.org/10.1126/science.aaa5058>
  39. Kenarsari SD, Yang D, Jiang G, Zhang S, Wang J, Russell AG, Wei Q, Fan M. Review of recent advances in carbon dioxide separation and capture. *RSC Advances*. 2013;3(45):22739–73. Available from: <https://pubs.rsc.org/en/content/articlehtml/2013/ra/c3ra43965h>
  40. Kim S, Marand E, Ida J, Gulians VV. Polysulfone and mesoporous molecular sieve MCM-48 mixed matrix membranes for gas separation. *Chemistry of Materials*. 2006;18(5):1149–55. Available from: <https://doi.org/10.1021/cm052305o>
  41. Koros WJ, Zhang C. Materials for next-generation molecularly selective synthetic membranes. *Nature Materials*. 2017;16(3):289–97.
  42. Kraftschik B, Koros WJ, Johnson J, Karvan O. Dense film polyimide membranes for aggressive sour gas feed separations. *Journal of Membrane Science*. 2013;428:608–19.
  43. Kumar M, Grzelakowski M, Zilles J, Clark M, Meier W. Highly permeable polymeric membranes based on the incorporation of the functional water channel protein Aquaporin Z. *Proceedings of the National Academy of Sciences*. 2007;104(52):20719–24. Available from: <https://doi.org/10.1073/pnas.0708762104>
  44. Li Y, Xin Q, Wu H, Guo R, Tian Z, Liu Y, Wang S, He G, Pan F, Jiang Z. Efficient CO<sub>2</sub> capture by humidified

- polymer electrolyte membranes with tunable water state. *Energy & Environmental Science*. 2014;7(4):1489–99. Available from: <https://pubs.rsc.org/en/content/articlehtml/2014/ee/c3ee43163k>
45. Liao Y, Loh C-H, Tian M, Wang R, Fane AG. Progress in electrospun polymeric nanofibrous membranes for water treatment: fabrication, modification and applications. *Progress in Polymer Science*. 2017. Available from: <https://doi.org/10.1016/j.progpolymsci.2017.10.003>
  46. Lin H, Van Wagner E, Freeman BD, Toy LG, Gupta RP. Plasticization-enhanced hydrogen purification using polymeric membranes. *Science*. 2006;311(5761):639–42. Available from: <https://doi.org/10.1126/science.1118079>
  47. Mahajan R, Koros WJ. Factors controlling successful formation of mixed-matrix gas separation materials. *Industrial & Engineering Chemistry Research*. 2000;39(8):2692–6. Available from: <https://doi.org/10.1021/ie990799r>
  48. Matteucci S, Yampolskii Y, Freeman BD, Pinnau I. Transport of gases and vapors in glassy and rubbery polymers. *Materials Science of Membranes for Gas and Vapor Separation*. 2006:1–47.
  49. McKeown NB, Budd PM. Polymers of intrinsic microporosity (PIMs): organic materials for membrane separations, heterogeneous catalysis and hydrogen storage. *Chemical Society Reviews*. 2006;35(8):675–83. Available from: <https://pubs.rsc.org/en/content/articlehtml/2008/5a/b600349d>
  50. Merkel TC, Lin H, Wei X, Baker R. Power plant post-combustion carbon dioxide capture: an opportunity for membranes. *Journal of Membrane Science*. 2010;359(1–2):126–39. Available from: <https://www.sciencedirect.com/science/article/pii/S0376738809007832>
  51. Merkel TC, Zhou M, Baker RW. Carbon dioxide capture with membranes at an IGCC power plant. *Journal of Membrane Science*. 2012;389:441–50. Available at: <https://www.sciencedirect.com/science/article/pii/S0376738811008283>
  52. Mondal S, Griffiths IM, Ramon GZ. Forefronts in structure–performance models of separation membranes. *Journal of Membrane Science*. 2019;588:117166. Available at: <https://www.sciencedirect.com/science/article/pii/S0376738818330394>
  53. Moore TT, Koros WJ. Non-ideal effects in organic–inorganic materials for gas separation membranes. *Journal of Molecular Structure*. 2005;739(1–3):87–98. Available at: <https://www.sciencedirect.com/science/article/pii/S0022286004007355>
  54. Moore TT, Mahajan R, Vu DQ, Koros WJ. Hybrid membrane materials comprising organic polymers with rigid dispersed phases. *AIChE Journal*. 2004;50(2):311–21. Available at: <https://doi.org/10.1002/aic.10029>
  55. Nik OG, Chen XY, Kaliaguine S. Functionalized metal organic framework-polyimide mixed matrix membranes for CO<sub>2</sub>/CH<sub>4</sub> separation. *Journal of Membrane Science*. 2012;413:48–61. Available at: <https://www.sciencedirect.com/science/article/pii/S037673881200289X>
  56. Park CH, Tocci E, Kim S, Kumar A, Lee YM, Drioli E. A simulation study on OH-containing polyimide (HPI) and thermally rearranged polybenzoxazoles (TR-PBO): relationship between gas transport properties and free volume morphology. *The Journal of Physical Chemistry B*. 2014;118(10):2746–57.
  57. Park HB, Han SH, Jung CH, Lee YM, Hill AJ. Thermally rearranged (TR) polymer membranes for CO<sub>2</sub> separation. *Journal of Membrane Science*. 2010;359(1–2):11–24. Available at: <https://www.sciencedirect.com/science/article/pii/S0376738809006942>
  58. Park HB, Jung CH, Lee YM, Hill AJ, Pas SJ, Mudie ST, *et al.* Polymers with cavities tuned for fast selective transport of small molecules and ions. *Science*. 2007;318(5848):254–8. Available at: <https://doi.org/10.1126/science.1146744>
  59. Park HB, Kamcev J, Robeson LM, Elimelech M, Freeman BD. Maximizing the right stuff: the trade-off between membrane permeability and selectivity. *Science*. 2017;356(6343):eaab0530.
  60. Peng N, Widjojo N, Sukitpaneit P, Teoh MM, Lipscomb GG, Chung TS, *et al.* Evolution of polymeric hollow fibers as sustainable technologies: past, present, and future. *Progress in Polymer Science*. 2012;37(10):1401–24. Available at: <https://www.sciencedirect.com/science/article/pii/S0022286012000147>
  61. Pinnau I, Toy LG. Gas and vapor transport properties of amorphous perfluorinated copolymer membranes based on 2,2-bis(trifluoromethyl)-4,5-difluoro-1,3-dioxole/tetrafluoroethylene. *Journal of Membrane Science*. 1996;109(1):125–33. Available at: <https://www.sciencedirect.com/science/article/pii/S037673889500193X>
  62. Rawtani D, Agrawal YK. Emerging strategies and applications of layer-by-layer self-assembly. *Nanobiomedicine*. 2014;1:8. Available at: <https://doi.org/10.5772/60009>
  63. Robeson LM. The upper bound revisited. *Journal of Membrane Science*. 2008;320(1–2):390–400.
  64. Rodenas T, Luz I, Prieto G, Seoane B, Miro H, Corma A, *et al.* Metal–organic framework nanosheets in polymer composite materials for gas separation. *Nature Materials*. 2015;14(1):48–55. Available at: <https://www.nature.com/articles/nmat4113>
  65. Roussanaly S, Anantharaman R, Lindqvist K, Zhai H, Rubin E. Membrane properties required for post-combustion CO<sub>2</sub> capture at coal-fired power plants. *Journal of Membrane Science*. 2016;511:250–64. Available at: <https://www.sciencedirect.com/science/article/pii/S0376738816301740>
  66. Sanders DF, Smith ZP, Guo R, Robeson LM, McGrath JE, Paul DR, *et al.* Energy-efficient polymeric gas separation membranes for a sustainable future: a review. *Polymer*. 2013;54(18):4729–61.
  67. Sanders DF, Smith ZP, Ribeiro Jr CP, Guo R, McGrath JE, Paul DR, *et al.* Gas permeability, diffusivity, and free volume of thermally rearranged polymers based on 3,3'-dihydroxy-4,4'-diamino-biphenyl (HAB) and 2,2'-bis-(3,4-dicarboxyphenyl) hexafluoropropane dianhydride (6FDA). *Journal of Membrane Science*. 2012;409:232–

41. Available at: <https://www.sciencedirect.com/science/article/pii/S037673881200261X>
68. Shao L, Low BT, Chung TS, Greenberg AR. Polymeric membranes for the hydrogen economy: contemporary approaches and prospects for the future. *Journal of Membrane Science*. 2009;327(1–2):18–31. Available at: <https://www.sciencedirect.com/science/article/pii/S037673880800971X>
69. Shen J, Liu G, Huang K, Jin W, Lee K, Xu N. Membranes with fast and selective gas-transport channels of laminar graphene oxide for efficient CO<sub>2</sub> capture. *Angewandte Chemie*. 2015;127(2):588–92. Available at: <https://doi.org/10.1002/ange.201409563>
70. Shen Y, Wang H, Liu J, Zhang Y. Enhanced performance of a novel polyvinyl amine/chitosan/graphene oxide mixed matrix membrane for CO<sub>2</sub> capture. *ACS Sustainable Chemistry & Engineering*. 2015;3(8):1819–29. Available at: <https://doi.org/10.1021/acssuschemeng.5b00409>
71. Smith AR, Klosek J. A review of air separation technologies and their integration with energy conversion processes. *Fuel Processing Technology*. 2001;70(2):115–34. Available at: <https://www.sciencedirect.com/science/article/pii/S037838200100131X>
72. Speight JG. Chapter 17 - Fouling as a Result of Corrosion. In: Speight JG, editor. *Fouling in Refineries*. Boston: Gulf Professional Publishing; 2015. p. 413–52. Available at: <https://doi.org/10.1016/B978-0-12-800777-8.00017-6>
73. Tena A, Lozano AE, Palacio L, Marcos-Fernández A, Prádanos P, de Abajo J, *et al.* Gas separation properties of systems with different amounts of long poly (ethylene oxide) segments for mixtures including carbon dioxide. *International Journal of Greenhouse Gas Control*. 2013;12:146–54. Available at: <https://www.sciencedirect.com/science/article/pii/S1750583612002472>
74. Tian Z, Wang S, Wang Y, Ma X, Cao K, Peng D, *et al.* Enhanced gas separation performance of mixed matrix membranes from graphitic carbon nitride nanosheets and polymers of intrinsic microporosity. *Journal of Membrane Science*. 2016;514:15–24. Available at: <https://www.sciencedirect.com/science/article/pii/S0376738816302320>
75. Tin PS, Chung T-S, Liu Y, Wang R. Separation of CO<sub>2</sub>/CH<sub>4</sub> through carbon molecular sieve membranes derived from P84 polyimide. *Carbon*. 2004;42(15):3123–31.
76. Tiwari RR, Jin J, Freeman B, Paul D. Physical aging, CO<sub>2</sub> sorption and plasticization in thin films of polymer with intrinsic microporosity (PIM-1). *Journal of Membrane Science*. 2017;537:362–71.
77. Wang S, Li X, Wu H, Tian Z, Xin Q, He G, *et al.* Advances in high permeability polymer-based membrane materials for CO<sub>2</sub> separations. *Energy & Environmental Science*. 2016;9(6):1863–90. Available at: <https://pubs.rsc.org/en/content/articlehtml/1961/ee/c6ee00811a>
78. Wang Z, Wang D, Zhang F, Jin J. Tröger's Base-Based Microporous Polyimide Membranes for High-Performance Gas Separation. *ACS Macro Letters*. 2014;3(7):597–601. Available at: <https://doi.org/10.1021/mz500184z>
79. Wijmans JG, Baker RW. The solution-diffusion model: a review. *Journal of Membrane Science*. 1995;107(1–2):1–21.
80. Wind JD, Staudt-Bickel C, Paul DR, Koros WJ. The effects of crosslinking chemistry on CO<sub>2</sub> plasticization of polyimide gas separation membranes. *Industrial & Engineering Chemistry Research*. 2002;41(24):6139–48.
81. Xie W, Geise GM, Freeman BD, Lee H-S, Byun G, McGrath JE. Polyamide interfacial composite membranes prepared from m-phenylene diamine, trimesoyl chloride and a new disulfonated diamine. *Journal of Membrane Science*. 2012;403:152–61. Available at: <https://www.sciencedirect.com/science/article/pii/S0376738812001445>
82. Xu L, Rungta M, Koros WJ. Matrimid® derived carbon molecular sieve hollow fiber membranes for ethylene/ethane separation. *Journal of Membrane Science*. 2011;380(1–2):138–47. Available at: <https://www.sciencedirect.com/science/article/pii/S0376738811004893>
83. Yampol'skii YP, Volkov VV. Studies in gas permeability and membrane gas separation in the Soviet Union. *Journal of Membrane Science*. 1991;64(3):191–228. Available at: <https://www.sciencedirect.com/science/article/pii/S037673889180092K>
84. Yang RT. Air separation by pressure swing adsorption using superior adsorbents. FG26-98FT40115-02. National Energy Technology Laboratory (NETL), Pittsburgh, PA, Morgantown, WV, and Albany, OR (United States); 2001. Available at: <https://doi.org/10.2172/789503>
85. Zhai H, Rubin ES. Techno-Economic Assessment of Polymer Membrane Systems for Postcombustion Carbon Capture at Coal-Fired Power Plants. *Environmental Science & Technology*. 2013;47(6):3006–14. Available at: <https://doi.org/10.1021/es3050604>
86. Zhang Y, Feng X, Yuan S, Zhou J, Wang B. Challenges and recent advances in MOF-polymer composite membranes for gas separation. *Inorganic Chemistry Frontiers*. 2016;3(7):896–909. Available at: <https://pubs.rsc.org/en/content/articlehtml/2016/qi/c6qi00042h>
87. Zhang Y, Sunarso J, Liu S, Wang R. Current status and development of membranes for CO<sub>2</sub>/CH<sub>4</sub> separation: A review. *International Journal of Greenhouse Gas Control*. 2013;12:84–107. Available at: <https://www.sciencedirect.com/science/article/pii/S1750583612002423>
88. Zhao Y, Ho WSW. CO<sub>2</sub>-selective membranes containing sterically hindered amines for CO<sub>2</sub>/H<sub>2</sub> separation. *Industrial & Engineering Chemistry Research*. 2013;52(26):8774–82. Available at: <https://doi.org/10.1021/ie301397m>