

# A Review on Emerging Microporous Material-based Membranes for Carbon Capture and Separation

Nicholaus Prasetya<sup>1</sup> , Nurul F. Himma<sup>2</sup> , Putu Doddy Sutrisna<sup>3</sup>, I G. Wenten<sup>4,5\*</sup>  and Bradley P. Ladewig<sup>1,6\*</sup> 

<sup>1</sup> Barrer Centre, Department of Chemical Engineering, Imperial College London, SW7 2AZ, United Kingdom

<sup>2</sup> Department of Chemical Engineering, Universitas Brawijaya, Jalan Mayjen Haryono 167, Malang 65145, Indonesia

<sup>3</sup> Department of Chemical Engineering, Universitas Surabaya, Jalan Raya Kalirungkut (Tenggilis), Surabaya 60293, Indonesia

<sup>4</sup> Department of Chemical Engineering, Institut Teknologi Bandung, Jalan Ganesha 10, Bandung 40132, Indonesia

<sup>5</sup> Research Center for Nanoscience and Nanotechnology, Institut Teknologi Bandung, Bandung 40132, Indonesia

<sup>6</sup> Institute for Micro Process Engineering (IMVT), Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

\* Correspondence: igw@che.itb.ac.id, bradley.ladewig@kit.edu

**Abstract:** Membrane technology has gained great attention as one of the promising strategies for carbon capture and separation. Intended for such application, membrane fabrication from various materials has been attempted. While gas separation membranes based on dense polymeric materials have been long developed, there is a growing interest to use porous materials as the membrane material. This review then focuses on emerging porous materials to be used for the fabrication of membranes that are designed for CO<sub>2</sub> separation. Criteria for selecting microporous material are first discussed, including physical and chemical properties, and parameters in membrane fabrication. Membranes based on emerging porous materials, such as metal-organic frameworks, porous organic frameworks, and microporous polymers, are then reviewed. Finally, special attention is given to recent advances, challenges, and perspectives in the development of such membranes for carbon capture and separation.

**Keywords:** microporous material; gas separation membrane; MOF; POF; microporous polymer; carbon capture

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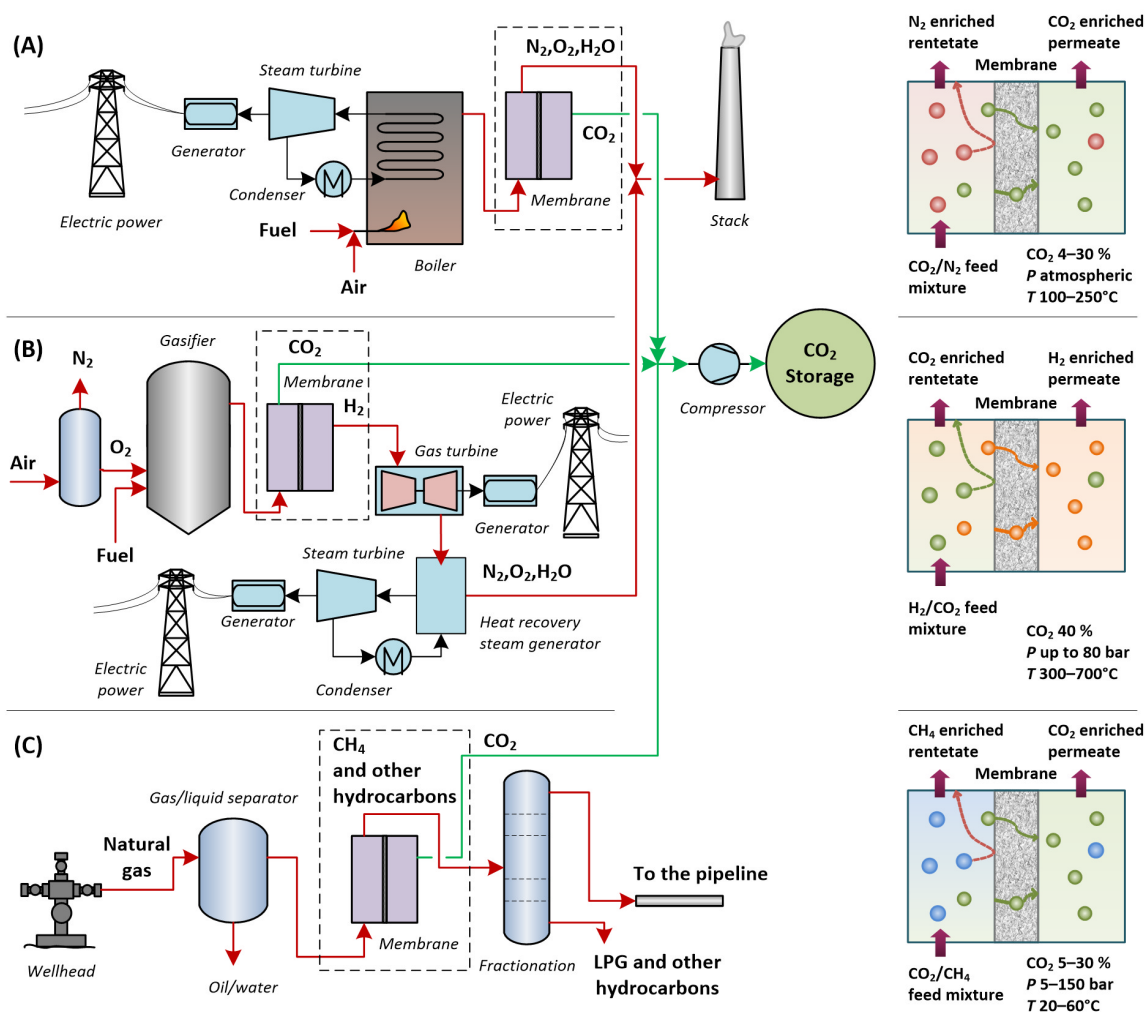
## 1. Introduction

Increased attention to the environmental sustainability has encouraged global efforts to reduce carbon emissions from various industrial processes. For this reason, carbon dioxide (CO<sub>2</sub>) separation is necessary to be applied in at least three important areas: pre-combustion to eliminate CO<sub>2</sub> from the main fuel (CO<sub>2</sub>/H<sub>2</sub> separation), post-combustion where CO<sub>2</sub> will be separated from flue gases (CO<sub>2</sub>/N<sub>2</sub> separation) and oxy-fuel combustion to produce a high concentration CO<sub>2</sub> gas stream from a combustion process of fuel and pure oxygen. In addition, CO<sub>2</sub> separation is also required in the natural gas processing and biogas upgrading (CO<sub>2</sub>/CH<sub>4</sub> separation).

The current technologies that are widely applied to accomplish these processes are absorption and adsorption. When employing these techniques, the two most crucial aspects are the economical aspect and energy penalty to regenerate the adsorbent or absorbent [1]. For the conventional aqueous amine absorber technique, the regeneration process is usually completed through heating to release the CO<sub>2</sub>. The energy penalty of this system comes from the process of heating and evaporating the water that is required to dilute the amine. When adsorbents are used, various techniques can be used for the adsorption processes, such as pressure swing adsorption (PSA), temperature swing adsorption

(TSA) and vacuum swing adsorption (VSA). Using adsorption technologies, the energy penalty comes from the energy required to complete the whole process (adsorption-desorption), for example from the requirement to heat the material and to desorb the CO<sub>2</sub> and to pressurize CO<sub>2</sub> to about 150 bar for geological storage.

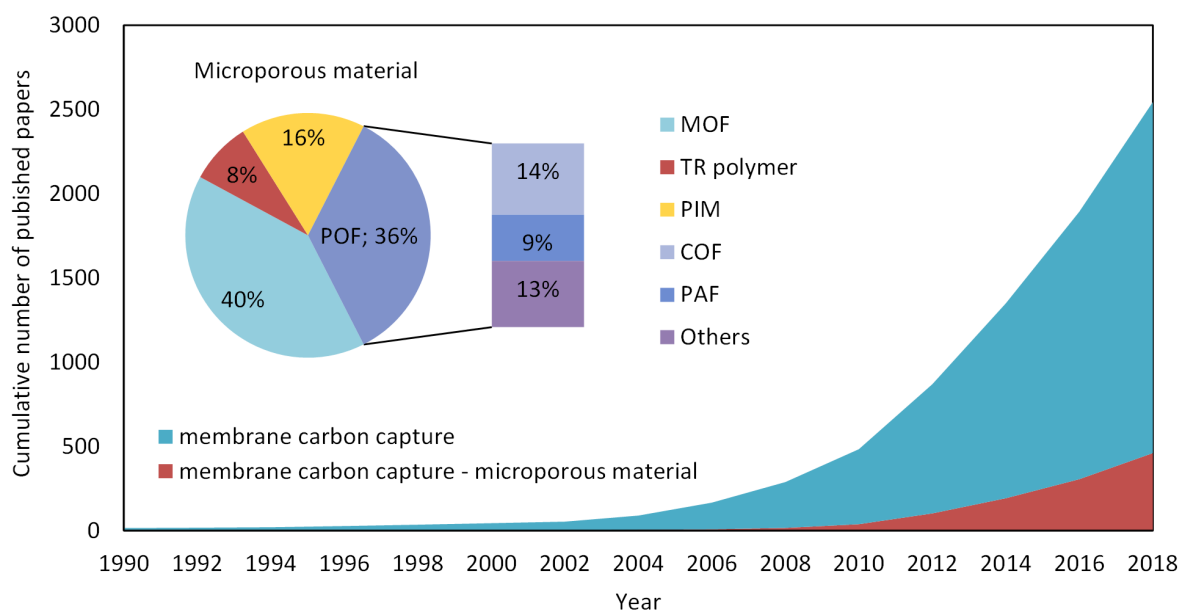
Apart from absorption/adsorption, membrane technology is an attractive alternative for carbon capture. Membrane technology could offer various advantages in this field in terms of footprint, energy consumption and cost [2,3]. Potential applications for membrane-based CO<sub>2</sub> separation are depicted in Figure 1. Various polymers have been used to produce a commercial membrane for gas separation either in a hollow fibre or spiral wound form. Cellulose acetate, polysulfone, polycarbonate, and polyimide are the most common polymers used to produce commercial membranes [2]. In addition, there is also a growing interest to explore inorganic materials to be used in gas separation membrane fabrication because of their advantages over polymers in terms of thermal and mechanical properties [2].



**Figure 1.** Potential applications for membranes in CO<sub>2</sub> separation: (A) post-combustion, (B) pre-combustion, and (C) natural gas processing. The corresponding membrane gas separation and its process conditions are shown in the right picture.

During the last two decades, there is also a strong interest in developing a new class of porous materials which have a large surface area and thus rendering them to be a promising candidate as a gas adsorbent. There are various names of these new materials depending on their structure and building blocks such as metal-organic frameworks (MOFs), porous organic frameworks (POFs),

thermally-rearranged (TR) polymers and polymers of intrinsic microporosity (PIMs). The first two are a highly crystalline material while the other two are usually amorphous. Apart from using them as merely an adsorbent, recent research and developments have also shown a growing interest to fabricate them as a membrane. As can be seen in Figure 2, the number of research publications in this area has been growing exponentially since 2008 with the lead of MOFs and Covalent Organic Frameworks (COFs). This has shown the growing interest in developing microporous materials as membrane to address the carbon capture problem. This is particularly due to their promising capabilities to enhance the membrane working capacity by increasing the membrane productivity and thus advancing the already mature membrane technology [4].



**Figure 2.** The cumulative number of published papers related to the membranes and microporous material-based membranes for carbon capture. The inserted pie diagram presents the percentage of published papers reporting each type of microporous material.

A number of review articles on porous materials and gas separation membranes have been published with various focuses[5–8]. In this review article, we choose to focus on emerging porous materials that can be utilized further as a membrane material for CO<sub>2</sub> separation. This is important since we believe that membrane-based processes should be the next promising process for CO<sub>2</sub> separation and porous materials could significantly contribute in this field.

## 2. Microporous material selection criteria for CO<sub>2</sub> capture and membrane fabrication

### 2.1. Microporous materials criteria

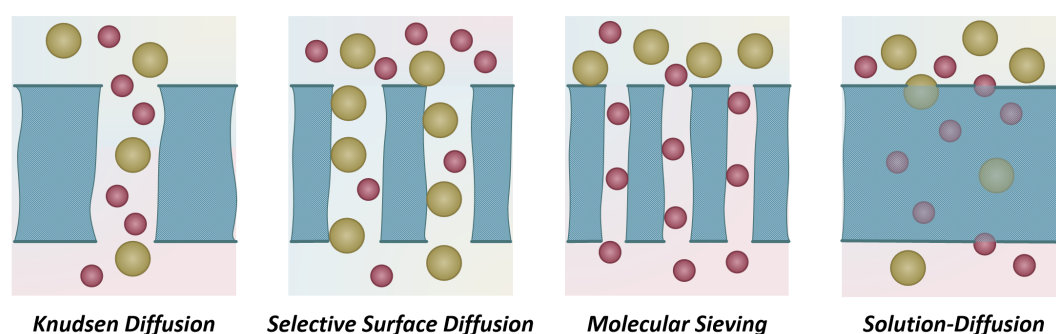
Both physical and chemical properties could affect the CO<sub>2</sub> separation performance in microporous materials which, once applied in membrane, could also impact the membrane performance for CO<sub>2</sub> separation. This section will then concisely discuss both aspects.

#### 2.1.1. Physical Properties

Several physical characteristics need to be considered for an effective microporous adsorbent including microporosity, surface area, free volume, and pore size. Most emerging microporous materials are made up from light elements and can achieve a very high gravimetric surface area in the order of thousands of square metres per gram (m<sup>2</sup>g<sup>-1</sup>) [9]. Therefore, they usually have a high gas

uptake, including for CO<sub>2</sub>. Besides surface area, the free volume is also an important characteristic affecting the gas uptake and it should be interconnected [10].

In terms of the pore size, different mechanisms can occur depending on the size between the pore and adsorbate (Figure 3). A material with a pore size close to the size of the targeted adsorbate is much preferred. This will impart a confinement effect (steric effect) to the targeted adsorbate resulting in adsorption enhancement [11]. This is called molecular sieving and occurs when the microporous material has the right pore size to exclude the larger gas molecules. Once the pore size increases and is suitable to accommodate both gases that are to be separated, various separation mechanisms could occur such as Knudsen diffusion and selective surface diffusion. Depending on the interaction between the gas and the framework, diffusion or equilibrium-based phenomenon would be the one dominating factor. The former happens if the pore size is just slightly larger than the largest gas molecule to be separated. In this case, a larger gas molecule would be excluded based on the diffusion mechanism since it diffuses slower than the smaller one. Meanwhile, the equilibrium based separation happens once both gases can diffuse easily inside the pore of the material and thus the separation is governed by the interaction between the framework and the gases [12]. In this case, a larger gas molecule could be more selectively adsorbed and passed through than the smaller gas molecule if the former has better interaction with the material. Therefore, designing the pore aperture for CO<sub>2</sub> separation is important to improve the microporous material selectivity to enhance both molecular sieving and Knudsen diffusion selectivity [13]. For CO<sub>2</sub> separation, ultramicroporosity with a pore size of less than 1 nm and preferably around 3.0-7.0 Angstrom is ideal [14,15].



**Figure 3.** Various separation mechanisms in microporous materials adsorbents and membrane.

However, tailoring physical properties needs to be accompanied with CO<sub>2</sub> preferential adsorption. For some cases, porous materials with an exceptionally high surface area and a very high CO<sub>2</sub> uptake are not followed by selective adsorption of CO<sub>2</sub> against other gases [11]. Therefore, chemical modification could address this issue to obtain a satisfactory CO<sub>2</sub> separation once a microporous-based material is formed into a membrane.

### 2.1.2. Chemical Properties

Compared to physical properties, chemical properties of emerging microporous materials are considered to be more important to enhance CO<sub>2</sub> capture performance [9]. A comprehensive review on this matter has been previously published such as for MOFs [16] and porous organic frameworks [14]. For the purpose of this paper, a concise explanation is necessary to justify the selection of the microporous materials.

For CO<sub>2</sub> separation, the functional groups that contain nitrogen, oxygen, sulfur or phosphorus can improve the affinity between CO<sub>2</sub> and the adsorbent [17]. This beneficial aspect has been explored using various functional groups incorporated inside microporous materials. The common example is to use amine. As in conventional absorption process, amine groups in microporous materials could enhance their CO<sub>2</sub> uptake and selectivity [18]. This is particularly important in low-pressure region

where adsorption occurs in the most energetic region of the solid surface since CO<sub>2</sub> can readily make a C-N covalent bonding with the amine group through the chemisorption process [18].

Nitrogen-rich functional groups are also beneficial for CO<sub>2</sub> capture [19,20]. Microporous materials for CO<sub>2</sub> separation could then be functionalized using this functional group such as triazole [21], azobenzene [22] and benzimidazole [23]. The presence of nitrogen-rich microporous materials has been reported to improve the selectivity of CO<sub>2</sub> against N<sub>2</sub> and CH<sub>4</sub> through various mechanisms such as the dipole-quadrupole interaction [24] and nitrogen-phobicity environment [22]. A functional group that is not only rich in nitrogen but also has a CO<sub>2</sub>-philic property such as tetrazole [25] is also beneficial in improving CO<sub>2</sub> separation since it provides a basic environment to attract more CO<sub>2</sub> into the pores.

The presence of polar functional groups is also beneficial for CO<sub>2</sub> capture to enhance CO<sub>2</sub> selectivity based on polarity. This has been proven for example in the family of ZIFs [26] and COFs [27]. The polar functional groups can have a greater attraction towards CO<sub>2</sub> resulting from the quadrupole moment and thus resulting in a lower parasitic energy loss when applied in a carbon capture plant. Its benefit could even be doubled when using multiple functional groups in a porous material [27].

For MOFs in particular, open metal sites can also help to adsorb more CO<sub>2</sub> since it can behave as a Lewis acid site [28]. This usually comes from the removal of terminated solvent molecules inside the MOFs pore. Therefore, MOFs that have a denser population of open metal sites in a unit cell exhibit higher CO<sub>2</sub> uptake at low-pressure region than those with lower, or no open metal sites [29]. As open metal sites, the presence of heteroatoms in MOFs is also beneficial in improving the CO<sub>2</sub> capture performance [16]. This property is particularly important if the materials are going to be applied at low-pressure operating conditions such as post-combustion CO<sub>2</sub> capture [12].

Another important aspect to be considered is the stability of the microporous materials and competitive adsorption from different adsorbates that is likely to occur in real applications. It is well known that some microporous materials are very sensitive to humidity leading to structural degradation [30]. In the practical application of CO<sub>2</sub> capture and separation, the presence of water vapour cannot be neglected and thus it is imperative to develop a material that is stable under these conditions. Only a few cases reported the beneficial impact on the presence of water vapour for separating CO<sub>2</sub> from N<sub>2</sub> or CH<sub>4</sub> such as in MIL-101 (Fe) [31]. Thus, this means that the materials need to have a hydrophobicity to a certain extent in order to avoid water vapour attack and to competitively adsorb to the active sites which can lower the overall CO<sub>2</sub> selectivity, in particular with porous materials that are functionalized with a polar functional group [11]. Apart from that, it is also imperative for the materials to stay highly selective towards CO<sub>2</sub> in the presence of other species in the gas stream such as sulfur dioxide [11].

## 2.2. Membrane fabrication

There are at least three core parameters to turn a microporous material into a membrane: high permeability and selectivity, ease of fabrication, and robust structure. All of these properties and its relationship with the emerging microporous materials is discussed in the following section.

### 2.2.1. Permeability and selectivity

Performance in gas separation membranes is usually evaluated against the Robeson Upper Bound [32]. The graph depicts the trade-off between permeability and selectivity: membranes with higher permeability usually have lower selectivity, and vice versa. Research in gas separation membranes based on emerging microporous materials then aims to surpass this limit [32]. The membrane permeability in a polymeric membrane could be described by solution-diffusion model with Barrer as the unit [1 Barrer = 10<sup>-10</sup> cm<sup>3</sup>(STP) cm/cm<sup>2</sup> s cmHg] [33]. In this model, the permeability is affected by two parameters: solution and diffusion. The former is related to gas molecule solubility in a membrane material. Meanwhile, the latter is related to the size of each gas molecule. For most of the commercially available polymeric membranes, the permeability is mainly affected by the void space built from

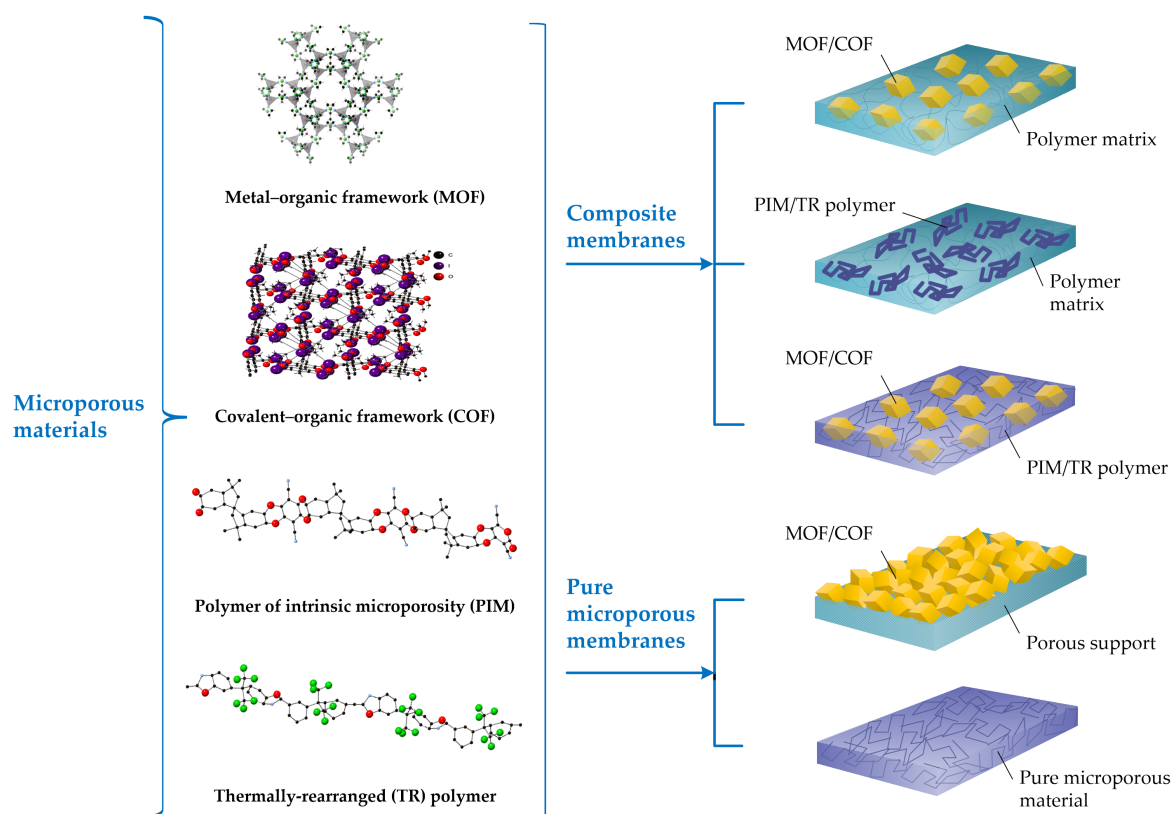
intermolecular space of the polymer which is called free volume [5,34]. The main drawback of the current polymeric membranes is their low fractional free volume (FFV) since it is not interconnected, resulting in low membrane permeability [5,34].

In a microporous materials-based membrane, the permeability is not solely affected by FFV. They can also be affected by the pore size and pore size distribution of the materials [35] and the pore structure (interconnected or isolated) [4]. In a microporous materials membrane, apart from a suitable pore size, it is expected that the pores are interconnected as indicated by high surface area [14] and not densified/compacted [36]. This is important to obtain a highly permeable membrane and thus, once equipped with a proper functionality, can result in a highly selective membrane for CO<sub>2</sub> separation [4,25].

Selectivity is also an important factor in determining membrane performance in gas separation. Selectivity is defined in relative terms between the permeability of one component against another, usually between the faster and the slower permeating gas. This then depends on the permeation rate of each gas in the membrane and each CO<sub>2</sub> separation application has different requirements regarding which gas should permeate faster. In post-combustion applications, a membrane with high CO<sub>2</sub> permeation is expected while impeding the N<sub>2</sub> transport. A membrane with similar property is also expected for natural gas purification where it must be selective in rejecting CH<sub>4</sub>. In contrast, for pre-combustion application, the membrane should have high permeability towards H<sub>2</sub> and impede the CO<sub>2</sub> transport.

#### 2.2.2. Ease of fabrication

Emerging microporous materials can be formed into a membrane either by fabricating a pure microporous membrane or a composite membrane as can be seen in Figure 4. For a pure microporous membrane, the simplest approach is by employing solution-casting method. This might be most suitable for materials that are solution processable such as PIMs [37]. Meanwhile, for non-solution processable materials such as MOFs and COFs, turning them into a pure microporous membrane is usually accomplished by growing a continuous layer on a porous support. However, the main challenge for this technique lies in growing a defect-free membrane. This issue could be addressed, for example, by inducing a heterogeneous crystallization on the substrate [38], growing a multilayer structure [39] or by chemically altering the substrate to enhance the bonding between the materials and the substrate [40].



**Figure 4.** Various approaches to fabricate CO<sub>2</sub> separation membranes based on microporous materials.

Because of this challenge, research has also explored composite membranes where two different materials are combined. This can be a composite of polymer and microporous materials (MOFs-polymer or PIMs-polymer for example) or between microporous materials (MOFs-PIMs composite for example). The advantage of this method is the simplicity of the fabrication process. Because one of the components is usually solution-processable, the other components can be dispersed in the solution, followed by membrane casting. However, the major issue in this area is compatibility between the two different components. Poor compatibility between two different materials will result in membrane defects and non-selective voids. If a good compatibility between two different materials could be obtained, a satisfactory separation performance and improved mechanical properties such as tensile strength [41], Young's modulus [41], and plasticization [42] could be obtained. In this case, emerging microporous materials such as MOFs and COFs contain organic compounds that will help to improve the compatibility with polymer. They could also be engineered to have 2D structure that could help in particle distribution in a polymer matrix [43]. In addition, both physical and chemical properties of either the microporous materials [44] or a polymer [45] could also be modified to improve their interaction.

### 2.2.3. Real-life performance

Applying membranes for CO<sub>2</sub> separation at industrial scale requires a robust testing condition. High pressure operating condition testing is required for membranes applied for pre-combustion CO<sub>2</sub> capture and natural gas sweetening. Meanwhile, both pre and post-combustion CO<sub>2</sub> capture requires operation at elevated temperature. Investigation at high operating pressure is also important since CO<sub>2</sub> is a condensable gas and at high operating pressure, the sorption of CO<sub>2</sub> starts to plasticize the membrane resulting in decrease of membrane selectivity [46].

The presence of feed impurities in CO<sub>2</sub> separation process must also be investigated [33,47]. This is because the presence of moisture and other contaminants can affect the membrane performance

and thus the plant operating cost [48]. For CO<sub>2</sub>/CH<sub>4</sub> separation, for instance, the natural gas stream usually contains a fraction of other hydrocarbons [49] and water vapour is also present in almost all CO<sub>2</sub> separation processes [31]. This might impact the membrane separation performance. Competitive adsorption on the microporous-materials based membrane should also be investigated. This is because it could cause permanent damage to microporous-porous based membranes for CO<sub>2</sub> separation [48]. In this case, a mixed gas scenario is highly recommended to study the competitive sorption and diffusion.

Lastly, long-term membrane performance must also be evaluated since polymeric membranes for gas separation could suffer from physical aging [50]. Physical aging is a thermodynamic phenomenon experienced particularly in a polymer with a poor chain packing because of the chain relaxation and convergence leading to the reduction of fractional free volume of the membrane [46,51]. This phenomenon is commonly observed with PIMs-based membranes resulting in CO<sub>2</sub> permeability reduction and slightly enhanced selectivity. From the industrial perspective, aging is an unfavourable condition since it leads to productivity reduction and performance unpredictability.

### 3. Metal-organic frameworks-based membrane

Metal-organic frameworks (MOFs) are built from a metal or a metal cluster connected by organic linker as a ligand. MOFs have gained an increased interest because of their numerous positive aspects such as large surface area, adjustable pore size, and post-synthetic modification (PSM) potential. MOFs have also been investigated for membrane fabrication. Generally, there are two ways to turn MOFs into a membrane: incorporation of MOFs inside a polymer matrix to fabricate a mixed matrix membrane (MMMs) and growing of MOF thin film on a porous substrate which will be discussed below regarding their performance for CO<sub>2</sub> separation.

MOFs-based MMMs have been widely investigated and are considered as a promising candidate for CO<sub>2</sub> separation since it can outperform the performance of most of the polymeric membranes [16]. Various factors need to be considered to fabricate MOF-based MMMs with satisfactory CO<sub>2</sub> separation performance such as polymer selection, composition ratio, and MOF morphology. Polymer selection is crucial since incorporating MOF into rubbery polymers is not beneficial to increase both CO<sub>2</sub> permeability and selectivity compared to glassy polymers [52]. This might be caused by MOFs pore intrusion by the rubbery polymer resulting in MOF ineffectiveness. Regarding MOF-polymer composition ratio, ideally, increasing MOFs loading in membranes should increase both membrane permeability and selectivity since they increase the free volume and enhance molecular sieving through chain rigidification [53,54]. However, up to a certain point, higher MOFs loading could only increase the membrane permeability but decrease the selectivity. This might be caused by several reasons such as particle agglomeration [55], particle sedimentation [56] and inhomogeneous particle dispersion leading to interfacial polymer-particle voids [57]. Thus, there is an optimum value for MOFs loading in a polymer matrix. Once the optimum value has been surpassed, inter-particle interaction starts to dominate which negatively impacts the MMMs performance [58].

Tailoring MOF property and morphology could also be an option to improve membrane performance. This could be done through various approaches such as PSM [59] and post-synthetic annealing (PSA) [60,61] to improve both MOF-polymer and MMM-CO<sub>2</sub> interaction. MOF's pores functionalization [62,63] and decoration with polymer [64] could also be used to improve the MMM molecular sieving ability and affinity towards CO<sub>2</sub>. The MMMs performance could also be improved by designing MOFs to be in 2D structure. In case of H<sub>2</sub>/CO<sub>2</sub> separation, the separation factor could be improved by incorporating MOF nanosheets since the nanosheets interlayer stacking creates a preferable pathway for H<sub>2</sub> to permeate compared to CO<sub>2</sub> [65]. MOF nanosheets could also enhance MMM productivity by the possibility to fabricate thinner membranes to increase the permeance [66]. Amorphous-MOF that was fabricated through in-situ thermal treatment in polymer matrix could also significantly improve the CO<sub>2</sub>/CH<sub>4</sub> selectivity [67]. Apart from polymer cross linking, the thermal treatment on the ZIF-8-Matrimid MMMs turned the ZIF-8 to be amorphous but has not yet changed



the overall structure and thus still retained its pore network to improve the molecular sieving property of the resulting membrane.

The MOF-based MMMs performance could also be enhanced by combining MOFs with other particles such as with other MOFs [68], graphene-based materials [69] and zeolites [70]. New MOF-composite fillers could also be synthesized such as ZIF-8-graphene oxide [71,72] and UiO-66-graphite oxide [73]. By combining MOF with other porous materials with different properties, it is expected that the composite membranes molecular sieving property and CO<sub>2</sub> affinity could be improved [69,72].

Once successfully fabricated, the performance of MMMs for CO<sub>2</sub> separation is influenced by various operating conditions. High operating pressure could reduce both MOF-based MMMs CO<sub>2</sub> permeability because of saturation of Langmuir adsorption site [74] and selectivity because of plasticization and if the MOF has structural flexibility such as ZIF-8 [75]. Enhancement in selectivity, however, can be expected for CO<sub>2</sub> separation since higher pressure leads to higher CO<sub>2</sub> adsorption onto the MOFs and can prevent the active MOFs sites to be occupied by other gases such as CH<sub>4</sub> [76]. Higher operating pressure can also be beneficial if flexible MOFs, such as MIL-53 (Al), is used which has higher CO<sub>2</sub> selectivity at higher pressure because of its breathable framework [75,77]. Temperature also affects the membrane performance. For MMMs built from glassy polymers, the increase in operating temperature is usually followed by the increase in polymer chain flexibility resulting in higher gases permeability [65,77]. Thus, it is important to maintain the operating condition where the membrane still retains high CO<sub>2</sub> selectivity since CO<sub>2</sub> permeance did not increase as fast as other gases such as CH<sub>4</sub> and N<sub>2</sub> resulting in lower selectivity [71,77]. The presence of contaminants will also impact the membrane performance. The presence of water vapour in the feed could negatively impact the permeation of light gases such as CO<sub>2</sub> and CH<sub>4</sub> [78]. Moreover, the negative impact is much more pronounced if the fillers used are more hydrophilic such as Cu-BTC and UiO-66 than in hydrophobic MOFs such as ZIF-8 since they are more attractive to water vapour [78].

MOF could also be turned into a MOF membrane by growing them onto a porous substrate. Growing a thin defect-free inter-crystalline layer is necessary to obtain a high flux and highly selective membrane which could be accomplished through various approaches [79]. One strategy is to focus on inducing heterogeneous nucleation on a porous substrate. This could be accomplished through seeding with MOF particles, to fabricate various MOF membranes such as MIL-53 (Al) [80], ZIF-7 [81], ZIF-8 [82], Mg-MOF-74 [83], and UiO-66-CH<sub>3</sub> [84]. Seeding could also be accomplished by using other inorganic particles such as TiO<sub>2</sub> to assist the growing of ZIF-8 MOF and improve the overall mechanical structure (Figure 5 (A), (B) and (C)). A seed-free technique can also be an option where both MOF nucleation and growing occur at the same time [85]. This could be done such as by preparing from an optimized and concentrated MOFs growing condition [86,87], a thermal ligand-deposition followed by crystal growing [88], gel-based processing [89], or utilization of substrate metal source to induce growing of MOF-film [90].

A defect-free MOFs membrane is expected to surpass the Knudsen selectivity value. The values for H<sub>2</sub>/CO<sub>2</sub>, CO<sub>2</sub>/N<sub>2</sub> and CO<sub>2</sub>/CH<sub>4</sub> are 4.7, 0.8 and 0.6, respectively. Although most MOF membranes could surpass these values, there are some cases where the separation performance could be negatively altered caused by preferential adsorption. This has been observed for H<sub>2</sub>/CO<sub>2</sub> separation where CO<sub>2</sub> is preferentially adsorbed on the MOFs resulting in reverse selectivity [87,91]. For CO<sub>2</sub>/N<sub>2</sub> and CO<sub>2</sub>/CH<sub>4</sub> separation, high adsorption capacity of CH<sub>4</sub> could also result in a significantly lower CO<sub>2</sub>/CH<sub>4</sub> selectivity than CO<sub>2</sub>/N<sub>2</sub> because of less-available sites for CO<sub>2</sub> to get adsorbed and permeate through the membrane [92]. Therefore, understanding the adsorption-diffusion trade-off in MOF membranes is important to obtain satisfactory CO<sub>2</sub> separation performance.

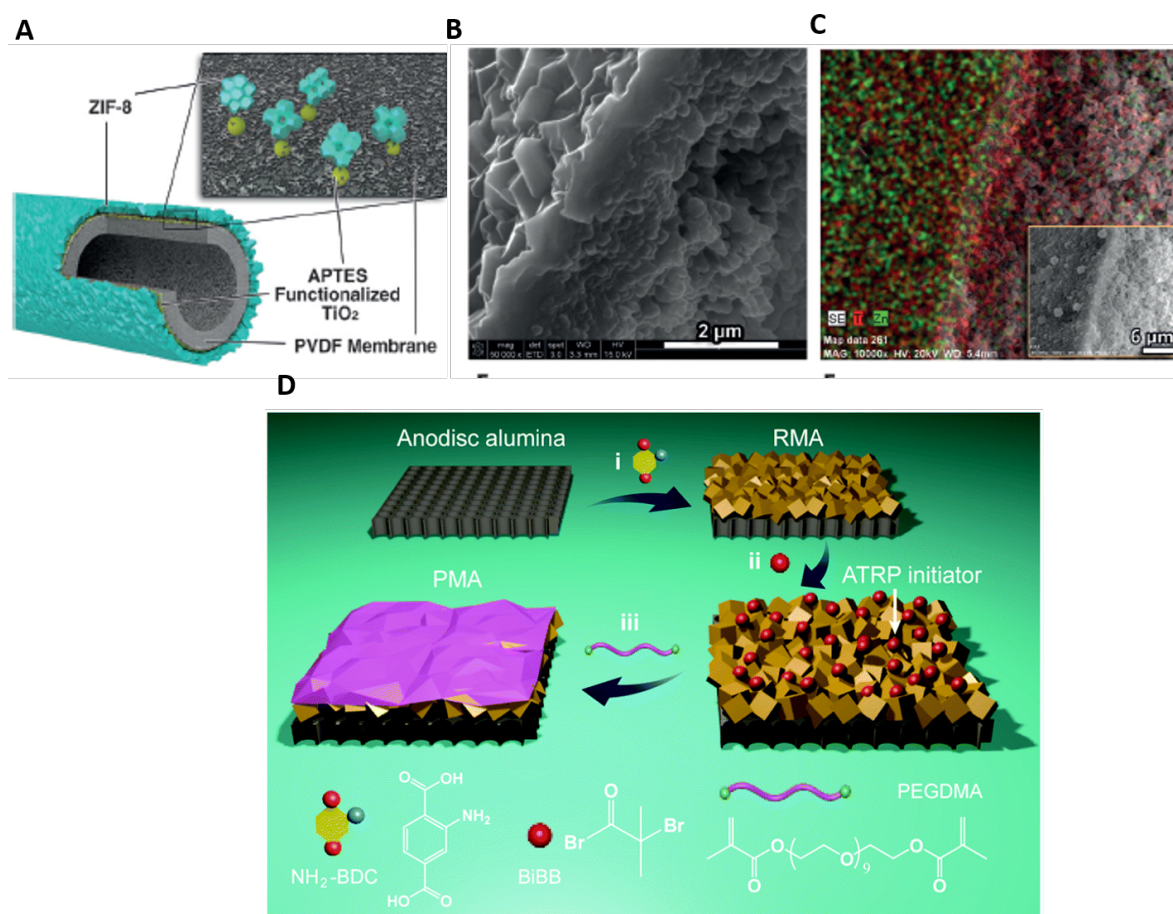
An increase in temperature does not always increase the gas permeability of MOF membranes, unlike the phenomenon usually observed in MOF-based MMM [83,93]. For instance, almost no change in CO<sub>2</sub> permeability was observed for ZIF-7 [94] and MOF-5 [95] membranes as the temperature was increased. In contrast, all gases permeance decreased with increasing temperature in a copper-based

MOF membrane [96] and in a ZIF-90 membrane [92]. Meanwhile, in  $\text{Zn}_2(\text{bim})_4$  nanosheet membrane, the  $\text{CO}_2$  permeation was observed to increase as temperature was increased [28]. This can be explained by the diffusion and adsorption phenomena in MOFs membrane. The former is a temperature-activated process, and an increase in diffusion and permeance is expected as the temperature is increased. However, the increase in temperature could also reduce the gas coverage on the MOFs surface because of lower adsorption at higher temperature [93]. As a result, each MOFs membrane has its own permeation activation energy. If this permeation activation energy is too small, temperature will barely affect the gas permeation through MOFs membrane. Despite this, it does seem that operating at high temperature for  $\text{H}_2/\text{CO}_2$  separation might be beneficial for MOFs which adsorb  $\text{CO}_2$  strongly, since higher temperature leads to less adsorbed  $\text{CO}_2$  and higher free volume in the MOFs could be obtained for enhanced  $\text{H}_2$  diffusion [97].

Differing from temperature, operating pressure in MOFs membrane permeation is more related to the adsorption. Increasing pressure usually results in higher gas flux but barely affects its normalized value [92,98]. A positive impact of higher operating pressure could be experienced in a highly  $\text{CO}_2$ -selective MOF membrane in the presence of gas mixture. In this case, preferential adsorption towards  $\text{CO}_2$  compared to other gases could improve the  $\text{CO}_2/\text{N}_2$  or  $\text{CO}_2/\text{CH}_4$  separation factor [98]. A contrasting situation, however, might be observed if there are different mechanisms taking place at the same time such as viscous flow in  $\text{CH}_4$  leading to the reduction of  $\text{CO}_2/\text{CH}_4$  selectivity at higher operating pressure [93,98].

Feed composition also affects the separation performance of MOF membranes. Increasing  $\text{CO}_2$  concentration in  $\text{H}_2/\text{CO}_2$  separation degrades its separation performance because of competitive adsorption [28]. Meanwhile, for  $\text{CO}_2/\text{N}_2$  and  $\text{CO}_2/\text{CH}_4$  separation, increasing the fraction of  $\text{CO}_2$  is beneficial since it will saturate the MOFs pores with  $\text{CO}_2$  and inhibits adsorption of both  $\text{N}_2$  and  $\text{CH}_4$ , and their diffusion through the membrane resulting in an improvement of separation performance [93,99]. Despite this, a study using ZIF-8 membrane has also shown the possibility to obtain a satisfactory separation performance with low  $\text{CO}_2$  partial pressure for  $\text{CO}_2/\text{CH}_4$  separation when operated at low temperature and low pressure [98]. This is because the diffusion of  $\text{CH}_4$  and other hydrocarbons will be limited while at the same time the surface of the MOF membrane is still saturated with  $\text{CO}_2$  because of its preferential adsorption [93].

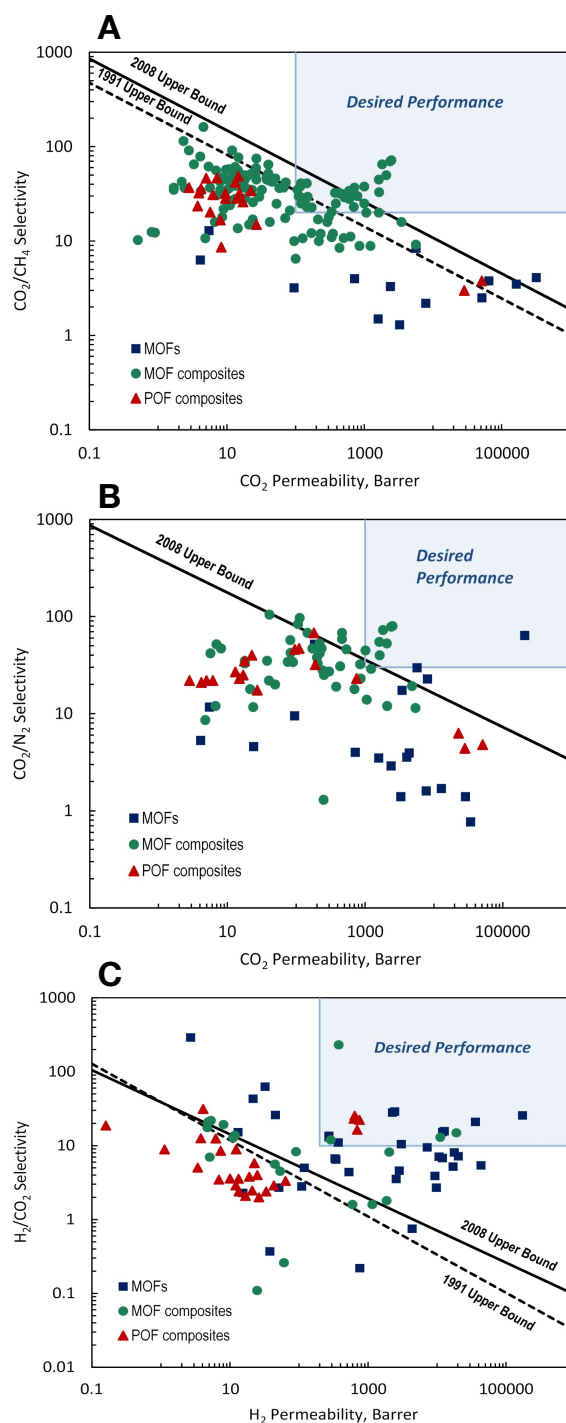
Finally, MOFs membrane could also be used as a gutter layer which is further covered by a more selective polymeric membrane layer [66,100,101] (Figure 5 (D)). This can be accomplished by using spin coating [101] or cross-linking approach [100]. Apart from enhancing  $\text{CO}_2$ -selectivity in the membrane, MOFs membrane as the gutter layer could also reduce the overall membrane resistance resulting in higher  $\text{CO}_2$  permeability [101]. Further optimization in this approach is to produce a very thin selective layer on top of the MOF gutter layer to reduce the overall membrane resistance.



**Figure 5.** Strategies for MOF membrane fabrications. Fabrication of ZIF-8 membrane on polymeric APTES-functionalized TiO<sub>2</sub> hollow fibre substrate (A) with its SEM cross sectional evaluation (B) and EDX mapping (C). The bottom-up fabrication of the polymer/MOF composite architecture (PMA) using MOF as the gutter layer (D). Adapted from [100,102]

Another approach is to fabricate a composite MOFs membrane. This technique utilizes another inorganic material aside from MOFs such as graphene oxide (GO) [103] and ionic liquid [104]. The role of the additional materials is to seal the inter-crystalline defects through both capillary force and covalent bonding and thus enhancing CO<sub>2</sub> selectivity [105]. However, the thickness of this additional material should be controlled so they will not add more resistance to the overall gas transport which could result in reduced CO<sub>2</sub> permeability [104].

The performance summary of MOF-based membrane for CO<sub>2</sub> separation is then given in Figure 6. It could be seen that whilst most research results could result in surpassing 2008 Robeson Upper Bound for most CO<sub>2</sub>-based separation, fabricating MOF as a composite membrane could yield better separation performance, particularly for CO<sub>2</sub>/CH<sub>4</sub> and CO<sub>2</sub>/N<sub>2</sub> separation. This might be caused since it could combine the properties from the constituent materials, particularly if they are combined with polymeric materials which already have their own intrinsic selectivity. Meanwhile for H<sub>2</sub>/CO<sub>2</sub> separation, pure MOF membranes do seem promising due to their already high permeability and enhanced molecular sieving from their suitable pore size.



**Figure 6.** Performance Summary of MOF and POF-based membranes for CO<sub>2</sub>/CH<sub>4</sub> separation (A), CO<sub>2</sub>/N<sub>2</sub> separation (B) and H<sub>2</sub>/CO<sub>2</sub> separation (C)

#### 4. Porous organic frameworks (POFs) based membrane

In addition to MOFs, there are other classes of porous material that are entirely built from organic compounds. They are classified with different names including covalent organic framework (COF), porous aromatic framework (PAF), covalent organic polymers (COP), porous organic polymers (POP), etc. For simplicity in this review, they are classified as porous organic frameworks (POF). This covers porous materials that are built from organic structures which can be crystalline such as COF and PAF or amorphous such as COP and POP. As in MOFs, these materials gained increased interest in the

area of CO<sub>2</sub> capture as an adsorbent because of their high surface area and tailorability to be selective towards CO<sub>2</sub>. Therefore, they are also promising to be turned into a membrane.

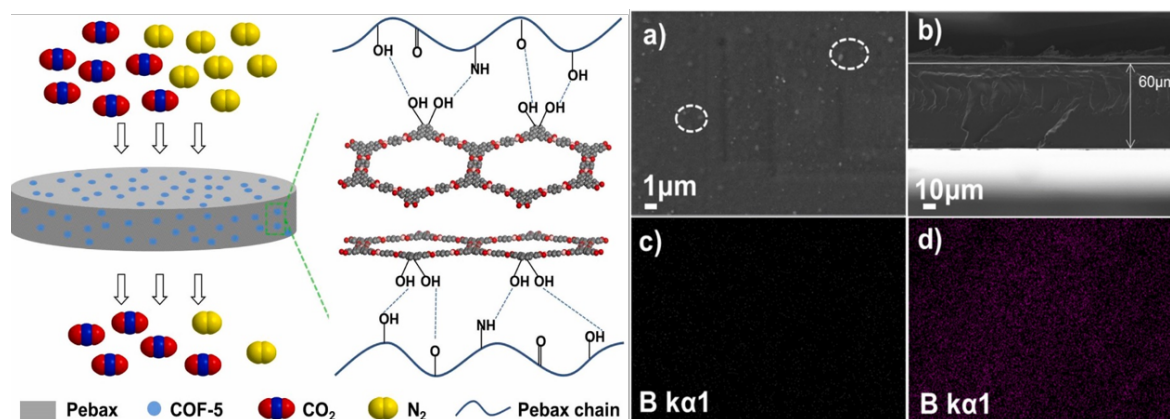
As in MOF, various studies for CO<sub>2</sub> capture using POFs have also been directed to the fabrication of POFs-based MMMs [14]. Since the POFs structure is entirely built from organic materials, it is expected that MMMs with a high particle loading could be obtained because of better POF-polymer interaction. This has been obtained by using PBI-BuI as the polymer matrix and TpBD and TpBA as fillers. Up to 50 wt% of a defect-free TpBA composite membrane could be obtained, resulting in high gas flux and CO<sub>2</sub>/CH<sub>4</sub> selectivity [106]. Polymer-particle interaction can also be further enhanced by establishing hydrogen bonding from functionalized COFs (Figure 7) [107]. Despite this, a similar threshold loading value in MMMs is also usually observed where further increase does not render any incremental positive impact to the resulting membranes [19,108].

POFs properties and morphology could then be tailored to improve the membrane performance. Employing POF with CO<sub>2</sub>-philic groups is beneficial in enhancing both membrane permeability and selectivity since it has preferential CO<sub>2</sub> adsorption to induce continuous CO<sub>2</sub> adsorption-desorption [20,109–111]. They also contribute in blocking other gases such as CH<sub>4</sub> to permeate through [20]. A nitrogen-rich COF could be employed for CO<sub>2</sub>/N<sub>2</sub> separation since they usually exhibit a higher CO<sub>2</sub>/N<sub>2</sub> selectivity which could be translated to blocking N<sub>2</sub> permeation in the membrane [19,112]. Meanwhile, molecular sieving in POF's pores could also be enhanced through decoration with polymer [113] or with MOF [114] resulting in enhanced MMM CO<sub>2</sub> separation performance.

POFs with 2D morphology could also be used to improve the MMMs performance. This could be obtained through exfoliation (top-down approach) as in NUS-2 and NUS-3 [108] or bottom-up approach where they are prepared during synthesis as in NUS-8 [115]. Although the POF crystallinity might be lost in the former method, their in-phase structure and porosity could still be maintained to enhance the gas separation performance. This 2D COF approach has been proven to improve MMM performance for both pre- and post-combustion CO<sub>2</sub> capture, even at low loading below 10 wt% thanks to the molecular sieving improvement through polymer crystallinity enhancement [115].

Operating conditions then play a significant role in affecting the POFs-based MMMs performances. Higher temperature leads to higher polymer chain mobility resulting in increase in FFV and faster gas permeation [116]. This could result in lower CO<sub>2</sub> separation factor which might be caused by enhanced diffusion rate of other gases such as CH<sub>4</sub> and N<sub>2</sub> compared with CO<sub>2</sub> [114,116]. Operating pressure can also affect the overall membrane performance. Once the pressure is increased, the Langmuir adsorption site of a membrane starts to be saturated and the adsorption site move to Henry sites. As a result, there will be a reduction in gas permeability caused by a decrease in gas solubility. This is more serious for strongly adsorbing gases such as CO<sub>2</sub> rather than the weakly-adsorbing ones such as CH<sub>4</sub> and N<sub>2</sub> and thus resulting in an overall decrease in CO<sub>2</sub> selectivity [114,117]. However, this might not be the case when a rubbery polymer is chosen as the continuous matrix since the permeability depends on the gas solubility and is directly proportional to pressure as the pressure is increased [117]. Lastly, different MMM performance is expected between single-gas and mixed-gas testing conditions. In the presence of other gases, competitive adsorption and diffusion occur inside the membrane which could usually lead to reduced membrane selectivity. However, employing POF with high CO<sub>2</sub>-affinity could reverse the trend and higher CO<sub>2</sub> selectivity could be obtained [116].

One of the most interesting features investigated using POF as a filler in MMMs is their ability to improve the membrane resistance towards aging such as found in PTMSP [109], poly(4-methyl-2-pentyne) (PMP) [51] and PIM-1 [51]. In PAF-based MMM, selective aging phenomenon was even observed. During this phenomenon, the membrane selectivity improves as it ages but with a minimal decrease in membrane permeability. This feature is important since it can enhance the molecular sieving ability of the MMM and thus improves its separation performance such as for CO<sub>2</sub>/N<sub>2</sub> separation [51].



**Figure 7.** Schematic diagram of functionalized-COF-5 — PEBAX MMM for CO<sub>2</sub>/N<sub>2</sub> separation and its SEM images of (a) surface; (b) cross-section; EDS mapping images of B element (c) pristine Pebax membrane; (d) COF-5/Pebax membrane (0.4 wt%). Reprinted from [107]

Despite the limited reports, growing POFs-based membranes could be a very attractive approach for CO<sub>2</sub> separation. This is proven by simulation studies showing the potential of COF membrane to have superior CO<sub>2</sub>/N<sub>2</sub> and CO<sub>2</sub>/CH<sub>4</sub> separation performance once a defect-free membrane could be fabricated [118,119]. However, the POF material should be carefully selected to achieve this by fulfilling some criteria such as having the right pore aperture or the ability to be stacked to establish interpenetrating pore networks to establish molecular sieving and have CO<sub>2</sub>-philic functional groups [119].

Once selected, there are various ways to fabricate POF-membranes. It could be fabricated through a solution processing method where the POFs are solubilized in a solvent followed by spin coating to deposit a POF film [120]. Substrate modification such as using APTES could also help to grow a defect-free POFs layer [40,121]. This technique could produce a bilayer COF membrane with enhanced molecular sieving from the interlaced pore built from two different COFs suitable for H<sub>2</sub>/CO<sub>2</sub> separation [121]. POFs membranes could also be fabricated using 2D POF which is directly stacked layer by layer [111] or aided by another inorganic particle such as GO which contributes to healing the membrane defects [122]. The narrow interlayer passages will act as a “gate” to achieve a molecular-sieving transport mechanism to enhance H<sub>2</sub>/CO<sub>2</sub> selectivity. Interfacial polymerization (IP) is another technique investigated to fabricate a defect-free benzimidazole-linked polymers (BILPs) POF membrane suitable for pre-combustion CO<sub>2</sub> capture [123]. The robust nature of BILPs resulted in a membrane that could be operated up to 10 bar and 498 K which is a typical condition for pre-combustion CO<sub>2</sub> capture.

Various operating conditions could also influence the POF membrane performance. High operating pressure and temperature could deteriorate the membrane performance built from fragile POFs [120,123]. Meanwhile, the presence of water vapour could lead to framework hydrolysis [111,120]. This could then be mitigated by choosing robust POF frameworks or functionalized POFs as membrane material [111,118,120]. Aging could also be another issue for POF membranes, particularly when fabricated from amorphous POFs [120]. In this case, the thin layer of POF is in a meta-stable state which could not achieve its equilibrium state during membrane fabrication and thus tends to minimize their free volume once the fabrication process is finished. This could be addressed, for example, by establishing a stronger POF network to avoid POF chain movement after membrane fabrication [120].

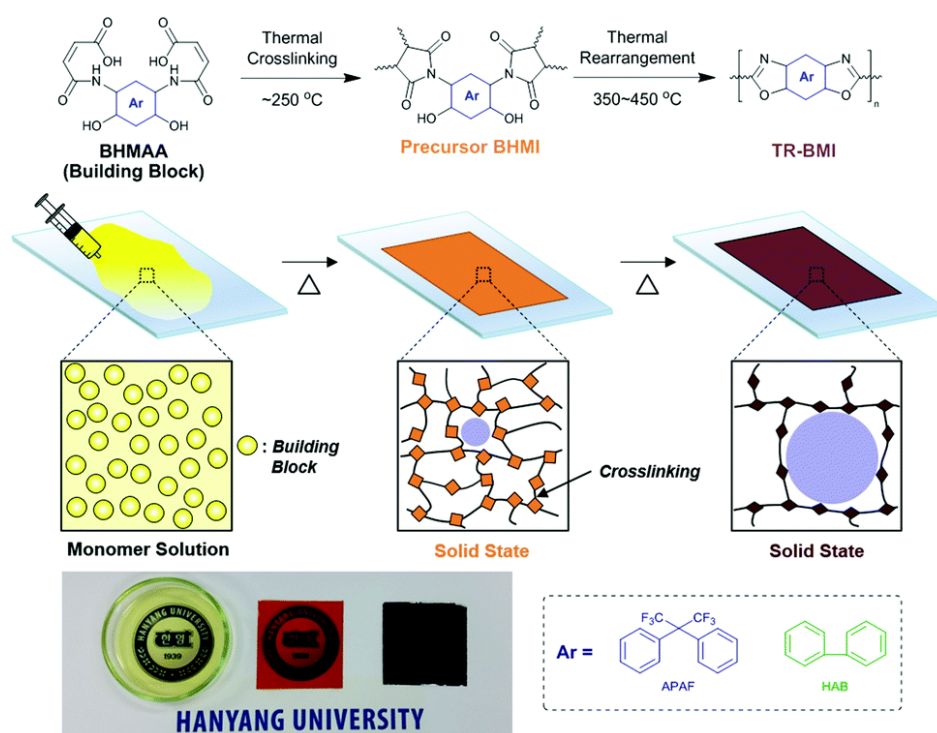
The performance summary of POF-based membrane for CO<sub>2</sub> separation is then given in Figure 6. Although research in this field are not as extensive as MOF-based membrane, it could be seen that the fabrication of POF-based composite does seem promising to enhance the CO<sub>2</sub> separation performance. However, most of them are still located at the borderline of the 2008 Robeson Upper Bound and thus more research is still required to push the membrane into the desired-performance region.

## 5. Microporous polymer-based membrane

Developing new polymer-based materials with high permeability and selectivity is required to advance the material selection for CO<sub>2</sub> separation membrane. For this purpose, polymers with high FFV as well as a rigid structure are required. The recently developed membrane materials could then be classified as thermally rearranged (TR) polymers and polymers of intrinsic microporosity (PIMs).

### 5.1. Thermally rearranged polymers

Although aromatic polymers with heterocyclic rings, such as polybenzoxazole (PBO), polybenzimidazole (PBI), and polybenzothiazole (PBZ) have a rigid chain structure and good gas separation performance, they are poorly soluble in common solvents. Therefore, a thermal approach was proposed to fabricate the insoluble aromatic polymer from a soluble polyimide precursor [124]. As the precursor polymers are soluble in common solvents, they can be easily processed into membranes using conventional solution casting method followed by heating to obtain aromatic polymeric membranes. The final membrane is called a TR polymer membrane.



**Figure 8.** Synthetic route and chemical structures of precursor BHMIs and TR-BMIs for membrane fabrication. From [125].

The preparation of TR polymer membranes usually consists of three steps as visualized in Figure 8: (i) synthesis of a soluble precursor polymer, which typically involves imidization process, (ii) membrane fabrication from the polymer precursor, and (iii) the thermal rearrangement of the membrane. The targeted characteristics of the final TR polymer membrane include FFV, microcavity size, and distribution, which can be manipulated by designing the polymer structure, synthesis route selection, and choosing the heat treatment protocols.

Different polymer structures can be controlled by varying the monomer structures. Two important criteria are chain rigidity and the presence of bulky bridging and/or pendant groups [5]. Monomers with high chain rigidity can minimize the chain relaxation during thermal treatment resulting in high FFV and gas permeability. The presence of bulky bridging and/or pendant groups on polymer chains can also increase free volume elements through disruption of the polymer chain packing density. Therefore, TR polymer membrane constructed from non-bulky and flexible polymer chains such as

4,4'-oxydiphthalic anhydride (OPDA) have the lowest CO<sub>2</sub> permeability and selectivity compared with other TR polymers constructed from a bulky and rigid structure [126].

Precursor polymers can be synthesized by thermal, azeotropic, chemical, or ester-acid imidization methods. The former is completed in the solid state while the rest are in liquid. Different imidization methods result in different precursor polymer structures which then influence the FFVs [127]. Compared with the rest, thermal imidization method favors the formation of FFV during imidization because of the low polymer chain mobility resulting in higher gas permeability once turned into a membrane. In case of CO<sub>2</sub> separation, TR-PBO prepared from chemically-imidized precursor (cTR-PBO) exhibited the highest CO<sub>2</sub> permeability followed by the thermally-imidized precursors (aTR-PBO). However, the latter had the highest CO<sub>2</sub>/N<sub>2</sub> and CO<sub>2</sub>/CH<sub>4</sub> selectivity [127,128]. Recently, intrinsically microporous polyimides (PIM-PIs) have also been used as the precursor polymer [129–131]. This strategy combines the PIMs and TR polymer structures to increase microporosity. The CO<sub>2</sub> permeability of the resulting membranes (PIM-TR-PBO or spiroTR-PBO) outperformed the PIM precursor and other TR-PBO membranes.

For thermal rearrangement, the precursor membranes are usually heated between 300 °C to 450 °C under a high-purity argon atmosphere [126]. During this process, the conversion of the polymer structure occurs and microcavities are formed which are influenced by the process parameters. Low temperature and short period rearrangement usually results in low-degree TR polymer formation [132] while high temperature formation could lead to precursor decomposition and brittle membrane [133]. Thermal treatment at optimum conditions then gives a high conversion to TR polymer resulting in increased FFV [131] and surface area [129,130]. The FFV in the resulting TR polymer membranes is usually in the range of 0.19–0.35 [126,127,131,134,135] which is comparable with high-free-volume glassy polymers such as PTMSP (0.29) [136], Teflon AF1600 (0.31), and Teflon AF2400 (0.33) [137]. Furthermore, the FFV in TR polymer membranes are three-dimensional interconnected microcavities that are analogues to micropores in certain adsorbents such as carbon molecular sieves [126]. This could then help in enhancing membrane gas permeability.

In selecting the best thermal treatment protocols, the chemical structure (chain rigidity) and the glass transition temperature (T<sub>g</sub>) of the precursor polymer need to be considered since they influence the thermal conversion temperature [138,139]. For instance, using a bisphenol A type dianhydride (BisADA) in the polymer synthesis lowered the precursor T<sub>g</sub>, which then successfully reduced the temperature of imide-to-benzoxazole conversion by about 100 °C [139]. The use of low thermal treatment temperature is also desirable for manufacturing purpose and mechanical properties of the resulting membrane.

As stated before, thermal rearrangement can also bring a negative impact on the TR mechanical properties since the membrane can become brittle [140]. This can be addressed by incorporation of spirobisindane [131], thermally labile units [141], and non-TR-able diamines [142,143] into TR polymer membranes. This could be attributed to the enhanced molecular chains by spiro kink group [131] and the presence of a flexible ether group from the non-TR-able unit [142]. In addition, formation of reduced GO scaffold inside TR polymer to create composite membranes can also provide mechanical robustness as well as remarkable CO<sub>2</sub> permeance [144].

The TR polymer membranes may also suffer physical aging because of their high FFV. Up to 50% decrease in CO<sub>2</sub> permeability was observed after 150 days of operation, which was accompanied by an increase in CO<sub>2</sub>/CH<sub>4</sub> selectivity from 27 to 35 compared with the fresh TR membrane [129]. In-situ restoring procedure using methanol [145] and the addition of oxidized CNTs to the precursor solution [146] has been proposed to address this issue.

The separation performance of TR polymer membranes is also influenced by operating conditions such as pressure, temperature, and feed composition. There was a decline in pure CO<sub>2</sub> permeability as the upstream pressure was increased, while the permeabilities of less condensable gases were almost not affected by the pressure [132,147,148]. As a result, the selectivity also decreased [148]. When mixed-gas CO<sub>2</sub>/CH<sub>4</sub> was used, the selectivity of TR polymer membranes improved because of the



preferential competitive sorption [148], and even increased with the elevated pressure because of the enhanced sorption of CO<sub>2</sub> over CH<sub>4</sub> [149]. Furthermore, the TR polymer membranes offer good resistance to CO<sub>2</sub>-induced plasticization. While the unconverted PI started to be plasticized at about 20 bar, the TR polymers only suffered mild plasticization and could even be resistant up to 50 bar [149]. They were also resistant against SO<sub>2</sub> and H<sub>2</sub>S plasticization which is important in real conditions with the presence of sulfur-based gases [150]. However, it seems that they still could not withstand the presence of water vapour, due to competitive adsorption [151]. Therefore, hydrophobic crosslinked TR polymer membranes are proposed to address this issue [152].

Performing CO<sub>2</sub> separation using TR polymer membrane at higher temperature resulted in increased CO<sub>2</sub> permeability, but in a lower extent compared to the other gases (O<sub>2</sub> and N<sub>2</sub>), resulting in decreased selectivity [151]. This is attributable to the reduced solubility that is less favorable for CO<sub>2</sub> transport. In gas mixtures with H<sub>2</sub>, the CO<sub>2</sub> permeability was significantly lower than H<sub>2</sub>, resulting in a high H<sub>2</sub>/CO<sub>2</sub> selectivity [153]. Thus, the TR polymer membrane has potential to be applied in pre-combustion CO<sub>2</sub> separation.

## 5.2. *Polymers of intrinsic microporosity*

Polymers of intrinsic microporosity (PIMs) were firstly developed by Budd and McKeown from a polycondensation reaction between tetrahydroxy-monomers containing spiro- or contorted centre with a tetrafluoro-monomers [154]. Differing from conventional polymers, the chain of PIMs has two distinguished properties: the absence of large-scale conformational change and the contorted structure. The former is caused by the rigidity of the PIMs backbone while the latter is caused by the random twisting of the polymer backbone [34]. As a result, gases could diffuse faster in PIMs-based membranes because of its high porosity. In addition, the presence of selective ultramicropores interconnected with big pores in PIMs also enhances its overall selectivity [155]. PIMs are considered as promising membrane material for CO<sub>2</sub> separation because of their satisfactory permeability and selectivity [37].

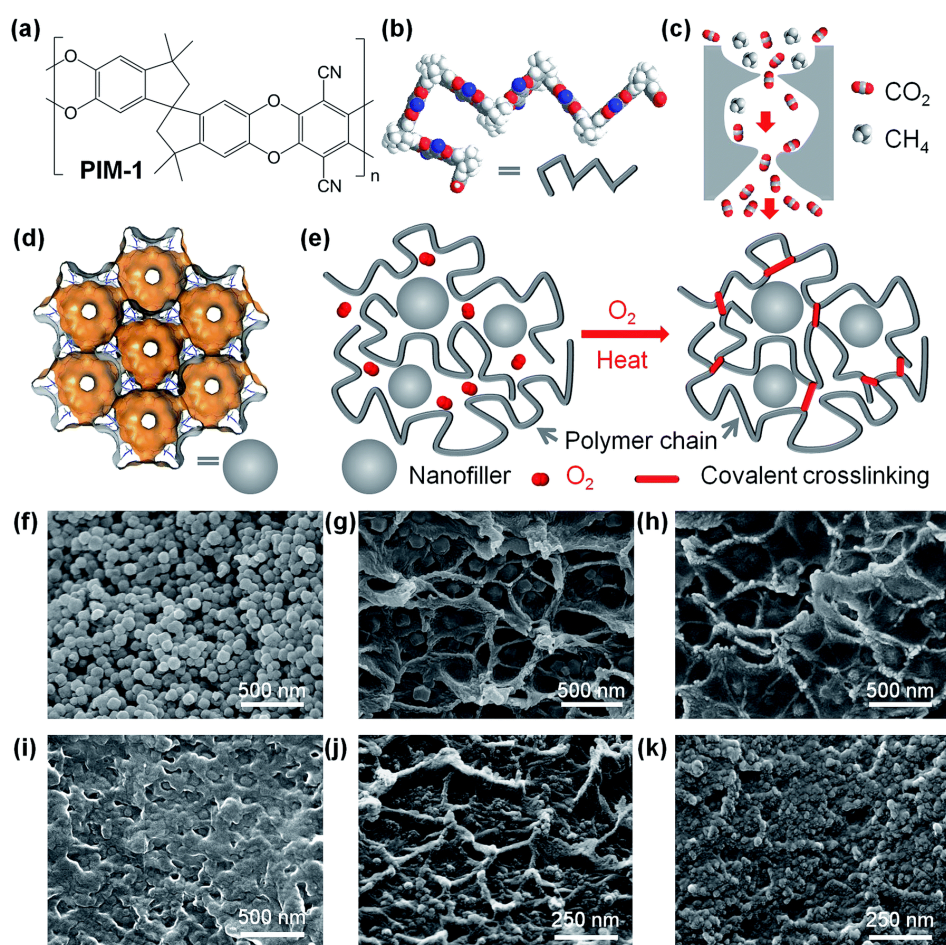
Since PIM is solution-processable, it could be easily turned into a membrane. In case of free-standing membrane, PIM could be used as the sole material or blended with other polymers or inorganic materials. Another way is to use PIMs as the selective layer material as a thin film nanocomposite (TFN), in which the selective layer can be composed of PIM [156] or a nanocomposite [157]. As a neat membrane, PIMs have a very high gas permeability compared to other polymers because of its high FFV [158]. However, this FFV degree depends upon the preparation and treatment during membrane fabrication [158,159]. PIMs that are treated with alcohols usually have higher gas permeability than the untreated ones because of the complete solvent removal during membrane casting and increasing the FFV [34,159,160].

The CO<sub>2</sub> separation performance of PIMs-based membranes can then be improved by various ways. PIMs have nitrile groups on their backbones that can be further functionalized with amine [161], thioamide [160], beta-cyclodextrin [162], and tetrazole [163] to enhance its affinity with CO<sub>2</sub>. Although becoming more selective, functionalized PIMs usually have lower CO<sub>2</sub> permeability because their pores are occupied by the functional groups. Cross-linking is another promising strategy. The cross-linking could be accomplished with UV-light illumination [164], thermally treatment [165] or by using chemical compounds such as pyrene [166]. The cross-linked PIMs membranes usually result in a reduction of the FFV and thus reduced gas permeability. However, this makes the PIM more diffusive-selective resulting in enhancement of H<sub>2</sub>/CO<sub>2</sub>, CO<sub>2</sub>/CH<sub>4</sub> and CO<sub>2</sub>/N<sub>2</sub> selectivity [165]. PIMs with enhanced CO<sub>2</sub> solubility could also be fabricated resulting in higher CO<sub>2</sub>/N<sub>2</sub> selectivity during mixed gas separation since they could hinder the N<sub>2</sub> permeation [163].

PIMs could also be blended with other polymers such as polyetherimide [167], Torlon [168], matrimid [169], and Tröger's Base polymer [170] to improve their gas separation performance. Among various polymers, Tröger's Base polymer seems to match well with PIM-1 [170]. Since PIMs have high FFV, incorporation of other materials usually results in reduction of CO<sub>2</sub> permeability. However, this

is usually followed by the improvement selectivity of CO<sub>2</sub> towards CH<sub>4</sub> and N<sub>2</sub> because the blended membrane will be more diffusive-selective [171].

Various fillers could also be incorporated inside PIMs to fabricate a PIM-based MMM. The fillers can be from MOFs [172], POFs [110,173,174] silica [175] and carbon nanotubes [176]. Once good interaction could be established, the additional void from the fillers could contribute in improving the molecular sieving mechanism and CO<sub>2</sub> separation factor [173,177]. However, since PIMs already have high FFV, careful filler selection is required since without a correct pore size, the introduced voids could just decrease the CO<sub>2</sub> selectivity, particularly in the presence of interfacial defects [174]. This could then be mitigated in various ways, such as using a cross-linked PIM to establish a more robust cage for filler encapsulation (Figure 9) or to cross-link the PIM with the filler [172].

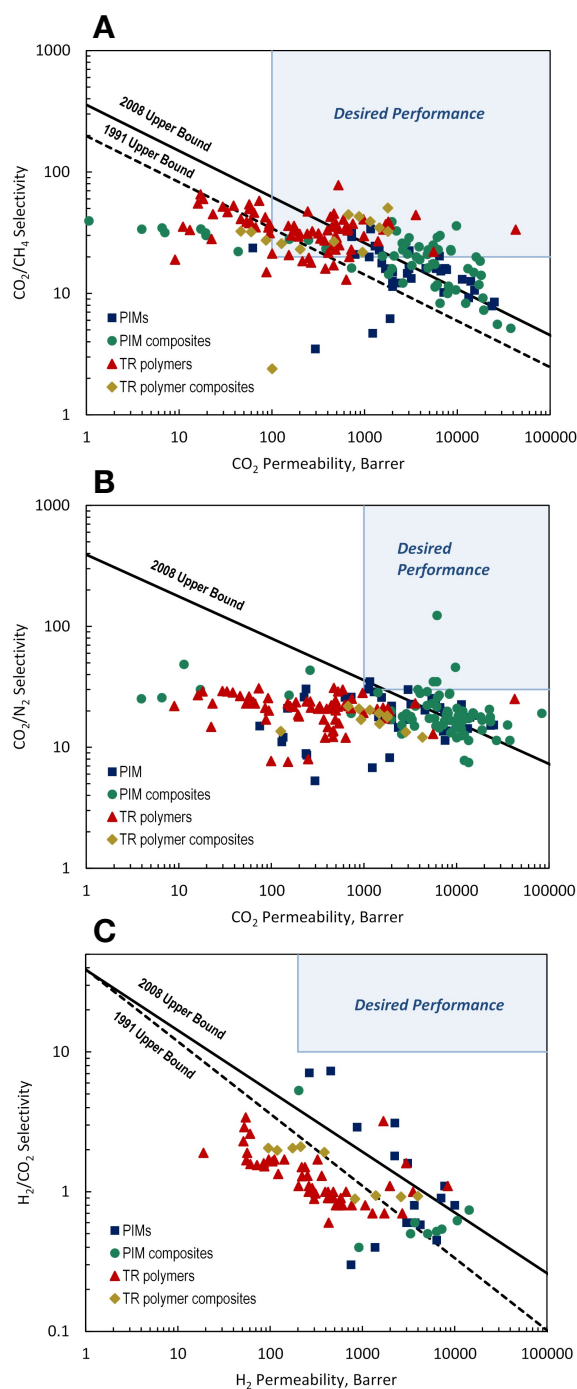


**Figure 9.** Thermal-oxidative crosslinking of PIM-1 polymer nanocomposites incorporated with nanofillers. (a) Chemical structure of PIM-1 polymer. (b) 3D model of PIM-1 polymer chain segment. (c) Schematic diagram of molecular sieve membranes fabricated from PIMs polymer showing hour-glass-shaped interconnected cavities for rapid and selective transport of gas molecules (e.g. CO<sub>2</sub> and CH<sub>4</sub>). (d) Molecular structure of ZIF-8. Yellow regions indicate Connolly surface probed by H<sub>2</sub> molecules. (e) Schematic diagram showing rigid polymer chains incorporated with nanofillers are covalently crosslinked to three-dimensional networks upon thermal-oxidative processing at suitable temperature (350–450 °C) in the presence of trace amount of oxygen. (f) SEM image of ZIF-8 nanocrystals. Cross-sectional SEM images of (g) PIM-1/ZIF-8 after annealing at 120 °C under vacuum (1 mbar), (h) TOX-PIM-1/ZIF-8 crosslinked at 385 °C for 24 h under vacuum (1 mbar), (i) PIM-1/ZIF-8 after annealing at 300 °C for 48 h under vacuum (1 mbar). (j) PIM-1/SiO<sub>2</sub> annealed at 120 °C, (k) TOX-PIM-1/SiO<sub>2</sub> annealed at 385 °C for 24 h under vacuum (1 mbar). From [178].

Once used in CO<sub>2</sub> separation process, high operating pressure could lead to PIM-membrane swelling and plasticization resulting in the reduction of gas selectivity [179] and the onset of CO<sub>2</sub>-induced plasticization pressure was lower for thinner membrane [180]. Therefore, in the presence of CH<sub>4</sub>, lower CO<sub>2</sub>/CH<sub>4</sub> selectivity is usually found in the plasticized membrane because of this phenomenon. Although the sorption selectivity barely changes, the CO<sub>2</sub>-induced plasticization reduced the molecular sieving ability of PIM membrane resulting in enhanced CH<sub>4</sub> diffusion and found to be more serious with ultramicroporous PIM [181,182]. The CO<sub>2</sub> permeance of PIM-1 membrane has been observed to decrease at higher temperature because of the negative activation energy [179]. This is in contrast with CH<sub>4</sub> permeance that has positive activation energy and thus resulting in CO<sub>2</sub>/CH<sub>4</sub> selectivity reduction at higher operating temperature. This could be addressed, for example by introducing MOF into PIM resulting in improvement of CO<sub>2</sub> permeance [179]. With the prevalence of feed impurities in real CO<sub>2</sub> stream, the CO<sub>2</sub> separation performance of PIM membranes could also deteriorate significantly in high humidity condition and in the presence of contaminants, leading to permanent membrane damage [48]. The presence of water contributes to the competitive sorption and permeation since it strongly interacts with the polar group resulting in less accessible sites for CO<sub>2</sub> adsorption while other contaminants might contribute in chemically altering the PIM structure [48].

Finally, physical aging is a serious problem in PIM-1 membranes. This is usually started with fast permeability reduction because of the presence of excess non-equilibrium FFV followed by a more gradual reduction since the polymer chain becomes less mobile after the first phase [182]. Membrane thickness and excess free volume could influence the PIM aging rate. Thinner PIM membranes age faster than the thicker ones [180]. PIM with high excess free volume (high current-specific-volume but low equilibrium-specific-volume) also ages faster because they have more driving force for aging to occur [182]. Although intrachain rigidity does not seem to address this issue [182], incorporating various fillers such as MOFs [177] and PAFs [51] are considered beneficial in suppressing the PIM aging rate by reducing the polymer chain mobility.

The performance summary of microporous polymer for CO<sub>2</sub> separation is given in Figure 10. As could be seen, although pristine microporous polymers have already had satisfactory CO<sub>2</sub> separation performance, which benefits from their satisfactory permeability and selectivity, fabricating them as a composite membrane could further enhance the performance. This might be caused by the enhanced molecular sieving induced by alteration of the interconnected-pores in the microporous polymers (such as through rigidification or pore size reduction) in the presence of other materials. However, more research is still required in the field of H<sub>2</sub>/CO<sub>2</sub> separation with an emphasis on increasing the selectivity.



**Figure 10.** Performance Summary of MOF and POF-based membranes for CO<sub>2</sub>/CH<sub>4</sub> separation (A), CO<sub>2</sub>/N<sub>2</sub> separation (B) and H<sub>2</sub>/CO<sub>2</sub> separation (C)

## 6. Challenges and future directions

Membranes fabricated from microporous materials are expected to satisfy at least four different aspects: performance (permeability and selectivity), structure and thickness, configuration, and system design [41]. In terms of membrane performance, it has been demonstrated that most of them have been able to surpass the 2008 Robeson's upper bound. Recent researches in PIM-based membrane has also shown the ability to push the boundary further [183]. However, the crucial question is how to make them industrially-applicable both from the performance and economic point of view.

In this case, material selection is undoubtedly important regardless of the type of the microporous materials. They must be robust and could withstand harsh operating conditions. In case of a composite membrane, materials compatibility is also important to obtain membranes with satisfactory performance. A composite of robust microporous materials could then be a promising alternative. This could be, for example, by using microporous polymers as the continuous phase to obtain high permeability membrane while also loaded with MOF or POF to enhance the molecular sieving ability.

Most studies on microporous materials-based membranes were focused on flat sheet configuration because of the fabrication simplicity. However, hollow fibre membranes are more attractive for gas separation in industry, but there are only a few reports in this field [36,124,184]. This still needs to be addressed in the future research of emerging microporous materials-based membranes. In case of MMMs for example, obtaining good particle dispersion to avoid agglomeration and membrane brittleness is important in successfully constructing hollow fibre configuration. Meanwhile, in hollow fibre TR polymer membranes, obtaining a defect-free skin layer is required with optimized process parameters [133,185]. For pure MOFs and COFs-based membranes, the major challenge is related to obtaining a defect-free membrane with reduced thickness to increase the gas permeance. If this could be obtained, their performance could be expected to be comparable with a single-crystal membrane which does not contain inter-crystalline defects [186]. Several promising ways can be considered to address this issue, such as narrowing the particle size, and improving interaction between the support and the membrane layer [85].

Regarding membrane productivity, reducing membrane thickness is necessary to reduce membrane resistance and increase its permeance [187]. This is usually obtained by fabricating a membrane in an asymmetric structure with a selective thin and dense layer that is supported by a porous structure. Whilst this strategy might work with solution-processable microporous polymers, this could be a major challenge with composite membranes. In this case, the particle size should be carefully controlled so they reside inside the selective layer and not on the porous layer [188]. This could be addressed, for instance, by constructing the material in 2D form to produce an ultrathin MMM with less than 1 micron thickness [179].

Finally, some crucial issues relating to operating conditions must also be addressed. CO<sub>2</sub>-induced plasticization is one of the major issues, particularly for polymeric membranes. It has been proven that TR polymer membranes with high degrees of TR conversion exhibit high resistance to CO<sub>2</sub>-induced plasticization, even against SO<sub>2</sub> and H<sub>2</sub>S [149,150]. Meanwhile, this could still be a major issue for a PIM-based membrane since incorporating intrachain rigidity in their structure does not seem to significantly improve the resistance [181]. MOFs incorporation into a polymer matrix in the form of MMM could then address the issue since they could contribute in the reduction of polymer chain movement resulting in membrane with higher plasticization resistance [75,189]. Since CO<sub>2</sub> feed stream also usually contains other impurities such as water vapour, NO<sub>x</sub> and SO<sub>x</sub> [190], a study must also be conducted in this scenario since mixed-gas study alone does not seem to be sufficient [48]. This is particularly important to elucidate any permanent damage to the membrane structure once exposed to this harsh environment. Meanwhile, for long term operation, the physical aging is still one of the major issues [180]. This is particularly important for a thin membrane since it has a faster aging rate than a thicker one. Incorporation of microporous materials such as PAF and MOFs could be an option to address this issue [109,172,191]. This is because they contribute to reduce the polymer chain movement resulting in performance stability as the membrane ages [109]. Interestingly, they could even also improve the CO<sub>2</sub>/CH<sub>4</sub> selectivity during aging because the larger CH<sub>4</sub> gas permeation rate were more significantly reduced [109]. Despite this advantage, a stable membrane performance is still preferred [187].

## 7. Conclusions

During the last two decades, there is a growing interest in developing novel microporous materials. As a promising adsorbent, these emerging microporous materials have also advanced the research

Membrane type	Challenges		
	Material selection	Membrane fabrication and module configuration	Membrane performance
Mixed matrix (MOFs, POFs, PIMs)	<ul style="list-style-type: none"> <li>- Selection of robust fillers (resistant towards water vapor, contaminants, etc)</li> <li>- Selection of the best compatible materials (fillers and polymers) that can withstand harsh operating condition</li> </ul>	<ul style="list-style-type: none"> <li>- Optimization of particle loading to balance membrane performance and mechanical strength</li> <li>- Asymmetric membrane production in a hollow fibre configuration</li> </ul>	<ul style="list-style-type: none"> <li>- Membrane thickness reduction for increased permeance</li> <li>- Operating condition optimization</li> <li>- Real-life condition and aging testing performance</li> </ul>
Pure MOFs and POFs	<ul style="list-style-type: none"> <li>- Compatibility between the porous support and both MOF and POFs</li> <li>- Selection of robust MOFs and POFs materials that can withstand harsh operating condition</li> </ul>	<ul style="list-style-type: none"> <li>- Growing a defect-free MOFs or POFs membrane in a benign way</li> <li>- Development of hollow fibre configuration</li> <li>- Consideration of polymeric substrate as a cheaper alternative for membrane support</li> </ul>	
Microporous polymer	<ul style="list-style-type: none"> <li>- Selection of robust materials that can withstand harsh operating condition</li> </ul>	<ul style="list-style-type: none"> <li>- Low-temperature thermal rearrangement for TR-based membrane</li> <li>-Development of asymmetric membrane structure in a hollow fibre configuration</li> </ul>	

**Table 1.** Summary of the challenges in development of microporous materials-based membranes for CO<sub>2</sub> separation

in the membrane field. This development is particularly important for CO<sub>2</sub> separation application, where membrane technology has been considered as one of the promising alternative processes to substitute the conventional processes.

This paper has thoroughly reviewed four different classes of emerging microporous materials that are considered promising for membrane application in CO<sub>2</sub> separation: metal-organic frameworks (MOFs), porous organic frameworks (POFs), polymers of intrinsic microporosity (PIMs) and thermally rearranged polymer (TR). All of them could be fabricated into a membrane either as a composite or as a pure microporous membrane. Once a perfect and defect-free membrane is obtained, almost all the emerging microporous material-based membrane have shown promising performance for CO<sub>2</sub> separation from H<sub>2</sub> (pre-combustion application), CH<sub>4</sub> (natural gas purification) and N<sub>2</sub> (post-combustion application). This is evident as most of the fabricated membranes are well located close or even surpass the 2008 Robeson Upper Bound.

However, translating this promising performance into a real industrial application for CO<sub>2</sub> separation is still a major challenge. There are several challenges that need to be addressed. From a membrane fabrication point of view, this includes membrane fabrication in hollow fibre form to enhance productivity and improving the interaction between two different components in a composite membrane. Mechanical strength could also be another issue, especially for composite membranes, since their tendency to have a brittle structure once loaded with higher particle loading. Another issue is the optimization of membrane operating condition. Optimum pressure and temperature should be investigated, particularly to address the CO<sub>2</sub>-induced plasticization. It is also imperative to test the successful membranes in the mixed gas scenario or using the real feed gas to elucidate the membrane robustness. Finally, membrane aging should also be thoroughly investigated in order to evaluate its long-term performance.

Further research in the development of emerging microporous materials for membrane-based CO<sub>2</sub> separation is undoubtedly still required. The research should not be exclusively directed in discovering new microporous materials but also to optimize the recently developed materials since they have a promising CO<sub>2</sub> separation performance. In addition, a comprehensive economic feasibility analysis might also be required so assess their suitability from an industrial perspective. If these aspects can go hand in hand, microporous materials-based membrane technology can likely replace the conventional technology and contributing in making CO<sub>2</sub> separation processes more efficient.

**Supplementary Materials:** Extensive supplementary materials are available in the separate document.

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