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Review

Footsteps of graphene filled polymer nanocomposites towards efficient membranes—Present and future

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Abstract: Due to rising global environmental challenges, air/water pollution treatment technologies, especially membrane techniques, have been focused on. In this context, air or purification membranes have been considered effective for environmental remediation. In the field of polymeric membranes, high-performance polymer/graphene nanocomposite membranes have gained increasing research attention. The polymer/graphene nanomaterials exposed several potential benefits when processed as membranes. This review explains the utilization of polymer and graphene-derived nanocomposites towards membrane formation and water or gas separation or decontamination properties. Here, different membrane designs have been developed depending upon the polymer types (poly(vinyl alcohol), poly(vinyl chloride), poly(dimethyl siloxane), polysulfone, poly(methyl methacrylate), etc.) and graphene functionalities. Including graphene in polymers influences membrane microstructure, physical features, molecular permeability or selectivity, and separations. Polysulfone/graphene oxide nanocomposite membranes have been found to be most efficient with an enhanced rejection rate of 90%–95%, a high water flux >180 L/m^2/h, and a desirable water contact angle for water purification purposes. For gas separation membranes, efficient membranes have been reported as polysulfone/graphene oxide and poly(dimethyl siloxane)/graphene oxide nanocomposites. In these membranes, N_2, CO_2, and other gases permeability has been found to be higher than even >99.9%. Similarly, higher selectivity values for gases like CO_2/CH_4 have been observed. Thus, high-performance graphene-based nanocomposite membranes possess high potential to overcome the challenges related to water or gas molecular separations.

Keywords: graphene; nanocomposite; membrane; water purification; gas separation

1. Introduction

Generally, membrane-based technologies have been used to remove toxic nanomaterials from the environment [1]. Among membrane materials, polymeric-based materials and nanomaterials have been adopted for separation purposes [2,3]. Owing to the technical benefits of nanocarbons, graphene, fullerene, and carbon nanotubes have been adopted as unique and valuable nanostructures [4,5]. Graphene-derived nanomaterials possess fine tendencies toward separation applications [6]. Especially, graphene has been reinforced in polymers to form high-performance nanocomposite membranes [7]. Polymer- and graphene-derived nanocomposite membranes have been efficiently used for the separation of hazardous molecules [8]. For the fabrication of polymer/graphene membranes, facile processing approaches have been used [9]. Solution processing, the phase inversion method, the infiltration technique, and other facile methods have been reported [10,11]. Polymer/graphene

membranes have been developed using polymers like polyamides, polysulfone, poly(dimethyl siloxane), poly(methyl methacrylate), and several others [12]. The nanocomposite membranes possess superior nanofiller dispersion, pore sizes, molecular permeation, and selectivity properties [13]. Owing to their effective characteristics, polymer/graphene nanocomposite membranes have been applied for technological sectors focusing on water, gaseous, and chemical separations [14]. The resulting membranes have been applied in commercial-scale water purification systems, gas sensing, and separation systems, fuel cell systems, and a myriad of other technical areas [15,16]. Most importantly, polymer- and graphene-based nanocomposite membranes have been fabricated for gas and water purification. Graphene mostly develops torturous pathways in the matrices to facilitate gas- or water-based ionic or molecular diffusion processes [17]. Homogeneous graphene dispersion in polymeric membranes has been used to enhance the separation of impurities and toxic molecules from air mixtures or contaminated water [18,19]. In this regard, several membrane processes have been studied, like nanofiltration, microfiltration, ultrafiltration, and reverse osmosis [20–22]. Afterward, graphene-derived nanocomposite membranes have been efficiently used for removing pollutants [23]. The polymer/graphene nanocomposite membranes have structural advantages relative to reported nanocomposite membrane designs in terms of facile processing and resulting performance benefits [24]. Research progressions have led to the advancement of efficient air/water membranes [25].

For efficient graphene membrane fabrication, membranes, and mechanisms of molecular transport need to be thoroughly understood. The self-standing nanocomposite membranes must be researched for new design novelties [26]. In addition to graphene, graphene derivatives like graphene oxide, reduced graphene oxide, etc. may widen the potential of these membranes. The ultimate thinness of the membranes has been desirable to allow high flux [27]. The narrow pore size distribution and surface chemistry have been identified as desirable factors to promote molecular sieving and diffusion through the membranes. According to the literature, the interlayer spacing between graphene nanosheets can promote molecular transportation through the membrane [28]. To better withstand the high temperature, pressure, and humidity conditions, membrane support materials must be used [29]. Such efforts fill gaps between the membrane designs, large-scale productions, and commercialization of the novel graphene nanocomposite membranes.

This review article discusses the developments of graphene nanocomposites towards efficient membrane applications. The inclusion of graphene in polymers has improved the membranes' permeation and selectivity properties for water purification and gaseous molecular separation. In this article, the design, structure, and properties of polymeric membranes filled with graphene or graphene oxide nanofillers have been scrutinized. Subsequently, the microstructure, durability, stability, permeability, and other membrane properties have been used. The competence of nanocomposite membranes has been studied for gas or water purification, especially for the separation of toxins, pollutants, and unwanted species. The polymer and graphene-based nanomaterials have a high surface area and exceptional structure for efficient membrane performance. Accordingly, the formation of polymer/graphene membranes has extended the scope of air purification and water management. To the best of my

knowledge, this article is ground-breaking in presenting efficient graphene-based membranes. The review outline, including literature, as well as relevant discussions, is novel and based on recent research assumptions for graphene-based membranes. Moreover, hardly any recent topical comprehensive review reports have been observed on the polymer/graphene nanocomposite membranes. The need for this review article also arises due to remarkably increased research reports on graphene nanocomposite membranes in the past two to three years. Hence, there is the utmost need for a recent innovative review on polymer/graphene nanocomposite membranes. According to recent reports on polymer/graphene nanocomposite membranes, it can be stated that substantial progress has been made in this field up until now. This article will definitely be beneficial for field scientists/researchers to expand their research toward the future success of high-performance industrial-scale nanocomposite membranes.

2. Graphene

Graphene is a one-atom-thick nanosheet of sp^2 hybridized carbon atoms [30]. **Figure 1** shows the structure of graphene and related derivative forms. This remarkable nanocarbon was discovered in 2004 [31].

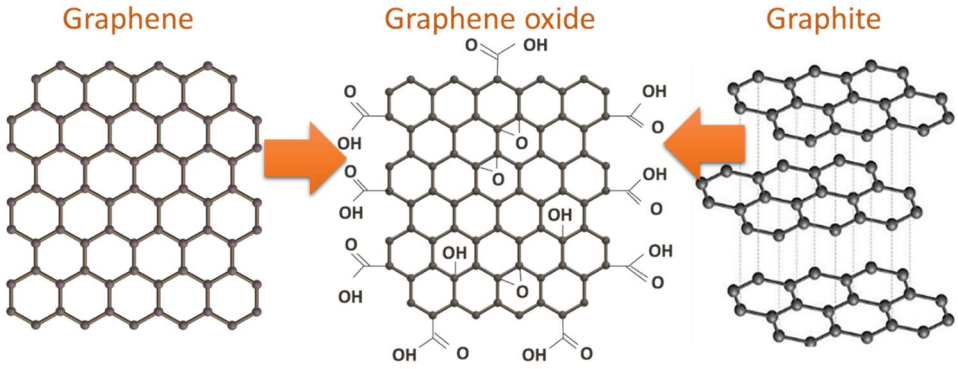

Figure 1. Graphene and related derivative forms.

Graphene has been developed using various techniques such as graphite exfoliation, plasma processes, chemical vapor deposition, and chemical or organic synthetic strategies [32]. It is a transparent carbon nanostructure [33] having a high thermal conductivity of 3000–5000 W/mK [34], Young's modulus of ~1 TPa [35], and weak van der Waals forces [36]. Graphene oxide is a graphene-based nanocarbon that is usually formed through the oxidation and stripping of graphite. This graphene derivative has a graphene nanosheet structure with carboxylic, hydroxyl, carbonyl, or other oxygen-containing surface groups [37]. Graphene and graphene oxide have been employed to form nanocomposite materials [38]. Graphene nanocomposites have been studied for their high electron conductivity, thermal and chemical stability, and physical properties [39]. In addition, the high-tech potential of graphene has been developed for coatings, membranes, energy devices, and biomedical sectors [40].

Graphene is composed of a single carbon atom layer arranged in a two-dimensional honeycomb lattice. A wide range of two-dimensional nanomaterials like graphene, graphene, nanoclays, MXenes, silicane, hexagonal boron nitride, transition metal dichalcogenides, etc. have been reported. A two-dimensional carbon nanostructure like graphene has probabilities to tailor and functionalize through

surface defects, modified groups, number of layers, morphology, etc. Graphene has been explored for doping, modification, strength, conductivity, and other physical characteristics, relative to other two-dimensional nanomaterials. Consequently, graphene has been found to be stronger than other zero-, one-, or two-dimensional materials due to its structural strength. Especially compared with other carbon nanomaterials like carbon nanotubes (one-dimensional) and fullerene (zero-dimensional), graphene nanosheets have revealed remarkable potential due to their high surface area nanostructures and better compatibility with polymer matrices. Research has realized the importance of graphene two-dimensional monolayers in several fields, with a special emphasis on their benefit to our society.

3. Polymer nanocomposite based membranes

Polymer-based membranes have been produced using a range of polymer matrices and preparation approaches [41]. Numerous carbonaceous nanoparticles and inorganic nanofillers were filled in the different polymeric matrices to develop the nanocomposite membranes [42]. The combination of these nanoparticles with polymers resulted in the formation of membranes with significant physical characteristics [43]. The resulting properties depend upon the nanoparticle type, nanoparticle amount, and polymer types as well [44]. These nanocomposite membranes have fine microstructure and separation properties for different types of molecules [45,46]. In other words, polymeric nanocomposite membranes act as molecular sieves for molecular separations [47]. The molecular permeation mechanisms depend on the interactions between the polymer and nanoparticles and their mutual effects [48]. In inorganic nanoparticle-filled membranes, silica nanoparticles have been used as nanofillers [49,50]. For silica-filled membranes, permeation and selective separation of O_2, CO_2, and N_2 gaseous molecules have been studied. Functional silica nanoparticle-filled poly(vinylidene-fluoride-hexafluoropropylene) membranes were prepared through the phase separation method [51]. The molecular separation of CO_2 molecules was studied. The nanocomposite membrane with 40 wt.% nanoparticles revealed a CO_2 uptake of 33.75 mg/g [52,53]. Silica nanoparticles developed fine pathways for gas diffusion [54,55]. Titania nanofiller [56] and zinc oxide nanoparticles [57] have also been used with the polymers. Such membranes may have high structural robustness and CO_2/H_2 selectivity of 2.77.

In addition, carbon nanoparticles have been reinforced in the polymeric membranes [58]. Various nanocarbon nanoparticles have been used as efficient nanofillers with polymers like carbon nanotube, nanodiamond, fullerene, etc. to form nanocomposite membranes. Graphene-based nanomaterials have a high surface area-to-volume ratio, light weight, facile processing, and structural flexibility [59]. The inclusion of very minor amounts of graphene nanofiller in the nanocomposites has been found to enhance the physical features due to their interfacial properties [60]. Interfacial bonding has been found to directly affect the mechanical and thermal properties of the nanocomposites. As compared to zero- and one-dimensional nanocarbons like fullerene and carbon nanotubes, graphene nanostructure has an advantageous two-dimensional nanostructure with a light and strong nanosheet

nanostructure and intrinsic charge mobility and permeability features [61]. Therefore, graphene nanocomposites reveal a range of potential applications and remarkable properties, from high-performance nanocomposites to technical nanostructures like membranes. In nanocomposites membranes, graphene has a better alignment, dispersion, porosity, and tortuous pathway formation than one-dimensional nanostructures for better molecular permeability [62]. The polymer-based nanocomposite membranes have been applied for water purification and gas permeation purposes [63–65].

4. Efficiency of graphene nanocomposite membranes for water or gas separations

Owing to the lack of inherent robustness, and structural, and fouling drawbacks, polymeric membranes have been continuously replaced with nanocomposite membranes for better performance [66,67]. Consequently, nanocomposite membranes have been recognized for their controlled and advantageous thermal stability, selectivity, and permeability features [68]. For water remediation applications, solution processing, blading, phase separation, and related membrane fabrication strategies have been focused on [69]. Membrane matrices like poly(vinyl alcohol), polysulfones, nylons, and numerous others [70,71]. Graphene and graphene oxide nanofillers have been used for the development of efficient membranes. Polystyrene, polysulfone, and polyethersulfone have been widely used as ultrafiltration membranes due to their fine strength, durability, pH operating range, and chemical stability [72]. However, their uses in water treatment have been restricted due to their hydrophobicity and related reduced permeability properties. Widely used ultrafiltration polymeric membrane materials have hydrophobic properties. Poly(vinyl fluoride), poly(vinyl chloride), and poly(methyl acrylic acid) have been adopted for these membranes. Membrane hydrophobicity has been found to decrease the water flux due to the organic compound accumulation on the membrane surface. In this regard, polymer modification has been suggested to induce membrane hydrophilicity to enhance the membrane antifouling properties for enhanced water filtration processes. The future of polymer-based water treatment membranes relies on the adoption of new modified polymer matrices as well as nanoparticle nanofillers in the nanocomposite matrices.

Most membranes have been used to remove soluble and non-soluble impurities through the processes of ultra-filtration, reverse osmosis, nanofiltration, microfiltration, etc. [73]. Ultrafiltration membranes have pore sizes of 0.01–0.1 μm, which are smaller than microfiltration membranes. However, these pores are larger than the pores of nanofiltration (0.0001 μm) and reverse osmosis membranes. Nanofiltration has been used to remove small organic molecules, like viruses. Ultrafiltration has been found to remove bacteria, microbes, and suspended solids from the water. Reverse osmosis works like filter media which attracts contaminants. The efficiency of the membrane filtration processes depends on the polymer type, surface functional groups, and physical characteristics of the polymeric membranes. The polymer modification has been used to attain efficient membrane separation processes and desired membrane performance. The modification may involve the incorporation

of copolymers and nanoparticles into the polymeric membranes to form blends or nanocomposites.

For the fabrication of polymer/graphene nanocomposite membranes, efficient techniques have been used [74,75]. The solution-casting technique follows the principle of Stokes' law [76]. In this technique, the polymer is dissolved in a solvent. The nanoparticles are also dispersed in a solvent. Both the polymer solution and the nanoparticle solution are mixed to form a homogeneous phase. Later, the solution phase is evaporated to form a polymer film or membrane. The phase inversion technique has also been focused on polymer/graphene nanocomposite membranes [77]. In this process, the controlled transformation of polymers is performed from the liquid to the solid phase. Consequently, steps like precipitation, controlled evaporation, and immersion precipitation are involved in this method. Furthermore, the polymer/graphene nanocomposites have been formed by interfacial polymerization [78]. Interfacial polymerization involves steps like the oil phase, emulsification, and solvent evaporation. All these technologies have been used to form nanocomposite membranes with finely dispersed graphene and derived nanofillers.

Consequently, poly(vinyl alcohol) and poly(vinyl chloride) matrices have been considered important as important matrices for graphene nanofillers [79–81]. Production and properties of poly(vinyl chloride) and graphene oxide nanocomposite membranes have been produced through the phase inversion method [82]. According to microscopic studies, these membranes revealed a macro-void structure. The nanocomposite membranes were investigated to remove bovine serum albumin from water. The separation performance was observed due to the hydrophilic nature of the membranes. Poly(vinyl alcohol) matrix has been filled with graphene or graphene oxide nanoparticles [83]. These nanomaterials based on poly(vinyl alcohol) and graphene oxide possess hydrogen and hydrophilic binding interactions. Moreover, the membrane design based on poly(vinyl alcohol) and graphene oxide was reported by Castro-Muñoz and researchers [84]. The poly(vinyl alcohol)/graphene oxide-based mixed matrix membranes were prepared using dense-film casting and solvent evaporation methods. The inclusion of 1 wt.% graphene oxide in the membrane resulted in a permeate flux of 0.14 $kg\,m^{-2}h^{-1}$. Sun and co-workers [85] used the pressure-assisted filtration process for the production of a poly(vinyl alcohol)/graphene oxide system. Including 10 wt.% nanoparticles caused superior water flux and salt rejection of 98 $kgm^{-2}h^{-1}$ and 99.9%, respectively. Thakur and co-researchers [86] utilized the direct laser writing method to form laser-induced graphene-based three-dimensional porous carbon nanomaterial. Three-dimensional laser-induced graphene had superior electron conductivity. Then, nanocomposite of poly(vinyl alcohol) and laser-induced graphene have been prepared for the formation of membranes. The poly(vinyl alcohol)/laser-induced graphene nanocomposites own fine mechanical, physical, and surface wettability characteristics. **Figure 2** displays a scheme for the development of poly(vinyl alcohol) and laser-induced graphene nanocomposite derived nanocomposite based water treatment membranes for nt. Consequently, the ultrafiltration poly(vinyl alcohol)/laser-induced graphene nanocomposite membranes showed separations of solute particles and bacterial species. **Figure 3** specifies the construction of poly(vinyl alcohol)/laser-induced graphene nanocomposite membranes.

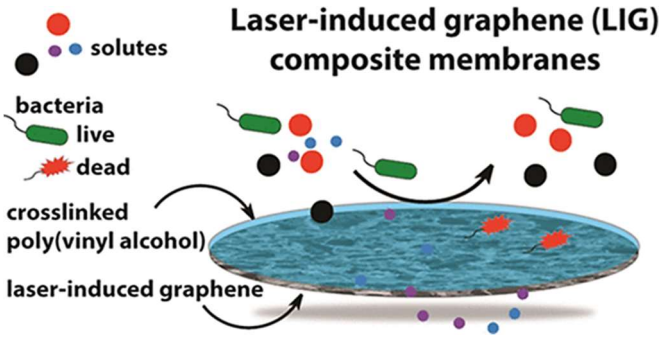

Figure 2. Schematic of poly(vinyl alcohol) and laser induced graphene nanocomposite membranes for water remediation [86]. Reproduced with permission from ACS.

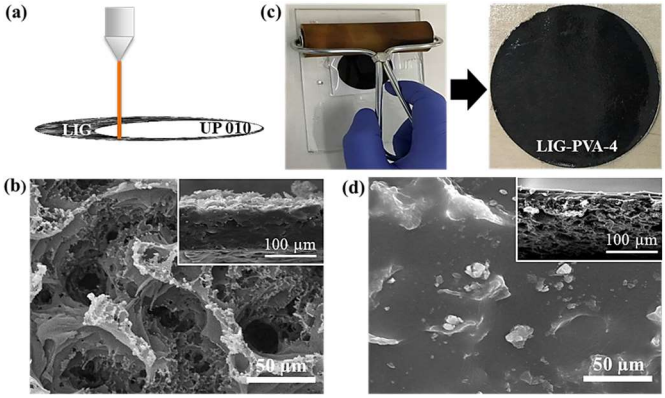

Figure 3. (a) Laser-induced graphene (LIG) is generated on UP 010 membranes through 10.6 µm CO_2 laser; **(b)** scanning electron microscopy images of as-prepared LIG including cross-section (inset); **(c)** fabrication technique for laser-induced graphene and poly(vinyl alcohol) (LIGPVA-4) membrane showing excess of poly(vinyl alcohol) (PVA) solution removal with a rubber roller; and **(d)** scanning electron microscopy images of LIG-PVA-4, including cross-section (inset) [86]. Reproduced with permission from ACS.

Initially, laser-induced graphene was coated on a polyethersulfone substrate. Then, the laser-induced graphene was coated with poly(vinyl alcohol) to form the nanocomposite membrane. Scanning electron microscopic studies on laser-induced graphene and poly(vinyl alcohol)/laser-induced graphene nanocomposite membranes revealed the development of a porous three-dimensional network with consistent pore size distributions. The rejection rate was found to be 99.9%.

The polysulfone and graphene-derived nanocomposites formed some advantageous membrane design combinations [87]. Zinadini et al. [88] reported on polysulfone and graphene oxide-derived membranes. The addition of nanoparticles to the membrane systems resulted in a unique microstructure and high water flux [89]. The polysulfone/graphene oxide-derived membranes revealed a contact angle of 55°–65° and a water flux of >20 kg/m^{2}h. Hydrogen bonding interactions have also been observed between the polysulfone matrix and graphene oxide, leading to the formation of efficient hydrophilic membranes. Here, the wet phase inversion method has been preferred for the fabrication of polysulfone and graphene oxide-derived membranes [90]. Rezaee and co-workers [91] reported on polysulfone/graphene oxide

nanocomposite membranes using the solution technique. **Table 1** demonstrates the influence of adding graphene oxide amounts on the pure water flux, porosity, and pore structure of the membranes. Enhancing the graphene oxide contents from 0.5 to 1 wt.% enhanced the pure water flux from 20 to 50 L/m^{2}h. The membrane porosity was also enhanced from 78% to 87%.

Table 1. Effect of GO content on pure water flux and pore structure parameters of the prepared membranes [91]. GO = graphene oxide; PSF = polysulfone; PSF/GO = polysulfone/graphene oxide. Reproduced with permission from Springer (Creative Commons CC BY).

Membrane	Pure water flux (L/m^{2}h)	Porosity (%)	Pore diameter (nm)
Pure PSF	19.7 ± 3.2	48.3 ± 2.6	6.9 ± 0.56
PSF/GO 0.5	32.3 ± 3.5	77.9 ± 2.2	8.3 ± 0.31
PSF/GO 1	49.9 ± 2.6	86.5 ± 1.8	9.1 ± 0.63
PSF/GO 2	46.4 ± 2.0	82.1 ± 2.6	8.7 ± 0.42

Adding 1 wt.% graphene oxide caused higher pure water flux, porosity, and pore diameter properties relative to the neat polymer and other nanofiller loaded membranes. The effect of a change in pH on the rejection rate was studied for membranes with different nanofiller contents (**Figure 4**). Better arsenate rejection performance was observed for 1 and 2 wt.% nanoparticle loading. Consequently, the nanofiller addition caused high separation efficiency due to homogeneous membrane structure, morphology, pore sizes, and optimum porosities [92]. Hence, polymer/graphene and polymer/graphene oxide nanocomposites have been studied for water remediation and filtration [93]. However, these membranes need further research efforts to resolve the challenges of low membrane stability and fouling effects.

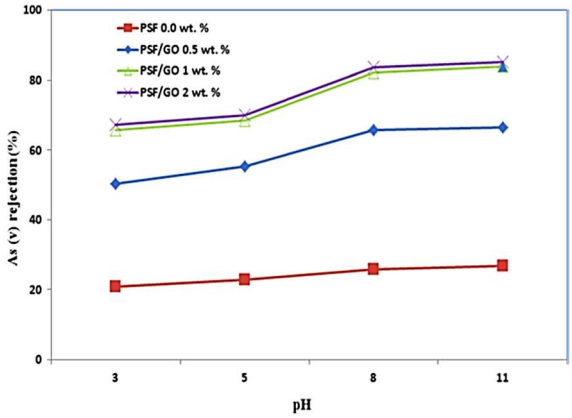

Figure 4. Percentage rejection of As (V) at different pHs by prepared membranes with various graphene oxide (GO) contents. (Operating pressure = 4 bar; initial As (V) concentration = 300 ± 10 µg/L; feed temperature = 25 ± 0.5 °C) [91]. As = arsenate; PSF = polysulfone; PSF/GO = polysulfone/graphene oxide. Reproduced with permission from Springer (Creative Commons CC BY).

Tulugan et al. [94] formed polysulfone/graphene nanocomposite-derived nanofiltration membranes. The water flux of the neat polysulfone membrane (33.2

$L/m^2/h$) was improved with the inclusion of graphene to 183.6 $L/m^2/h$. Moreover, the nanofiltration membranes have a high adsorption rate of 79.8%, relative to neat polymer membranes (26.7%). Alshahrani et al. [95] used the interfacial polymerization method for polysulfone/reduced graphene oxide membrane fabrication. Including 0.015% nanofiller in polyamide led to a water permeability of 48.9 L/m^2 h, higher than the neat polyamide membrane (25.0 L/m^2 h). In addition, these membranes have a high salt rejection of 80–95%. Yu et al. [96] developed polyamide-polysulfone membranes through interfacial polymerization. The water permeability of membranes was found to be 48.90 L/m^2h at 22 bar, which was superior to the neat polyamide membrane of 25.0 L/m^2h. Salt rejection was observed in the range of 80%–95%.

In addition to water permeation or desalination membranes, polymer/graphene membranes have been frequently investigated for gas molecule transportation [97]. Koenig and colleagues [98] formed pristine graphene membranes on a silicon substrate for the separation of H_2 and CO_2 gases. The structure and morphology of membranes have been reported. In addition, membranes have been studied for CO_2/CH_4, CO_2/O_2, and CO_2/N_2 permeation and separation processes [99]. The performances were found to be related to membrane pore sizes as well as affinity towards different molecular species [100]. Subsequently, graphene designs have been investigated for fine gas separations [101]. To improve the properties of graphene towards gas permeation, polymer and graphene-based membranes have been reported [102]. Li and researchers [103] fabricated the polymer/graphene nanocomposite membranes with a pore size of 0.34 nm. The membranes were tested for high selectivity for H_2/CO_2 and H_2/N_2 gases. These membranes still need to be focused on improving pore sizes towards CO_2 sieving [104]. For gas separation membranes, poly(dimethyl siloxane) has been considered [105]. Ultrathin membranes of poly(dimethyl siloxane) have been designed to focus on the carbon dioxide and other toxic gases removal [106]. Nevertheless, pristine poly(dimethyl siloxane) membranes have certain drawbacks due to a lack of structural robustness. In this regard, reports on poly(dimethyl siloxane) and graphene oxide-derived nanocomposite membranes have been found in the literature [107]. Such nanocomposite membranes have been prepared using ultrasonication and solvent-based methods. The poly(dimethyl siloxane)/graphene oxide membranes have fine CO_2 permeability and CO_2/CH_4 separation characteristics. Poly(methyl methacrylate) is a thermoplastic polymer widely applied for membrane applications [108]. Baldanza and researchers [109] produced poly(methyl methacrylate) and graphene-based nanocomposite membranes through a wet deposition technique. The 'lift-off/float-on' method was used for the formation of these membranes [110]. **Figure 5** shows the formation of poly(methyl methacrylate) and twenty layers of graphene-based nanocomposite membrane. The membrane thickness and nominal volume fraction were observed at around 550 nm and 0.06%, respectively. According to scanning electron microscopy, a regular lamination sequence was observed. Neat poly(methyl methacrylate) and poly(methyl methacrylate)/graphene membranes were studied for the permeability coefficients of humidified CO_2 and O_2 (**Figure 6**). The nanocomposite membrane had significantly low permeability properties. Adding graphene nanofiller reduced the CO_2 and O_2 permeability coefficients of the membrane to 1.30×10^{-17} and 0.21×10^{-17} $mol \cdot m \cdot m^{-2} \cdot Pa^{-1} \cdot s^{-1}$, respectively (**Table 2**). The property was declined owing to the development of diffusion pathways in the

membrane. These membranes had high permeability coefficients suitable for commercial scale uses of poly(methyl methacrylate)/graphene membranes [111].

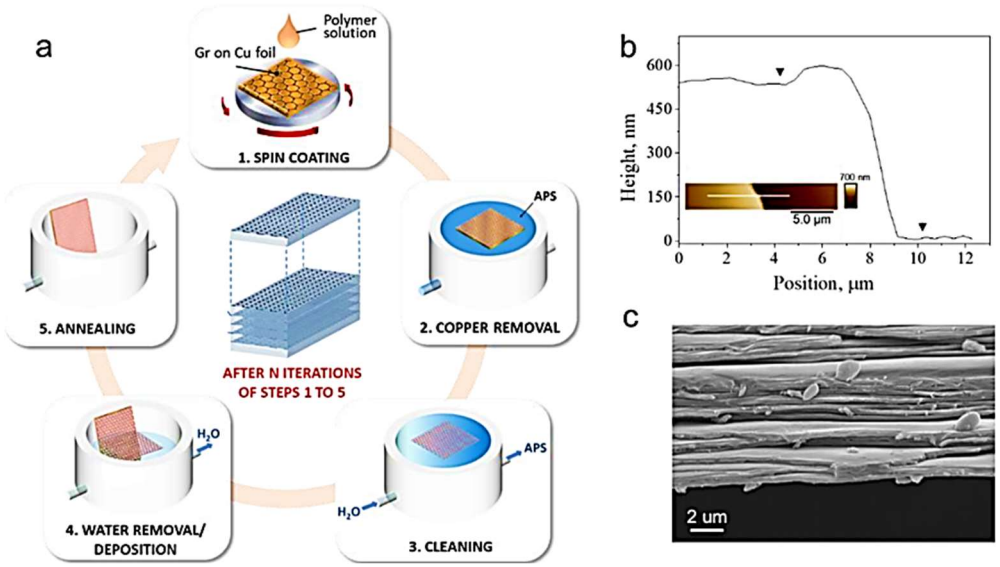

Figure 5. (a) Schematic illustration of the iterative 'lift-off/float-on' process combined with wet depositions adopted to produce the Gr-PMMA nanolaminates; **(b)** Thickness evaluation of the single Gr-PMMA layer deposited on a Si wafer: representative cross-section of the scratch and atomic force microscopy image as inset; and **(c)** scanning electron microscopy image in the cross-section plane of the nanolaminate [109]. Gr = graphene; Gr-PMMA = poly(methyl methacrylate/graphene nanocomposite); APS = ammonium peroxydisulfate. Reproduced with permission from MDPI.

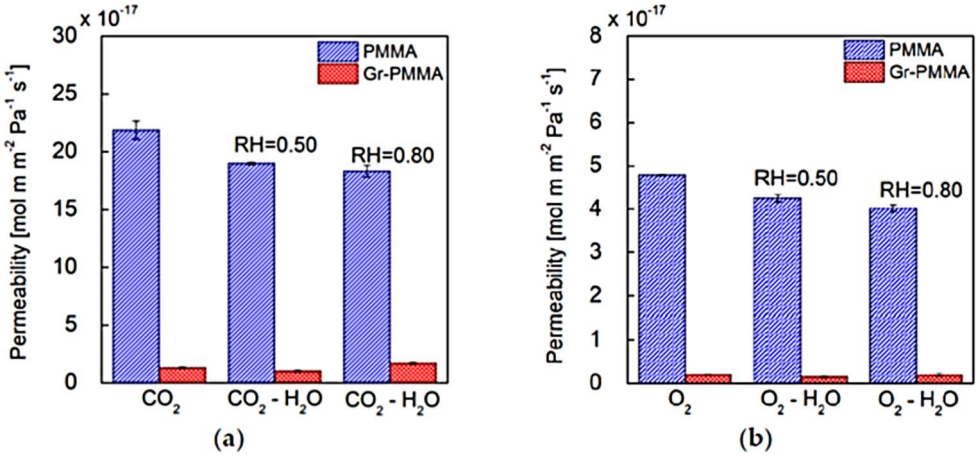

Figure 6. Gas permeability coefficients at 25 °C through poly(methyl methacrylate) (PMMA) (blue bars) and Gr-PMMA (poly(methyl methacrylate/graphene nanocomposite)) (red bars) for **(a)** CO_2 and humidified CO_2 and **(b)** O_2 and humidified O_2 [109]. Reproduced with permission from MDPI.

Table 2. Permeability coefficients of CO_2 or O_2 through the nanocomposite at different R.H. levels [109]. PMMA = poly(methyl methacrylate); Gr-PMMA = poly(methyl methacrylate/graphene nanocomposite). Reproduced with permission from MDPI.

Nanolaminate/ permeating gas	P [mol·m·m^{-2} ·Pa^{-1} ·s^{-1}]	P [Barrer]
PMMA/CO_2	21.9 (±0.8) × 10^{-17}	6.5 (±0.2) × 10^{-1}
Gr-PMMA/CO_2	1.30 (±0.1) × 10^{-17}	0.39 (±0.03) × 10^{-1}
PMMA/O_2	4.79 (±0.01) × 10^{-17}	1.434 (±0.003) × 10^{-1}
Gr-PMMA/O_2	0.21 (±0.01) × 10^{-17}	0.063 (±0.003) × 10^{-1}

Polysulfone is also an important thermoplastic polymer for gas purification membrane systems [112]. In this contest, the mixed matrix membranes of polysulfone have been reported [113]. These membranes have been reported for the separation or selective separation of CO_2 and other noxious gases [114]. Sainath and co-workers [115] produced the mixed matrix polysulfone/graphene oxide membrane for the selective separation of gases. Adding 0.25 wt.% graphene oxide caused 3–4 times higher CO_2/CH_4 selectivity relative to the pristine membrane. The results were obtained due to better nanofiller dispersion and the formation of diffusing routes in the nanocomposite membranes [116]. Gas separation membranes of copolymers have also gained success in gas separation applications such as poly(1-trimethylsilyl-1-propyne)/graphene oxide [117–119] and poly(phenyl sulfonepyridine)/graphene oxide nanocomposites [120]. Similarly, poly(2,6-dimethyl-1,4-phenylene oxide) has been adopted for gas separation membrane matrix [121–123]. Rea and co-workers [124] fabricated the poly(2,6-dimethyl-1,4-phenylene oxide) and graphene-based nanocomposite membranes. The 0.3–15 wt.% nanoparticle contents were filled in the membranes. **Figure 7** shows the morphology of the poly(2,6-dimethyl-1,4-phenylene oxide)/graphene nanocomposite membrane. A few layers of graphene were observed in the polymer matrix, showing layered morphology and fine dispersion.

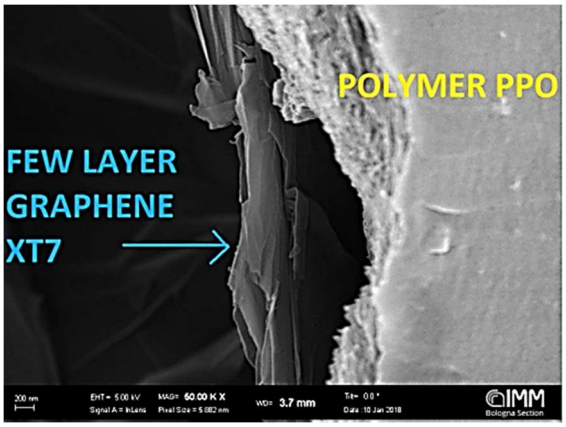

Figure 7. Scanning electron microscopy image of PPO and a few-layer graphene membrane [124]. PPO = poly(2,6-dimethyl-1,4-phenylene oxide). Reproduced with permission from MDPI.

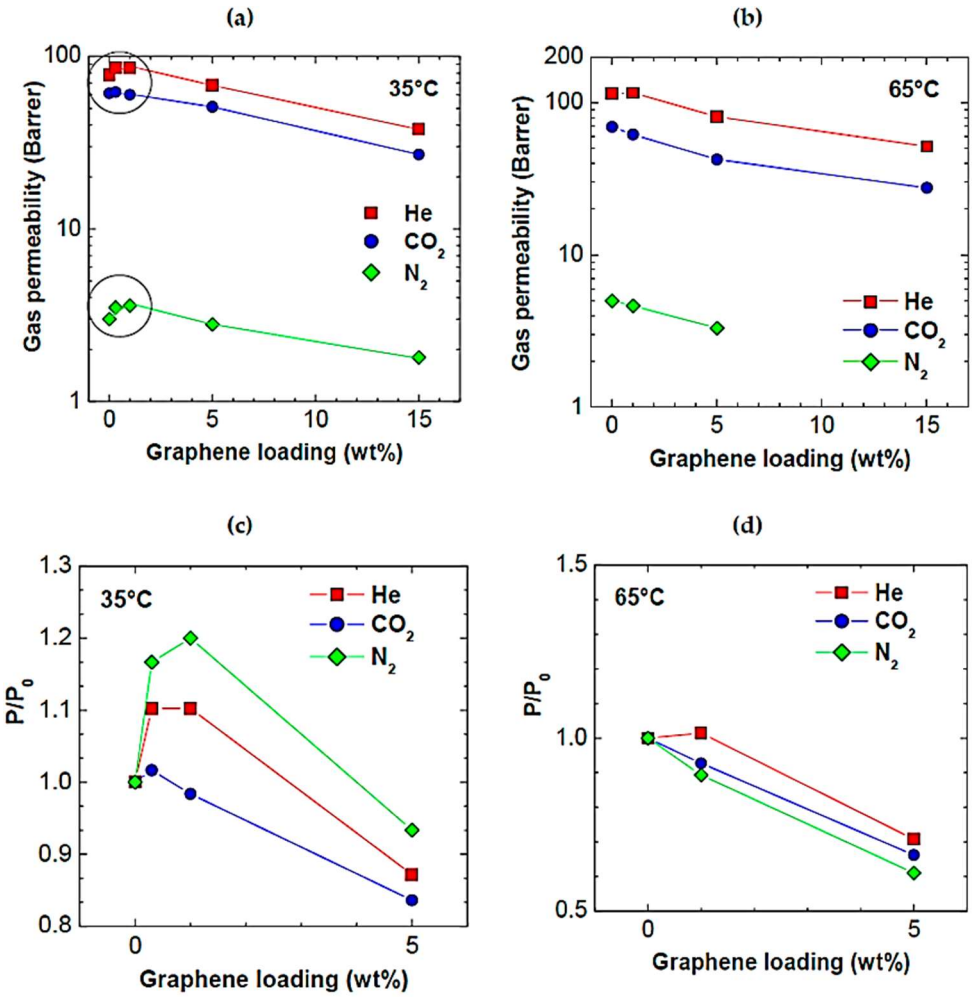

Figure 8. Gas permeability before **(a)** 35 °C; **(b)** 65 °C; and after graphene addition **(c)** 35 °C; **(d)** 65 °C, as a function of graphene loading in the poly(1-trimethylsilyl-1-propyne) matrix [124]. Reproduced with permission from MDPI.

The gas permeability was found to decrease at 35 and 65 ºC with the addition of graphene (**Figure 8**). The effect on the permeation properties was observed due to the variation in loading level and dispersion in the polymer matrix. Hence, numerous polymeric membranes have been prepared with graphene or graphene oxide nanofillers for gas permeation [125]. The gas permeability and selectivity properties rely on the nanoparticle alignment in the matrices, which may affect the membrane pore sizes and microstructures [126,127].

5. Important prospects

Numerous polymer/graphene nanocomposite membrane systems have been proposed for superior water permeation, desalination, gas separation, and selective separation characteristics. Key points of this review article include the (i) fundamentals of graphene; (ii) fundamentals of polymer membranes; (iii) efficiency of graphene nanocomposite membranes for water remediation or gas separations; (iv) important aspects of the nanocomposite membranes; (v) graphene amount and dispersion; (vi) graphene interactions with membrane matrix; (vii) membrane porosity, morphology, and surface properties; and (viii) membrane permeability and selectivity

properties. Additionally, graphene-based systems have advanced mechanical stability and thermal stability properties. Generally, fine graphene dispersion in matrices has been considered for fine molecular transportation characteristics such as barrier, permeation, and selective separation (**Figure 9**). These membrane properties can be limited due to poor nanoparticle dispersion, surface properties, and imperfect membrane pore formation. Another limiting factor is the fabrication of graphene-based membranes on industrial or commercial levels. The large-scale processing depends upon technique, polymer/nanofiller types, and functionalization affecting the microstructure, durability, and water/gaseous molecular transportation.

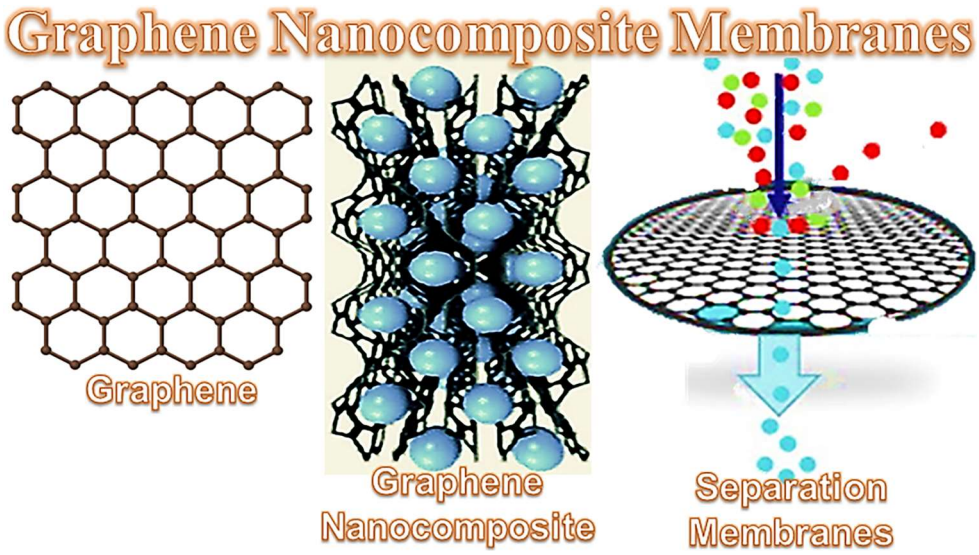

Figure 9. Graphene for gas separation membranes.

According to a literature comparison (**Table 3**), polysulfone nanocomposite membranes have been prepared with carbon nanotubes [128], zeolites [129], and silicon dioxide [130]. The polysulfone/graphene or graphene oxide-based membranes revealed better nanoparticle dispersion, antifouling, water flux, and permeability properties. By comparing the utilization of graphene or graphene oxide nanofillers in the water purification membranes, most of the membranes have been prepared using the graphene oxide nanofiller. The inclusion of graphene oxide or reduced graphene oxide in membranes led to superior water flux, permeability, and rejection properties. The reason seems to be the functionalization of graphene nanosheets, which causes better interactions and dispersion with the polymers relative to neat graphene nanofillers.

Solution casting, phase inversion, and ultrasonication. Techniques that have been frequently used include gas separation polymer/graphene and polymer graphene oxide membranes. As compared to polysulfone/graphene and polysulfone/graphene oxide membranes [115,131], lower CO_2 permeability and ideal CO_2/CH_4 selectivity of 4.2% and 2.7%, respectively, were observed for commercial polysulfone/zeolite membranes [132]. For gas separation membranes, both graphene, graphene oxide, and modified graphene oxide have been applied. A number of studies have been reported on graphene and derivative-based membranes [133]. By comparing various studies on graphene and graphene-derived membranes (**Table 4)**, graphene oxide-based

membranes were found to have higher selectivity and permeability values than graphene-based systems. For example, the polysulfone [103] system revealed much higher gas selectivity than the corresponding graphene-based membranes [115,131]. The reason seems to be the nanostructure of graphene, which has impermeability towards molecular passage. However, the formation of graphene oxide or modified graphene nanostructures may cause surface defects, leading to better compatibility, interactions, and interface formation. Consequently, superior permeability and selectivity of graphene oxide-based membranes have been observed. Thus, the polymer/graphene oxide membranes reveal better gas separation properties to overcome the tradeoffs between permeability and selectivity of the nanocomposite membranes. Nevertheless, these membranes are still in their developmental stages, and further studies have been desirable to understand the transport mechanisms as well as the structural specifications.

Table 3. Specifications of polymer/graphene nanocomposite membranes for water separation.

Polymer	Nanofiller	Fabrication route	Membrane properties	Ref
Poly(vinyl alcohol)	Graphene oxide	Mixed matrix membranes; dense-film casting technique; solvent evaporation	Permeate flux 0.14 kg $m^{-2}h^{-1}$; permeation rate 75%	[84]
Poly(vinyl alcohol)	Graphene oxide	Pressure-assisted filtration process	water flux 98 k $gm^{-2}h^{-1}$; salt rejection 99.9%	[85]
Poly(vinyl alcohol)	Laser-induced graphene	Ultrafiltration, direct laser writing method	Three-dimensional network; consistent pore size distribution; rejection rate 99.9%	[86]
Polysulfone	Graphene oxide	Phase inversion method	Water flux >20 kg/m^2h; contact angle 55°–65°	[89]
Polysulfone	Graphene oxide	Solution casting	Pure water flux 20–50 L/m^2h; porosity 78%–87%.	[91]
Polysulfone	Graphene oxide	Nanofiltration	Contact angle 7°; water flux 33.2 183.6 L/m^2/h; adsorption rate 79.8%	[94]
Polysulfone	Reduced graphene oxide	Interfacial polymerization	Water permeability 48.9 L/m^2h; permeability 25.0 L/m^2 h; salt rejection 80%–95%	[95]
Polysulfone-polyamide	Sulfonated graphene oxide	Interfacial polymerization	Fluorine treatment; F^- retention effect; water flux 83.2%	[96]

Here, research progress in the field of polymer/graphene nanocomposite membranes needs to be analyzed according to the membrane design, type, and specific end application in order to assess the crucial difficulties in this field. Research progress in the field of polymer/graphene membranes can be primarily categorized as desalination or separation membranes for the removal of salts, biological, and organic pollutants by attaining optimally high water flux. The design and essential characteristics of polymer/graphene nanocomposite-based water permeation membranes have been studied.

The nanocomposite membranes have been investigated for their morphological properties, permeability, flux, desalination, and toxin removal.

Table 4. Specs of polymer/graphene nanocomposite membranes for gas separation.

Polymer	Nanofiller	Fabrication route	Physicochemical properties	Membrane properties	Ref
Polymer	Graphene or graphene oxide	Solution casting	Ion-molecule interaction; 1.8–20 nm thickness	H_2/N_2 selectivity 900; H_2/CO_2 selectivity 3400; pore size ~0.34 nm	[103]
Polysulfone	Graphene oxide	Solution route; N-Methyl-2-pyrrolidone solvent	Physical interaction between oxygenated functional groups of graphene oxide and polymer; Interactions between functional groups of nanocomposites and gas molecules	CO_2/CH_4 selectivity ~45	[115]
Polysulfone	Graphene	Phase inversion; hollow fiber mixed matrix membrane	Nanosize synthesized graphene; Interfacial interaction between graphene and polymer matrix	CO_2/N_2 selectivity 158%; CO_2/CH_4 selectivity 74%	[131]
Polysulfone	Zeolite	Mixed matrix membranes	Interlinked morphology	CO_2 permeability and ideal CO_2/CH_4 selectivity were slightly 4.2% and 2.7%, respectively	[132]
Polyphenylsulfone-pyridine	Graphene oxide	Vacuum infiltration technique	Wettability and surface charge response to pH; acidic pH = 3 form hydrophilic state contact angle 63.3°; alkaline pH = 11 form hydrophobic state contact angle 106.5°; charge-density-tunable nanoporous; power of ≈ 0.76 W m^{-2}	Dispersion; morphology	[120]
Poly(dimethyl siloxane)	Graphene	Solution casting; p-xylene solvent	π-π interactions in matrix-nanofiller	0.2 wt.% nanofiller; N_2, CO_2, Ar, and CH_4 permeation 60%; CO_2/CH_4 selectivity 4.2	[134]
Poly(dimethyl siloxane)	Graphene oxide	Solution/ ultrasonication methods; tetrahydrofuran solvent	Interfacial interactions between functional groups of graphene oxide and polymer; density 1.09–1.12; Thickness 1.9–2.8 nm	5 wt.% nanofiller; CO_2/CH_4 selectivity 112%; CO_2 permeability 29%.	[107]
Poly(dimethyl siloxane)	Graphene oxide	Solution casting	Matrix-nanofiller interactions; interaction between graphene oxide and polymer	8 wt.% nanofiller; H_2, O_2, N_2, CH_4 and CO_2 permeability 99.9%	[135]
Poly(methyl methacrylate)	Graphene	Wet deposition method	Water adsorption, membrane wrinkles; degree of dispersion/orientation of the graphene nanosheet, structure organization of polymeric chains at the interface with graphene nanosheet	CO_2 permeability coefficient 1.30×10^{-17} $mol \cdot m \cdot m^{-2} \cdot Pa^{-1} \cdot s^{-1}$; O_2 permeability coefficient 0.21×10^{-17} $mol \cdot m \cdot m^{-2} \cdot Pa^{-1} \cdot s^{-1}$	[109]

Table 4. (*Continued*).

Polymer	Nanofiller	Fabrication route	Physicochemical properties	Membrane properties	Ref
Poly(1-trimethylsilyl-1-propyne)	Graphene oxide	Solution casting; chloroform solvent	Anchoring of graphene oxide nanosheets lowers membrane flexibility; and less free volume; covalent cross-linking of polymer	1 wt.% graphene; diffusion coefficient of CO_2 (25%); N_2 (14); CH_4 (9%)	[118]
Poly(1-trimethylsilyl-1-propyne)	Graphene	Solution route	Interaction between filler and polymer matrix; 0.93–1.36 MPa; 38–44 MPa	0.05 wt.% nanofiller; CO_2 permeability 3.5 × 10^3 Barrer	[119]
Poly(2,6-dimethyl-1,4-phenylene oxide)	Graphene	Solution route	Void formation at the interface; glassy polymer filled with graphene; graphene inclusion for the physical constraint to relaxation of polymer chains	0.3–15 wt.% nanofiller reduced permeability	[124]

The mechanical properties like flexibility, strength, toughness, and other important properties of membranes have been deliberated. Graphene nanoparticle dispersion has been found to be important in enhancing the matrix-nanofiller interactions and improving the final membrane characteristics. In this context, compatibility between the polymer and graphene nanoparticles may cause better nanoparticle dispersion and miscibility effects. The molecular diffusion and permeability properties rely on the pore size, shape, and nanoparticle dispersal in the polymeric matrices. All these properties not only affect the selectivity/permeability features but also the membrane strength and functional life for membrane applications. Major challenges identified in this sector have been found to be complications owing to poor nanoparticle dispersion, phase separation, optimum fabrication parameters, and the identification of perfect membrane designs for commercial-scale production of these membranes. In this way, desirable barrier effects can be achieved for selective molecular transportation through the membranes to separate the salts, toxic ions, biological species, and other toxins. Thus, not much research has been observed regarding the separation mechanisms and overcoming the challenges of fabricating well-defined designs for commercial-level use. Future research in the mentioned directions will be beneficial for the formation of efficient water separation membranes.

Secondly, an important application of polymer/graphene nanocomposite membranes has been observed for gas separation. Here, matrices like polysulfone, poly(dimethyl siloxane), poly(methyl methacrylate), and other block copolymers have been used and filled with graphene nanofillers using facile solution, sonication, phase inversion, infiltration, and other techniques. For this application, efficient design combinations have been observed for separating the toxic or desired gas from gaseous mixtures. The resulting membrane must have optimum porosity, permeability, selectivity, and other membrane features for the separation of molecular species. As discussed above, all the membrane characteristics have been found to be dependent upon the processing, nanoparticle alignment, functionality, and compatibility with the polymer phases. By controlling all these features, complex gas mixtures can be separated using novel membrane designs. In addition, membrane thicknesses have also

been found to be important to control not only the gas transport and flux characteristics, but also the membrane durability and cyclic performance. For gas separation, identification of the perfect processing technique, membrane parameters, and ultrathin polymer/graphene nanocomposite membrane formation have been found to be limiting factors or challenges. In this field, there is a lack of research regarding the separation mechanisms, structure-property relationships, and well-defined membrane designs for the separation of specific gaseous pollutants. Hence, due to a lack of targeted research in this area, desired permeability, selectivity, and working life have been found challenging. More focused research efforts have definitely been needed in these directions to form high-performance membranes through facile processing with well-defined parameters.

6. Conclusions

Hence, this article presents the gas separation performance of polymer/graphene nanocomposite membranes, keeping in view the important literature reports. Graphene as well as modified graphene nanoparticles have been filled in the nanocomposite membranes. The resulting membrane systems have been analyzed for fine water and gas molecular separation as well as permeation properties. The polymer/graphene nanocomposite membranes have been examined for the nature of pores, microstructure, sturdiness, and gas or water molecular separation efficiencies. Various combinations of polymers and graphene, or modified graphene, have been developed for the formation of efficient membrane systems. Nevertheless, there are several challenges in the way of the formation and application of polymer/graphene nanocomposite membranes. The related challenges may be comprised of polymer type, nanoparticle modification, nanoparticle dispersion, and nanoparticle interaction with the polymer. Despite the advantages, there are numerous problems limiting the rapid development of graphene-based nanocomposite membranes. Even though facile solution methods have been used, no perfect design with all the defined parameters, high surface area, and even thickness has been identified so far for large-scale functioning. Facile methods have been found to be ineffective in producing membranes with all defined membrane parameters on a large scale. Pore clogging and membrane fouling (biofouling, micro fouling, macrofouling) due to the presence of organic/inorganic pollutants (dyes, metal particles, microbes, bacteria, etc.) have been found to prevent rapid water purification. Hence, the development of evenly structured ultrathin, enduring, lightweight, low price, antifouling, and extended life polymer/graphene membranes has been found difficult to attain for large-scale commercial systems. Overcoming all these challenges may yield fine future opportunities for high-tech, commercial-grade graphene-filled membranes.

Thus, the research progress on graphene nanocomposite membranes led to several advances in types, designs, and applications to overcome the challenges in this field. For an increase in physical properties, nanoparticle dispersion has been found to be important for matrix-nanofiller interactions, microstructure, mechanical features, and for advanced membrane characteristics. Consequently, the compatibility of matrix graphene has been recommended to improve for better miscibility and reinforcing effects. The membrane performance also depends upon the pore shapes, sizes, and

distribution in the matrices. The random nanofiller dispersion or pore distribution in membranes may influence the strength, durability, and life of the membranes. For commercial-scale membrane production, membrane design features must be analyzed. Hence, future research must resolve the challenge of identifying directions for high-performance gas separation membranes.

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References

1. Gkotsis P, Kougias P, Mitrakas M, et al. Biogas upgrading technologies – Recent advances in membrane-based processes. International Journal of Hydrogen Energy. 2023; 48(10): 3965-3993. doi: 10.1016/j.ijhydene.2022.10.228
2. Wang T, Zeng S, Gu Z. Crown Ether Nanopores in Graphene Membranes for Highly Efficient CO_2/CH_4 and CO_2/CO Separation: A Theoretical Study. ACS Applied Nano Materials. 2023; 6(13): 12372-12380. doi: 10.1021/acsanm.3c02075
3. Krishnan MR, Alsharaeh EH. High-performance functional materials based on polymer nanocomposites—A review. Journal of Polymer Science and Engineering. 2023; 6(1): 3292. doi: 10.24294/jpse.v6i1.3292
4. Kausar A. Advances in Polymer/Fullerene Nanocomposite: A Review on Essential Features and Applications. Polymer-Plastics Technology and Engineering. 2016; 56(6): 594-605. doi: 10.1080/03602559.2016.1233278
5. Su J, Wei Y, Li H. Preparation of defect free TFC FO membranes using robust and highly porous ceramic substrate. Journal of Polymer Science and Engineering. 2018; 1(4). doi: 10.24294/jpse.v1i4.413
6. Yang E, Goh K, Chuah CY, et al. Asymmetric mixed-matrix membranes incorporated with nitrogen-doped graphene nanosheets for highly selective gas separation. Journal of Membrane Science. 2020; 615: 118293. doi: 10.1016/j.memsci.2020.118293
7. Nauman Javed RM, Al-Othman A, Tawalbeh M, et al. Recent developments in graphene and graphene oxide materials for polymer electrolyte membrane fuel cells applications. Renewable and Sustainable Energy Reviews. 2022; 168: 112836. doi: 10.1016/j.rser.2022.112836
8. Chumakova NA, Kalai T, Rebrikova AT, et al. Novel Orientation-Sensitive Spin Probes for Graphene Oxide Membranes Study. Membranes. 2022; 12(12): 1241. doi: 10.3390/membranes12121241
9. Lee J, Park CY, Kong CI, et al. Ultrathin Water-Cast Polymer Membranes for Hydrogen Purification. ACS Applied Materials & Interfaces. 2022; 14(5): 7292-7300. doi: 10.1021/acsami.1c21780
10. Mohsenpour S, Leaper S, Shokri J, et al. Effect of graphene oxide in the formation of polymeric asymmetric membranes via phase inversion. Journal of Membrane Science. 2022; 641: 119924. doi: 10.1016/j.memsci.2021.119924
11. He X, Ou D, Wu S, et al. A mini review on factors affecting network in thermally enhanced polymer composites: filler content, shape, size, and tailoring methods. Advanced Composites and Hybrid Materials. 2021; 5(1): 21-38. doi: 10.1007/s42114-021-00321-1
12. Fatemi SM, Fatemi SJ, Abbasi Z. Gas separation using graphene nanosheet: insights from theory and simulation. Journal of Molecular Modeling. 2020; 26(11). doi: 10.1007/s00894-020-04581-4
13. Sharma S, Verma A, Rangappa SM, et al. Recent progressive developments in conductive-fillers based polymer nanocomposites (CFPNC's) and conducting polymeric nanocomposites (CPNC's) for multifaceted sensing applications. Journal of Materials Research and Technology. 2023; 26: 5921-5974. doi: 10.1016/j.jmrt.2023.08.300
14. Kausar A. Nanoporous graphene in polymeric nanocomposite membranes for gas separation and water purification—standings and headways. Journal of Macromolecular Science, Part A. 2023; 60(2): 81-91. doi: 10.1080/10601325.2023.2177170
15. Kausar A. Poly(methyl methacrylate) nanocomposite reinforced with graphene, graphene oxide, and graphite: a review. Polymer-Plastics Technology and Materials. 2019; 58(8): 821-842. doi: 10.1080/25740881.2018.1563112

16. Kausar A. Applications of polymer/graphene nanocomposite membranes: a review. Materials Research Innovations. 2018; 23(5): 276-287. doi: 10.1080/14328917.2018.1456636
17. Kumar SR, Wang JJ, Wu YS, et al. Synergistic role of graphene oxide-magnetite nanofillers contribution on ionic conductivity and permeability for polybenzimidazole membrane electrolytes. Journal of Power Sources. 2020; 445: 227293. doi: 10.1016/j.jpowsour.2019.227293
18. Anegbe B, Ifijen IH, Maliki M, et al. Graphene oxide synthesis and applications in emerging contaminant removal: a comprehensive review. Environmental Sciences Europe. 2024; 36(1). doi: 10.1186/s12302-023-00814-4
19. Li Y, Lin Z, He X. New nonporous fillers-based hybrid membranes for gas separations and water treatment process. Current Trends and Future Developments on (Bio-) Membranes. Published online 2024: 53-105. doi: 10.1016/b978-0-323-99311-1.00002-7
20. Gupta S, Singh A, Sharma T, et al. Applications of ultrafiltration, nanofiltration, and reverse osmosis in pharmaceutical wastewater treatment. Development in Wastewater Treatment Research and Processes. Published online 2024: 33-49. doi: 10.1016/b978-0-323-99278-7.00017-1
21. Jalali SHS. Investigation of nanofiltration systems efficiency for removal of chromium and copper from groundwater resources. Environmental Quality Management. Published online January 9, 2024. doi: 10.1002/tqem.22178
22. Ribeiro Pinela S, Larasati A, Meulepas RJW, et al. Ultrafiltration (UF) and biological oxygen-dosed activated carbon (BODAC) filtration to prevent fouling of reversed osmosis (RO) membranes: A mass balance analysis. Journal of Water Process Engineering. 2024; 57: 104648. doi: 10.1016/j.jwpe.2023.104648
23. Rana K, Kaur H, Singh N, et al. Graphene-based materials: Unravelling its impact in wastewater treatment for sustainable environments. Next Materials. 2024; 3: 100107. doi: 10.1016/j.nxmate.2024.100107
24. Nwosu CN, Iliut M, Vijayaraghavan A. Graphene and water-based elastomer nanocomposites – a review. Nanoscale. 2021; 13(21): 9505-9540. doi: 10.1039/d1nr01324f
25. Lawal AT. Recent progress in graphene based polymer nanocomposites. Cogent Chemistry. 2020; 6(1): 1833476. doi: 10.1080/23312009.2020.1833476
26. Raza A, Hassan JZ, Mahmood A, et al. Recent advances in membrane-enabled water desalination by 2D frameworks: Graphene and beyond. Desalination. 2022; 531: 115684. doi: 10.1016/j.desal.2022.115684
27. Zhang W, Xu H, Xie F, et al. General synthesis of ultrafine metal oxide/reduced graphene oxide nanocomposites for ultrahigh-flux nanofiltration membrane. Nature Communications. 2022; 13(1). doi: 10.1038/s41467-022-28180-4
28. Lecaros RLG, Matira AR, Tayo LL, et al. Homostructured graphene oxide-graphene quantum dots nanocomposite-based membranes with tunable interlayer spacing for the purification of butanol. Separation and Purification Technology. 2022; 283: 120166. doi: 10.1016/j.seppur.2021.120166
29. Rehman F, Memon FH, Bhatti Z, et al. Graphene-based composite membranes for isotope separation: challenges and opportunities. Reviews in Inorganic Chemistry. 2021; 42(4): 327-336. doi: 10.1515/revic-2021-0035
30. You X, Zhang Q, Yang J, et al. Review on 3D-printed graphene-reinforced composites for structural applications. Composites Part A: Applied Science and Manufacturing. 2023; 167: 107420. doi: 10.1016/j.compositesa.2022.107420
31. Berger C, Song Z, Li X, et al. Electronic Confinement and Coherence in Patterned Epitaxial Graphene. Science. 2006; 312(5777): 1191-1196. doi: 10.1126/science.1125925
32. Yu W, Gong K, Li Y, et al. Flexible 2D Materials beyond Graphene: Synthesis, Properties, and Applications. Small. 2022; 18(14). doi: 10.1002/smll.202105383
33. Narayanam PK, Botcha VD, Ghosh M, et al. Growth and photocatalytic behavior of transparent reduced GO–ZnO nanocomposite sheets. Nanotechnology. 2019; 30(48): 485601. doi: 10.1088/1361-6528/ab3ced
34. Shen X, Zeng X, Dang C. Graphene Composites. Handbook of Graphene. Published online June 17, 2019: 1-25. doi: 10.1002/9781119468455.ch53
35. Zandiatashbar A, Lee GH, An SJ, et al. Effect of defects on the intrinsic strength and stiffness of graphene. Nature Communications. 2014; 5(1). doi: 10.1038/ncomms4186
36. Qin H, Chen Y, Wu Y, et al. Defect-Engineered Thermal Transport in Wrinkled Graphene: A Comprehensive Molecular Dynamics Study. The Journal of Physical Chemistry C. 2022; 126(12): 5759-5766. doi: 10.1021/acs.jpcc.2c00324
37. Yu W, Sisi L, Haiyan Y, et al. Progress in the functional modification of graphene/graphene oxide: a review. RSC Advances. 2020; 10(26): 15328-15345. doi: 10.1039/d0ra01068e

38. Sinha A, So H. Structural Effects of Crumpled Graphene and Recent Developments in Comprehensive Sensor Applications: A Review. Small Structures. 2023; 4(10). doi: 10.1002/sstr.202300084
39. Rahman M, Islam KS, Dip TM, et al. A review on nanomaterial-based additive manufacturing: dynamics in properties, prospects, and challenges. Progress in Additive Manufacturing. Published online October 14, 2023. doi: 10.1007/s40964-023-00514-8
40. Lawal AT. Graphene-based nano composites and their applications. A review. Biosensors and Bioelectronics. 2019; 141: 111384. doi: 10.1016/j.bios.2019.111384
41. Kononova S, Gubanova G, Korytkova E, et al. Polymer Nanocomposite Membranes. Applied Sciences. 2018; 8(7): 1181. doi: 10.3390/app8071181
42. Mendes-Felipe C, Veloso-Fernández A, Vilas-Vilela JL, et al. Hybrid Organic–Inorganic Membranes for Photocatalytic Water Remediation. Catalysts. 2022; 12(2): 180. doi: 10.3390/catal12020180
43. Mohamed A, Yousef S, Tonkonogovas A, et al. High performance of PES-GNs MMMs for gas separation and selectivity. Arabian Journal of Chemistry. 2022; 15(2): 103565. doi: 10.1016/j.arabjc.2021.103565
44. Behboudi A, Mohammadi T, Ulbricht M. High performance antibiofouling hollow fiber polyethersulfone nanocomposite membranes incorporated with novel surface-modified silver nanoparticles suitable for membrane bioreactor application. Journal of Industrial and Engineering Chemistry. 2023; 119: 298-314. doi: 10.1016/j.jiec.2022.11.049
45. Saini N, Awasthi K. Insights into the progress of polymeric nano-composite membranes for hydrogen separation and purification in the direction of sustainable energy resources. Separation and Purification Technology. 2022; 282: 120029. doi: 10.1016/j.seppur.2021.120029
46. Wang C, Park MJ, Yu H, et al. Recent advances of nanocomposite membranes using layer-by-layer assembly. Journal of Membrane Science. 2022; 661: 120926. doi: 10.1016/j.memsci.2022.120926
47. Patel H, Acharya NK. Spectroscopic and Transport Behavior of HAB-6FDA Thermally Rearranged (TR) Nanocomposite Membranes. Published online November 8, 2021. doi: 10.21203/rs.3.rs-1030872/v1
48. Song P, Wang H. High-Performance Polymeric Materials through Hydrogen-Bond Cross-Linking. Advanced Materials. 2019; 32(18). doi: 10.1002/adma.201901244
49. Vatanpour V, Jouyandeh M, Akhi H, et al. Hyperbranched polyethylenimine functionalized silica/polysulfone nanocomposite membranes for water purification. Chemosphere. 2022; 290: 133363. doi: 10.1016/j.chemosphere.2021.133363
50. Barzegar T, Hassanajili S. Fabrication and characterization of dual layer PEBAX-SiO_2/polyethersulfone nanocomposite membranes for separation of CO_2/CH_4 gases. Journal of Applied Polymer Science. 2021; 139(6). doi: 10.1002/app.51624
51. Khdary NH, Abdelsalam ME. Polymer-silica nanocomposite membranes for CO_2 capturing. Arabian Journal of Chemistry. 2020; 13(1): 557-567. doi: 10.1016/j.arabjc.2017.06.001
52. Lakhotia SR, Mukhopadhyay M, Kumari P. Surface-Modified Nanocomposite Membranes. Separation & Purification Reviews. 2017; 47(4): 288-305. doi: 10.1080/15422119.2017.1386681
53. Ahmadian-Alam L, Mahdavi H. A novel polysulfone-based ternary nanocomposite membrane consisting of metal-organic framework and silica nanoparticles: As proton exchange membrane for polymer electrolyte fuel cells. Renewable Energy. 2018; 126: 630-639. doi: 10.1016/j.renene.2018.03.075
54. Shanmugasundar S, Kannan N, Sundaravadivel E, et al. Study on the inflammatory response of PMMA/polystyrene/silica nanocomposite membranes for drug delivery and dental applications. PLOS ONE. 2019; 14(3): e0209948. doi: 10.1371/journal.pone.0209948
55. Liu TY, Yuan HG, Liu YY, et al. Metal–Organic Framework Nanocomposite Thin Films with Interfacial Bindings and Self-Standing Robustness for High Water Flux and Enhanced Ion Selectivity. ACS Nano. 2018; 12(9): 9253-9265. doi: 10.1021/acsnano.8b03994
56. Shen L, Huang Z, Liu Y, et al. Polymeric Membranes Incorporated With ZnO Nanoparticles for Membrane Fouling Mitigation: A Brief Review. Frontiers in Chemistry. 2020; 8. doi: 10.3389/fchem.2020.00224
57. Douna I, Farrukh S, Pervaiz E, et al. Blending of ZnO Nanorods in Cellulose Acetate Mixed Matrix Membrane for Enhancement of CO_2 Permeability. Journal of Polymers and the Environment. 2023; 31(6): 2549-2565. doi: 10.1007/s10924-022-02594-z
58. Bakhtin DS, Sokolov SE, Borisov IL, et al. Mitigation of Physical Aging of Polymeric Membrane Materials for Gas Separation: A Review. Membranes. 2023; 13(5): 519. doi: 10.3390/membranes13050519

59. Ramesh M, Rajeshkumar L, Bhoopathi R. Carbon substrates: a review on fabrication, properties and applications. Carbon Letters. 2021; 31(4): 557-580. doi: 10.1007/s42823-021-00264-z
60. Dhand V, Rhee KY, Kim H J, et al. A Comprehensive Review of Graphene Nanocomposites: Research Status and Trends. Journal of Nanomaterials. 2013; 2013: 1-14. doi: 10.1155/2013/763953
61. Xia K, Zhan H, Gu Y. Graphene and Carbon Nanotube Hybrid Structure: A Review. Procedia IUTAM. 2017; 21: 94-101. doi: 10.1016/j.piutam.2017.03.042
62. Liu WW, Chai SP, Mohamed AR, et al. Synthesis and characterization of graphene and carbon nanotubes: A review on the past and recent developments. Journal of Industrial and Engineering Chemistry. 2014; 20(4): 1171-1185. doi: 10.1016/j.jiec.2013.08.028
63. de Sá MH, Pinto AMFR, Oliveira VB. Passive direct methanol fuel cells as a sustainable alternative to batteries in hearing aid devices – An overview. International Journal of Hydrogen Energy. 2022; 47(37): 16552-16567. doi: 10.1016/j.ijhydene.2022.03.146
64. Johnson DJ, Hilal N. Nanocomposite nanofiltration membranes: State of play and recent advances. Desalination. 2022; 524: 115480. doi: 10.1016/j.desal.2021.115480
65. Wu J, Chung T. Supramolecular Polymer Network Membranes with Molecular-Sieving Nanocavities for Efficient Pre-Combustion CO_2 Capture. Small Methods. 2021; 6(1). doi: 10.1002/smtd.202101288
66. Sahu A, Dosi R, Kwiatkowski C, et al. Advanced Polymeric Nanocomposite Membranes for Water and Wastewater Treatment: A Comprehensive Review. Polymers. 2023; 15(3): 540. doi: 10.3390/polym15030540
67. Nadda AK, Banerjee P, Sharma S, et al. Membranes for Water Treatment and Remediation. Springer Nature Singapore; 2023. doi: 10.1007/978-981-19-9176-9
68. Saraswathi MSSA, Nagendran A, Rana D. Tailored polymer nanocomposite membranes based on carbon, metal oxide and silicon nanomaterials: a review. Journal of Materials Chemistry A. 2019; 7(15): 8723-8745. doi: 10.1039/c8ta11460a
69. Yang C, Jin C, Chen F. Micro-tubular solid oxide fuel cells fabricated by phase-inversion method. Electrochemistry Communications. 2010; 12(5): 657-660. doi: 10.1016/j.elecom.2010.02.024
70. Cho JW, Paul DR. Nylon 6 nanocomposites by melt compounding, Polymer, 2001, 42(3): 1083-1094. doi: 10.1016/S0032-3861(00)00380-3
71. Yuan X, Zhang Y, Dong C, et al. Morphology of ultrafine polysulfone fibers prepared by electrospinning. Polymer International. 2004; 53(11): 1704-1710. doi: 10.1002/pi.1538
72. Khan S, Ullah I, Rahman MU, et al. Inorganic-polymer composite electrolytes: basics, fabrications, challenges and future perspectives. Reviews in Inorganic Chemistry. 2024. doi: 10.1515/revic-2023-0030
73. Khan S, Ajmal S, Hussain T, et al. Clay-based materials for enhanced water treatment: adsorption mechanisms, challenges, and future directions. Journal of Umm Al-Qura University for Applied Sciences. Published online October 16, 2023. doi: 10.1007/s43994-023-00083-0
74. Ajaj Y, AL-Salman HNK, Hussein AM, et al. Effect and investigating of graphene nanoparticles on mechanical, physical properties of polylactic acid polymer. Case Studies in Chemical and Environmental Engineering. 2024; 9: 100612. doi: 10.1016/j.cscee.2024.100612
75. Khan I, Khan I, Saeed K, et al. Polymer nanocomposites: an overview. Smart Polymer Nanocomposites. Published online 2023: 167-184. doi: 10.1016/b978-0-323-91611-0.00017-7
76. Sin C, Baranovskii ES. Hölder continuity of solutions for unsteady generalized Navier–Stokes equations with p(x,t)-power law in 2D. Journal of Mathematical Analysis and Applications. 2023; 517(2): 126632. doi: 10.1016/j.jmaa.2022.126632
77. Ray M, Verma A, Maiti A, et al. Nano-Engineered Polymer Matrix-Based Composites. Polymer Nanocomposites. Published online July 18, 2023: 21-39. doi: 10.1201/9781003343912-2
78. Wang Y, Nie W, Wang L, et al. Understanding the graphene-polymer interfacial mechanical behavior via coarse-grained modeling. Computational Materials Science. 2023; 222: 112109. doi: 10.1016/j.commatsci.2023.112109
79. Wang H, Xie G, Fang M, et al. Electrical and mechanical properties of antistatic PVC films containing multi-layer graphene. Composites Part B: Engineering. 2015; 79: 444-450. doi: 10.1016/j.compositesb.2015.05.011
80. Akhina H, Gopinathan Nair MR, Kalarikkal N, et al. Plasticized PVC graphene nanocomposites: Morphology, mechanical, and dynamic mechanical properties. Polymer Engineering & Science. 2017; 58(S1). doi: 10.1002/pen.24711

81. Pakizeh M, Karami M, Kooshki S, et al. Advanced toluene/n-heptane separation by pervaporation: investigating the potential of graphene oxide (GO)/PVA mixed matrix membrane. Journal of the Taiwan Institute of Chemical Engineers. 2023; 150: 105025. doi: 10.1016/j.jtice.2023.105025
82. Zhao Y, Lu J, Liu X, et al. Performance enhancement of polyvinyl chloride ultrafiltration membrane modified with graphene oxide. Journal of Colloid and Interface Science. 2016; 480: 1-8. doi: 10.1016/j.jcis.2016.06.075
83. Mruthyunjayappa KC, Paramashivaiah SA, Mallikarjunappa EK, et al. A combined experimental and computational study of flexible polyvinyl alcohol (PVA)/graphene oxide (GO) nanocomposite films for superior UV shielding with improved mechanical properties. Materials Today Communications. 2023; 35: 105662. doi: 10.1016/j.mtcomm.2023.105662
84. Castro-Muñoz R, Buera-González J, de la Iglesia Ó, et al. Towards the dehydration of ethanol using pervaporation cross-linked poly(vinyl alcohol)/graphene oxide membranes. Journal of Membrane Science. 2019; 582: 423-434. doi: 10.1016/j.memsci.2019.03.076
85. Sun J, Qian X, Wang Z, et al. Tailoring the microstructure of poly(vinyl alcohol)-intercalated graphene oxide membranes for enhanced desalination performance of high-salinity water by pervaporation. Journal of Membrane Science. 2020; 599: 117838. doi: 10.1016/j.memsci.2020.117838
86. Thakur AK, Singh SP, Kleinberg MN, et al. Laser-Induced Graphene–PVA Composites as Robust Electrically Conductive Water Treatment Membranes. ACS Applied Materials & Interfaces. 2019; 11(11): 10914-10921. doi: 10.1021/acsami.9b00510
87. Sali S, Mackey HR, Abdala AA. Effect of Graphene Oxide Synthesis Method on Properties and Performance of Polysulfone-Graphene Oxide Mixed Matrix Membranes. Nanomaterials. 2019; 9(5): 769. doi: 10.3390/nano9050769
88. Zinadini S, Zinatizadeh AA, Rahimi M, et al. Preparation of a novel antifouling mixed matrix PES membrane by embedding graphene oxide nanoplates. Journal of Membrane Science. 2014; 453: 292-301. doi: 10.1016/j.memsci.2013.10.070
89. Ammar A, Al-Enizi AM, AlMaadeed MA, et al. Influence of graphene oxide on mechanical, morphological, barrier, and electrical properties of polymer membranes. Arabian Journal of Chemistry. 2016; 9(2): 274-286. doi: 10.1016/j.arabjc.2015.07.006
90. Ganesh BM, Isloor AM, Ismail AF. Enhanced hydrophilicity and salt rejection study of graphene oxide-polysulfone mixed matrix membrane. Desalination. 2013; 313: 199-207. doi: 10.1016/j.desal.2012.11.037
91. Rezaee R, Nasseri S, Mahvi AH, et al. Fabrication and characterization of a polysulfone-graphene oxide nanocomposite membrane for arsenate rejection from water. Journal of Environmental Health Science and Engineering. 2015; 13(1). doi: 10.1186/s40201-015-0217-8
92. Liao Z, Zhu J, Li X, et al. Regulating composition and structure of nanofillers in thin film nanocomposite (TFN) membranes for enhanced separation performance: A critical review. Separation and Purification Technology. 2021; 266: 118567. doi: 10.1016/j.seppur.2021.118567
93. Xu Y, Bai H, Lu G, et al. Flexible Graphene Films via the Filtration of Water-Soluble Noncovalent Functionalized Graphene Sheets. Journal of the American Chemical Society. 2008; 130(18): 5856-5857. doi: 10.1021/ja800745y
94. Tulugan K, Tian P, Li X, et al. PSF/GO filtering membrane fabricated by electro-spinning applied on arsenic contaminated underground water. Journal of Engineering Research. Published online January 2024. doi: 10.1016/j.jer.2024.01.001
95. Alshahrani AA, El-Habeeb AA, Almutairi AA, et al. Preparation, Characterization and Evaluation of Polyamide-Reduced Graphene Oxide as Selective Membranes for Water Purification. Journal of Composites Science. 2024; 8(1): 24. doi: 10.3390/jcs8010024
96. Yu J, Jing W, Liu E, et al. Sulfonated graphene oxide modified polysulfone-polyamide forward osmosis membrane and its application in fluorine-containing wastewater treatment. Materials Chemistry and Physics. 2024; 313: 128757. doi: 10.1016/j.matchemphys.2023.128757
97. Deng X, Zou C, Han Y, et al. Computational Evaluation of Carriers in Facilitated Transport Membranes for Postcombustion Carbon Capture. The Journal of Physical Chemistry C. 2020; 124(46): 25322-25330. doi: 10.1021/acs.jpcc.0c07627
98. Koenig SP, Wang L, Pellegrino J, et al. Selective molecular sieving through porous graphene. Nature Nanotechnology. 2012; 7(11): 728-732. doi: 10.1038/nnano.2012.162
99. Lee J, Aluru NR. Water-solubility-driven separation of gases using graphene membrane. Journal of Membrane Science. 2013; 428: 546-553. doi: 10.1016/j.memsci.2012.11.006

100. Liu N, Cheng J, Hou W, et al. Unsaturated Zn–N_2–O active sites derived from hydroxyl in graphene oxide and zinc atoms in core shell ZIF-8@ZIF-67 nanocomposites enhanced CO_2 adsorption capacity. Microporous and Mesoporous Materials. 2021; 312: 110786. doi: 10.1016/j.micromeso.2020.110786
101. Rezakazemi M, Sadrzadeh M, Matsuura T. Thermally stable polymers for advanced high-performance gas separation membranes. Progress in Energy and Combustion Science. 2018; 66: 1-41. doi: 10.1016/j.pecs.2017.11.002
102. Du Y, Huang L, Wang Y, et al. Recent developments in graphene-based polymer composite membranes: Preparation, mass transfer mechanism, and applications. Journal of Applied Polymer Science. 2019; 136(28). doi: 10.1002/app.47761
103. Li H, Song Z, Zhang X, et al. Ultrathin, Molecular-Sieving Graphene Oxide Membranes for Selective Hydrogen Separation. Science. 2013; 342(6154): 95-98. doi: 10.1126/science.1236686
104. Yang Y, Bolling L, Priolo MA, et al. Super Gas Barrier and Selectivity of Graphene Oxide-Polymer Multilayer Thin Films. Advanced Materials. 2012; 25(4): 503-508. doi: 10.1002/adma.201202951
105. Liu J, Pan Y, Xu J, et al. Introducing amphipathic copolymer into intermediate layer to fabricate ultra-thin Pebax composite membrane for efficient CO_2 capture. Journal of Membrane Science. 2023; 667: 121183. doi: 10.1016/j.memsci.2022.121183
106. Zhang W, Shi Y, Wang B, et al. High-strength electrospun polydimethylsiloxane/polytetrafluoroethylene hybrid membranes with stable and controllable coral-like structures. Composites Part A: Applied Science and Manufacturing. 2023; 164: 107316. doi: 10.1016/j.compositesa.2022.107316
107. Koolivand H, Sharif A, Chehrazi E, et al. Mixed-matrix membranes comprising graphene-oxide nanosheets for CO_2/CH_4 separation: A comparison between glassy and rubbery polymer matrices. Polymer Science, Series A. 2016; 58(5): 801-809. doi: 10.1134/s0965545x16050084
108. Zakaria NA, Zaliman SQ, Leo CP, et al. Electrochemical cleaning of superhydrophobic polyvinylidene fluoride/polymethyl methacrylate/carbon black membrane after membrane distillation. Journal of the Taiwan Institute of Chemical Engineers. 2022; 138: 104448. doi: 10.1016/j.jtice.2022.104448
109. Baldanza A, Pastore Carbone MG, Brondi C, et al. Chemical Vapour Deposition Graphene–PMMA Nanolaminates for Flexible Gas Barrier. Membranes. 2022; 12(6): 611. doi: 10.3390/membranes12060611
110. Pavlou C, Pastore Carbone MG, Manikas AC, et al. Effective EMI shielding behaviour of thin graphene/PMMA nanolaminates in the THz range. Nature Communications. 2021; 12(1). doi: 10.1038/s41467-021-24970-4
111. Agrawal KV, Benck JD, Yuan Z, et al. Fabrication, Pressure Testing, and Nanopore Formation of Single-Layer Graphene Membranes. The Journal of Physical Chemistry C. 2017; 121(26): 14312-14321. doi: 10.1021/acs.jpcc.7b01796
112. Vinodh R, Atchudan R, Kim HJ, et al. Recent Advancements in Polysulfone Based Membranes for Fuel Cell (PEMFCs, DMFCs and AMFCs) Applications: A Critical Review. Polymers. 2022; 14(2): 300. doi: 10.3390/polym14020300
113. Costa Flores M, Figueiredo KCS. Asymmetric oxygen-functionalized carbon nanotubes dispersed in polysulfone for CO_2 separation. Journal of Applied Polymer Science. 2022; 140(2). doi: 10.1002/app.53303
114. Said N, Mansur S, Zainol Abidin MN, Ismail AF. Fabrication and characterization of polysulfone/iron oxide nanoparticle mixed matrix hollow fiber membranes for hemodialysis: Effect of dope extrusion rate and air gap. Journal of Membrane Science and Research. 2023; 9(1)
115. Sainath K, Modi A, Bellare J. In-situ growth of zeolitic imidazolate framework-67 nanoparticles on polysulfone/graphene oxide hollow fiber membranes enhance CO_2/CH_4 separation. Journal of Membrane Science. 2020; 614: 118506. doi: 10.1016/j.memsci.2020.118506
116. Wan Z, Jiang Y. Synthesis-structure-performance relationships of nanocomposite polymeric ultrafiltration membranes: A comparative study of two carbon nanofillers. Journal of Membrane Science. 2021; 620: 118847. doi: 10.1016/j.memsci.2020.118847
117. Kalmykov D, Balynin A, Yushkin A, et al. Membranes Based on PTMSP/PVTMS Blends for Membrane Contactor Applications. Membranes. 2022; 12(11): 1160. doi: 10.3390/membranes12111160
118. Olivieri L, Ligi S, De Angelis MG, et al. Effect of Graphene and Graphene Oxide Nanoplatelets on the Gas Permselectivity and Aging Behavior of Poly(trimethylsilyl propyne) (PTMSP). Industrial & Engineering Chemistry Research. 2015; 54(44): 11199-11211. doi: 10.1021/acs.iecr.5b03251
119. Alberto M, Bhavsar R, Luque-Alled JM, et al. Impeded physical aging in PIM-1 membranes containing graphene-like fillers. Journal of Membrane Science. 2018; 563: 513-520. doi: 10.1016/j.memsci.2018.06.026
120. Zhu X, Zhou Y, Hao J, et al. A Charge-Density-Tunable Three/Two-Dimensional Polymer/Graphene Oxide Heterogeneous Nanoporous Membrane for Ion Transport. ACS Nano. 2017; 11(11): 10816-10824. doi: 10.1021/acsnano.7b03576

121. Zhang D, Xu S, Wan R, et al. Functionalized graphene oxide cross-linked poly(2,6-dimethyl-1,4-phenylene oxide)-based anion exchange membranes with superior ionic conductivity. Journal of Power Sources. 2022; 517: 230720. doi: 10.1016/j.jpowsour.2021.230720
122. Chen J, Zhang M, Shen C, et al. Preparation and Characterization of Non-N-Bonded Side-Chain Anion Exchange Membranes Based on Poly(2,6-dimethyl-1,4-phenylene oxide). Industrial & Engineering Chemistry Research. 2022; 61(4): 1715-1724. doi: 10.1021/acs.iecr.1c04171
123. Chu X, Miao S, Zhou A, et al. A strategy to design quaternized poly(2,6-dimethyl-1,4-phenylene oxide) anion exchange membranes by atom transfer radical coupling. Journal of Membrane Science. 2022; 649: 120397. doi: 10.1016/j.memsci.2022.120397
124. Rea R, Ligi S, Christian M, et al. Permeability and Selectivity of PPO/Graphene Composites as Mixed Matrix Membranes for CO_2 Capture and Gas Separation. Polymers. 2018; 10(2): 129. doi: 10.3390/polym10020129
125. Theravalappil R, Rahaman M. Patents on graphene-based polymer composites and their applications. Polymer Nanocomposites Containing Graphene. Published online 2022: 615-638. doi: 10.1016/b978-0-12-821639-2.00018-5
126. Kausar A, Ahmad I, Eisa MH, et al. Manufacturing Strategies for Graphene Derivative Nanocomposites—Current Status and Fruitions. Nanomanufacturing. 2023; 3(1): 1-19. doi: 10.3390/nanomanufacturing3010001
127. Kanehashi S, Chen GQ, Scholes CA, et al. Enhancing gas permeability in mixed matrix membranes through tuning the nanoparticle properties. Journal of Membrane Science. 2015; 482: 49-55. doi: 10.1016/j.memsci.2015.01.046
128. Fajardo-Diaz JL, Takeuchi K, Morelos-Gomez A, et al. Enhancing boron rejection in low-pressure reverse osmosis systems using a cellulose fiber–carbon nanotube nanocomposite polyamide membrane: A study on chemical structure and surface morphology. Journal of Membrane Science. 2023; 679: 121691. doi: 10.1016/j.memsci.2023.121691
129. Fathizadeh M, Aroujalian A, Raisi A. Effect of added NaX nano-zeolite into polyamide as a top thin layer of membrane on water flux and salt rejection in a reverse osmosis process. Journal of Membrane Science. 2011; 375(1-2): 88-95. doi: 10.1016/j.memsci.2011.03.017
130. Li J, Cheng L, Song W, et al. In-situ sol-gel generation of SiO_2 nanoparticles inside polyamide membrane for enhanced nanofiltration. Desalination. 2022; 540: 115981. doi: 10.1016/j.desal.2022.115981
131. Zahri K, Wong KC, Goh PS, et al. Graphene oxide/polysulfone hollow fiber mixed matrix membranes for gas separation. RSC Advances. 2016; 6(92): 89130-89139. doi: 10.1039/c6ra16820e
132. Anbealagan LD, Ng TYS, Chew TL, et al. Modified Zeolite/Polysulfone Mixed Matrix Membrane for Enhanced CO_2/CH_4 Separation. Membranes. 2021; 11(8): 630. doi: 10.3390/membranes11080630
133. Abdul Hamid MR, Shean Yaw TC, Mohd Tohir MZ, et al. Zeolitic imidazolate framework membranes for gas separations: Current state-of-the-art, challenges, and opportunities. Journal of Industrial and Engineering Chemistry. 2021; 98: 17-41. doi: 10.1016/j.jiec.2021.03.047
134. Berean KJ, Ou JZ, Nour M, et al. Enhanced Gas Permeation through Graphene Nanocomposites. The Journal of Physical Chemistry C. 2015; 119(24): 13700-13712. doi: 10.1021/acs.jpcc.5b02995
135. Ha H, Park J, Ando S, et al. Gas permeation and selectivity of poly(dimethylsiloxane)/graphene oxide composite elastomer membranes. Journal of Membrane Science. 2016; 518: 131-140. doi: 10.1016/j.memsci.2016.06.028