



Review

Polymer/Graphene Nanocomposite Membranes: Status and Emerging Prospects

Ayesha Kausar ^{1,*} and Patrizia Bocchetta ²

¹ Nanosciences Division, National Center for Physics, Quaid-i-Azam University Campus, Islamabad 44000, Pakistan

² Department of Innovation Engineering, University of Salento, Edificio La Stecca, Via per Monteroni, 73100 Lecce, Italy; patrizia.bocchetta@unisalento.it

* Correspondence: dr.ayeshakauser@yahoo.com

Abstract: Graphene is a unique nanocarbon nanomaterial, frequently explored with polymeric matrices for technical purposes. An indispensable application of polymer/graphene nanocomposites has been observed for membrane technology. This review highlights the design, properties, and promising features of the polymer/graphene nanomaterials and nanocomposite membranes for the pervasion and purification of toxins, pollutants, microbials, and other desired contents. The morphology, pore size, pore structure, water flux, permeation, salt rejection, and other membrane properties are examined. Graphene oxide, an important modified form of graphene, is also utilized in nanocomposite membranes. Moreover, polymer/graphene nanofibers are employed to develop high-performance membranes for methodological purposes. The adaptability of polymer/graphene nanocomposites is observed for water management and purification technologies.

Keywords: graphene; graphene oxide; nanocomposite; membrane; permeation



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1. Introduction

Nowadays, research interest in membrane technology has expanded into technical solicitations and industries [1,2]. Membrane technology has been pragmatic for the management of toxins, pollutants, and impurities present in domestic and industrial water sources. Graphene and graphene oxide have been applied as useful additives in polymeric membranes [3]. Consequently, polymer/graphene nanocomposite-derived separation membranes have been developed and smeared for water treatment. Graphene is capable of forming consistent torturous pathways in the membranes supporting diffusion processes [4]. Moreover, contaminants and desired molecules are removed and separated using the polymeric membranes with graphene dispersion [5]. Consequently, the organic and inorganic toxins were removed using the polymer/graphene nanocomposite membranes [6]. In this regard, different types of polymer/graphene nanocomposite membranes have been developed, including nanofiltration [7,8], microfiltration [8,9], ultrafiltration [10,11], and osmosis [12,13] membranes. The newly developed membranes have been studied for important membrane characteristics, aiming towards permeation or separation applications. The membrane performance has been assessed for salt rejection, ion/molecule separation, water flux or permeate flux, membrane surface charge, surface roughness, self-cleaning, and antibacterial properties. Figure 1 shows the publication trend since the year 1990. According to a careful estimation, the amount of research on these materials has grown exponentially to >14,000 articles in the year 2022 [14].

In this review, the design and properties of the polymer/graphene nanocomposite membranes are considered. Graphene and graphene oxide nanofillers have played a crucial role in the structuring, morphology, and anticipated performance of these membranes. Thus, the potential of polymer/graphene nanocomposite membranes has been investigated for water pollutant and microbial elimination. In these membranes, the polymer/graphene

nanofiber nanocomposites are also prepared and used. The polymer/graphene nanofibers have been found to further enhance their membrane performance, owing to a high surface area. Thus, the polymer/graphene nanocomposite membranes have broadened the scope of water management technologies. To the best of our knowledge, this review paper is likely to be an innovative contribution to the current literature, owing to the inventiveness of the outlining and encompassing literature. This review is comprehensive and intends to comprise essential technical developments in the field of membrane-related sectors.

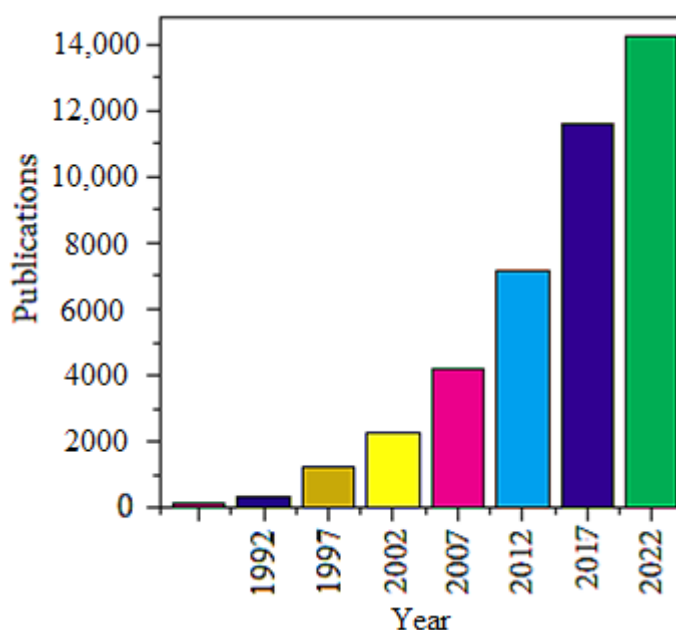


Figure 1. Publication trend of graphene since 1990–2022.

2. Polymeric Nanocomposite Membranes

Polymeric nanocomposite membranes have resolved the emergent challenges of purification [15]. Various inorganic nanoparticles and organic nanoparticles have been used in polymeric membranes [16,17]. Polymeric nanocomposite membranes have been intended to be used to attain an optimum permeation recovery, rate flux recovery rate, self-cleaning, photocatalytic, and antibacterial properties [18–20]. The properties of nanocomposite membranes have been found to enhance with nanofiller loading, for example, in the case of polymeric membranes with zinc oxide nanofiller enhancing the permeation recovery rate up to 100% [21]. The flux recovery rate of the nanocomposite membrane increased to 80%. The antibacterial activity rate observed was 0.21 against *Escherichia coli* and *Staphylococcus aureus* bacterial strains. The photocatalytic efficiency was ~93% and an amount of 78% was attained for the self-cleaning ability. The type of nanofillers and dispersion may also enhance the flux and permeability features of the membranes [22]. A comparative study revealed that the high water flux of polymer/graphene membranes reached 99.8%, relative to the polymer/carbon nanotube membrane (73%) [23]. The nanoparticle dispersion defines the diffusion pathways for the improved permeability. Polymeric nanocomposite membranes have several interactions, such as electrostatic or Van der Waals forces [24], hydrogen bonding [25], and covalent interactions [26]. Nevertheless, several challenges, such as the pore size, pore distribution, and nanofiller dispersion, need to be addressed for the optimization of high-performance nanocomposite membranes [27,28].

There are several advantages to using graphene nanofillers in polymeric membranes, relative to other nanofillers [29]. The inclusion of graphene yields lightweight and high-strength polymeric nanocomposite materials. Compared to other nanomaterials, graphene is structurally unique and its lateral dimensions are larger, with a thickness at the atomic scale [30]. Graphene has been considered to be a promising nanomaterial in liquid barrier

applications. Better aligned graphene nanosheets do not allow the diffusion of small liquid molecules through their plane and may cause selective permeation. Graphene and its derivatives have the ability to form ion-selective membranes [31]. Graphene oxide nanosheets have a relatively larger interlayer distance and empty spaces, relative to the carbon nanotube and other nanocarbon nanofillers in polymeric matrices. Molecular simulations and experiments have also established that graphene and its derivatives are beneficially reinforced in the permeation of membrane applications [32].

3. Graphene

Graphene is a one-atom-thick two-dimensional sheet of sp^2 hybridized carbon atoms [33,34]. The discovery of graphene dates back to 2004 [35]. Graphene has been known to synthesize using organic synthesis, chemical vapor deposition, graphite exfoliation/intercalation, mechanical cleavage, and other techniques [36–38]. Graphene possesses fascinating structural and physical physiognomies. It is claimed to be the thinnest and most transparent nanomaterial [39,40]. Graphene is >200 times stronger than steel, with a Young's modulus of 1 TPa [41]. Graphene has a high electron mobility of $200,000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and a thermal conductivity of 3000–5000 W/mK [42,43]. The nanosheet may have the propensity to crumble due to Van der Waals forces [44–46]. Graphene with hydrophilic surface functionalities, such as hydroxyl, carbonyl, epoxide, and carboxylic groups, has often been referred to as graphene oxide (GO) [47]. Figure 2 shows the structure of graphene and graphene oxide.

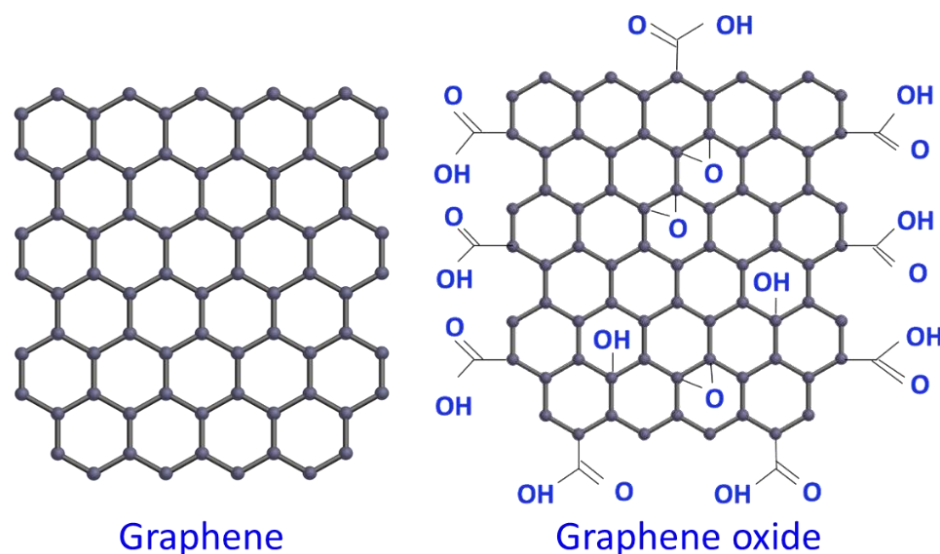


Figure 2. Graphene and graphene oxide.

Graphene-based nanocomposites possess a high electrical conductivity, thermal conductivity, thermal stability, chemical stability, and mechanical sturdiness features [48]. Graphene-based nanocomposites have been utilized in membranes [49,50], anticorrosion coatings [51], electronics [52], sensors [53], energy storage devices [54,55], batteries [56], microbial fuel cells [57], and tissue engineering [58].

4. Polymer/Graphene Nanofibers for Nanocomposite Membranes

Polymeric nanofibers have been developed using various polymeric matrices, such as polyethylene, polypropylene, polyamide, polyacrylonitrile, polyester, etc. [59–61]. Polymeric nanofibers possess a fine resilience, strength, toughness, thermal/chemical constancy, and environmental stability. Important uses of polymeric nanofibers have been found in membranes, packaging, textiles, and biomedical gear [62–66]. Moreover, high-performance, temperature-stable polymeric nanofibers have been applied in advanced technical fields related to automotive and aerospace applications [67,68]. The most important application of

polymeric nanofibers concerns membrane technology. In this regard, polymeric nanocomposite nanofibers have been tested [69]. Graphene-reinforced polymeric nanofibers have been used to design nanocomposite membranes [70–73].

Polyacrylonitrile nanofibers and derived membranes with graphene and GO have been exploited for technical applications [74,75]. Poly(lactic acid), GO-based nanofibers and the resulting membranes have been employed in tissue engineering scaffolds [76]. Moreover, chitosan/graphene nanofibers have been pragmatically used for antibacterial materials and membranes [77]. The dispersion of graphene and GO nanosheets in polymeric nanofibers and membranes has been considered for the enhancement of properties [78]. Furthermore, nanocomposite membranes have superior interfacial interactions between the matrix and nanofillers, leading to superior physical properties [79,80]. In nanofiber membranes, the dispersal of nanoparticles controls the crusade of molecules through the system. Polymer/graphene nanofiber nanocomposites have been frequently fabricated using electrostatic spinning [81,82], melt spinning [83], wet spinning [84], and several other techniques. Electrostatic spinning or electrospinning is a technique which uses electric force to draw polymer fibers from a solution/melt. Melt spinning is an extrusion process used for fiber formation. The desired polymer is melted for extrusion through a spinneret and fibers are solidified by cooling. The wet spinning method is used to form fibers from a polymer solution through spinning. Among these methods, the electrospinning technique has been commonly espoused for nanocomposite nanofibers [85]. Polymer/graphene nanofiber and related nanocomposite membranes have exceptional electrical conductivity, mechanical strength, thermal stability, antibacterial, purification, and permeation properties [86–89]. An important recent study was reported by Ali et al. [90]. They prepared chitosan/gelatin nanofiber (GS/GL NF) scaffolds containing graphene nanosheets for wound healing. Figure 3 shows the electrospinning process and parameters used to form the GS/GL NF. The transmission electron microscopy (TEM) image shows the reinforcement of graphene nanosheets in the GS/GL NF (Figure 4). The arrows were used to point to the graphene nanosheets within the nanofibers. Figure 5 reveals the porosities of the electrospun nanofibrous membranes. The electrospinning method was found to enhance the porosity of the nanofibers up to 0.15 wt.% graphene loading.

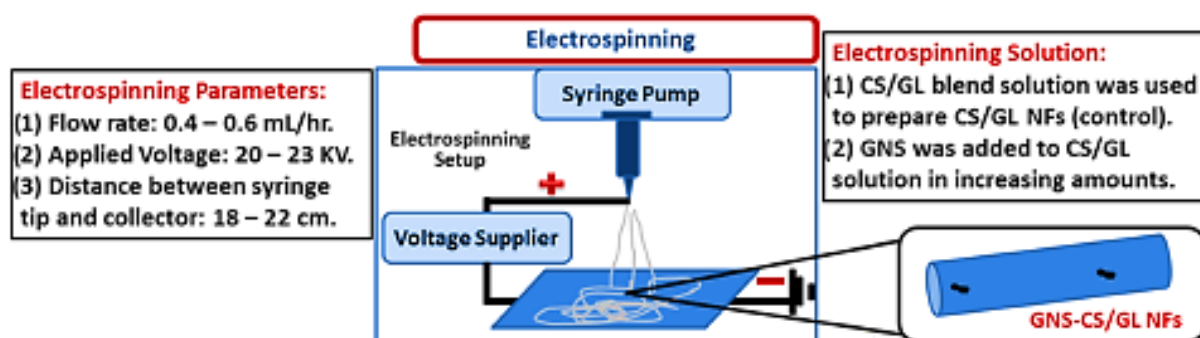


Figure 3. Schematic of electrospun nanofiber formation [90]. GS/GL NF—chitosan/gelatin nano fiber; GNS—graphene nanosheet. Reproduced with permission from ref. [90]. Copyright 2022 American Chemical Society.

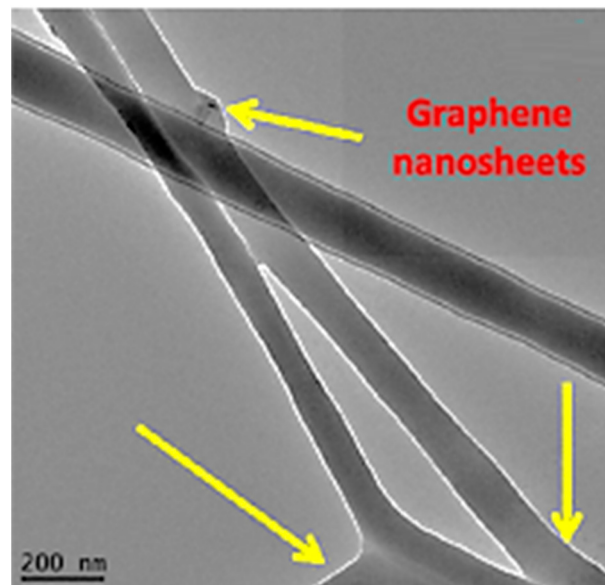


Figure 4. TEM image of 0.15 wt.% graphene-loaded chitosan/gelatin nanofibers [90]. Reproduced with permission from ref. [90]. Copyright 2022 American Chemical Society.

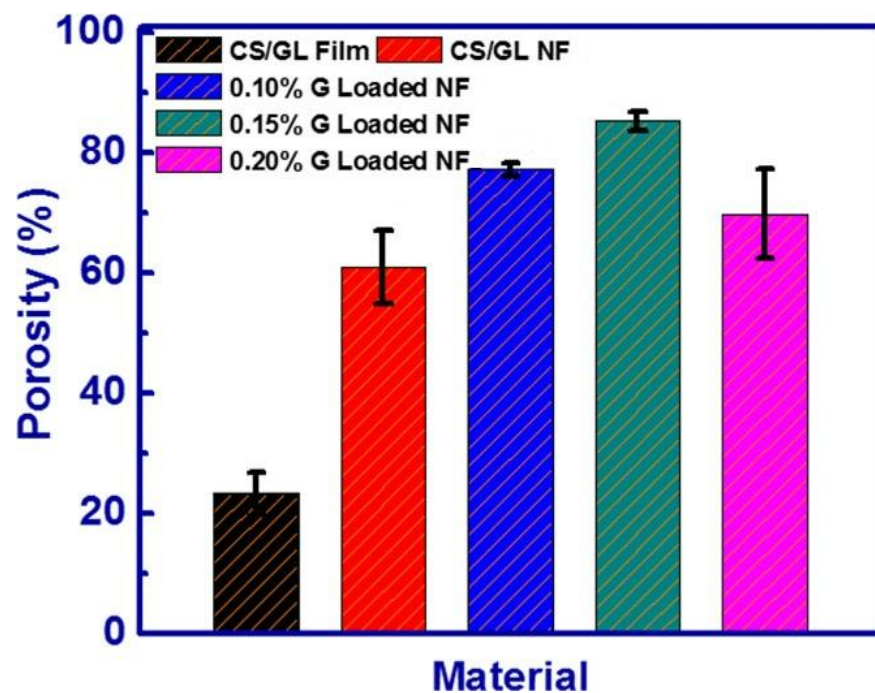


Figure 5. Porosity % of the fabricated nanofiber scaffolds [90]. GS/GL NF—chitosan/gelatin nano fiber. Reproduced with permission from ref. [90]. Copyright 2022 American Chemical Society.

Electrospun poly(vinyl fluoride)/GO nanofiber-based membranes were developed [56]. The membranes were used for arsenate removal. The maximum adsorption capacity obtained was over 180 mg/g. The polymer nanofiber/graphene or graphene oxide-based membranes were beneficially applied in oil–water separation [91], water treatment [92], and radiation shielding materials [93]. High-performance advantages of polymer nanofiber/graphene membranes relative to polymer/graphene nanocomposites were observed due to the high surface area provided by the polymeric nanofibers [94].

5. Polymer/Graphene Nanocomposite Membranes for Water Permeation

Primarily, the application of polymer/graphene nanocomposites has focused on the synthesis aspects [95–97]. Nanocomposites constructed using graphene nanofillers had a light weight, low cost, durability, and high strength [98]. Despite traditional composites, polymer/graphene nanocomposites have been employed and designed with facile techniques and advanced properties [99]. Water treatment methodologies have engaged these membranes for the desalination and management of water [100]. The use of nanocomposite membranes with various polymers and nanoparticles has been adopted in membrane technology [101,102]. Nanocomposite membranes have had several of their properties enhanced, including their specific porosity, hydrophilicity, robustness, heat stability, permeability, and selectivity. Phase inversion and solution casting methods have been commonly applied for the preparation of nanocomposite membranes [103]. Different types of phase inversion methods have been used to form membranes, such as precipitation from the solution precipitation, vapor phase, precipitation by controlled evaporation, thermally induced phase separation, and immersion precipitation, etc. [104]. The most commonly used technique is the solvent-based phase inversion. Figure 6 portrays the fabrication of nanocomposite membranes through this phase inversion technique [105].

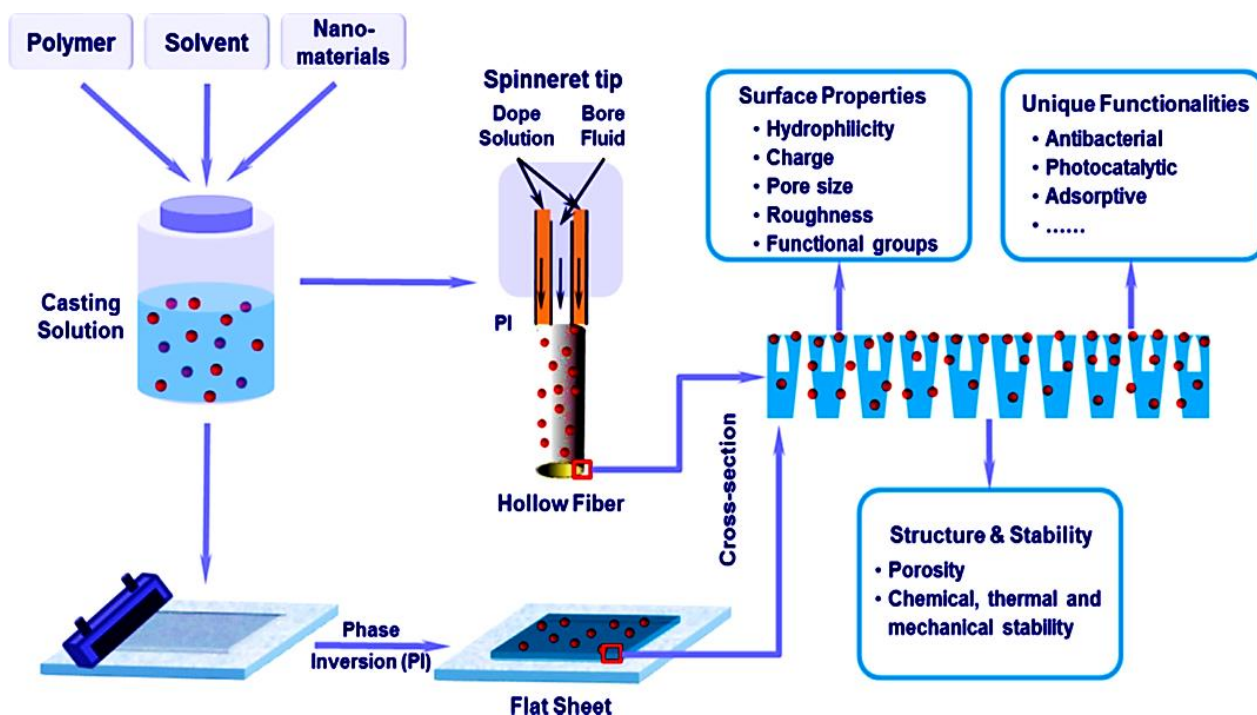


Figure 6. Fabrication of conventional nanocomposite membranes. Reproduced with permission from ref. [15]. Copyright 2015 Elsevier.

Polymers such as polysulfone [106], nylon [107], poly(vinyl acetate) [108], poly(vinyl alcohol) [109], etc., have been effectively used with graphene and GO nanoparticles. Phase inversion-generated nanocomposite membranes have been used for nanofiltration, micro-filtration, or ultrafiltration processes. The choice of solvent used in the phase inversion technique may cause a better dispersion of the graphene and GO nanoparticles in the polymer matrices [110,111].

5.1. Poly(Vinyl Alcohol) Membranes with Graphene Nanofiller

Poly(vinyl alcohol) (PVA) and graphene or GO-derived nanocomposites have been previously mentioned [109,112]. Hydrophilic GO-developed hydrogen bonding interactions with a PVA matrix. Das et al. [113] formed poly(vinyl alcohol)/graphene oxide (PVA/GO)

membranes through electrospinning. The PVA/GO membrane had high crystallinity and thermal stability characteristics. In some cases, graphene or GO have been used as the major matrix material to form membranes [114]. Sun et al. [115] formed poly(vinyl alcohol)/graphene oxide (PVA/GO)-based pervaporation desalination membranes. The PVA/GO crosslinked membranes were prepared using the pressure-assisted filtration technique on cellulose microfiltration substrate. Figure 7 illustrates the membrane fabrication stages. In these membranes, GO was used as a major matrix material and PVA was used as a binder. Figure 8 displays the brick–mortar model for the neat GO and PVA/GO membranes. The nanocomposite membranes with various GO contents exposed the intercalated nanostructure. The diffusion permeability of the nanocomposite membrane was dependent on the GO loading. The 10 wt.% GO-loaded membrane had a water flux of $98.1 \text{ kg m}^{-2} \text{ h}^{-1}$ and a salt rejection of 99.9%. The membranes revealed a fine capability to handle a high brine concentration.

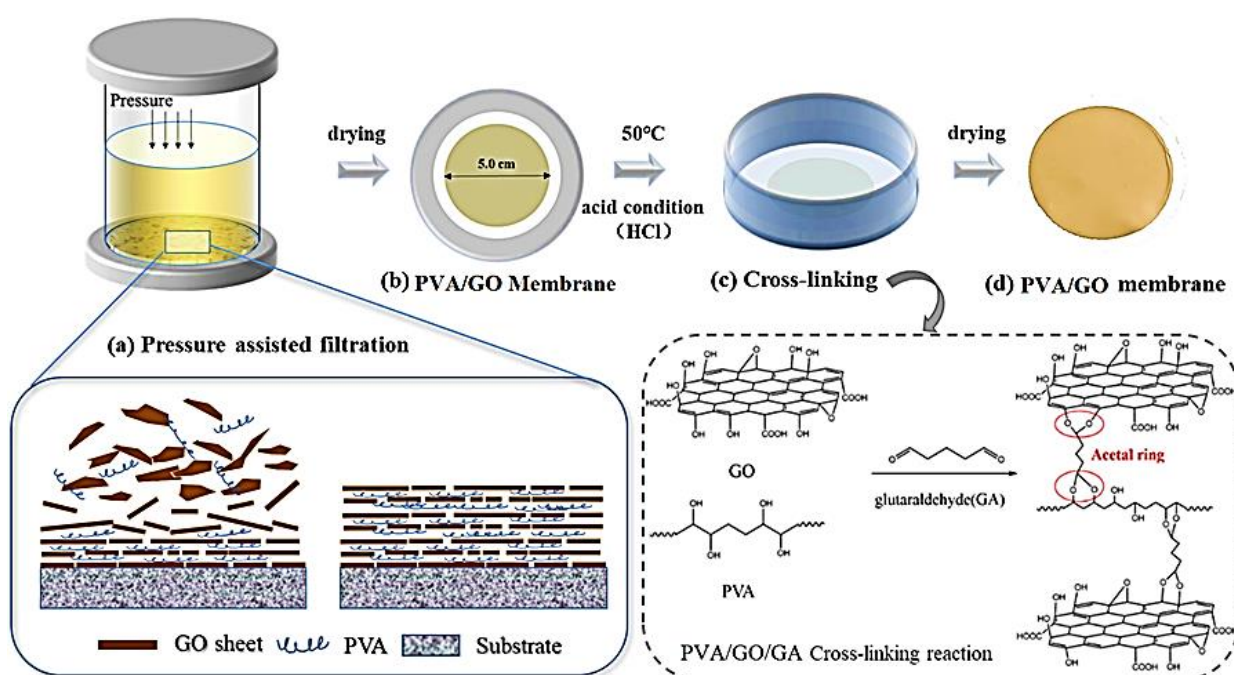


Figure 7. Schematic of GO membrane fabrication: (a) pressure-assisted filtration step for construction of PVA/GO thin layer on a microfiltration substrate; (b) formation of PVA/GO membrane after drying; (c) crosslinking treatment of PVA/GO membrane; and (d) formation of crosslinked PVA/GO membrane after drying [115]. GO—graphene oxide; PVA—poly (vinyl alcohol); PVA/GO—poly (vinyl alcohol)/graphene oxide. Reproduced with permission from ref. [115]. Copyright 2020 Elsevier.

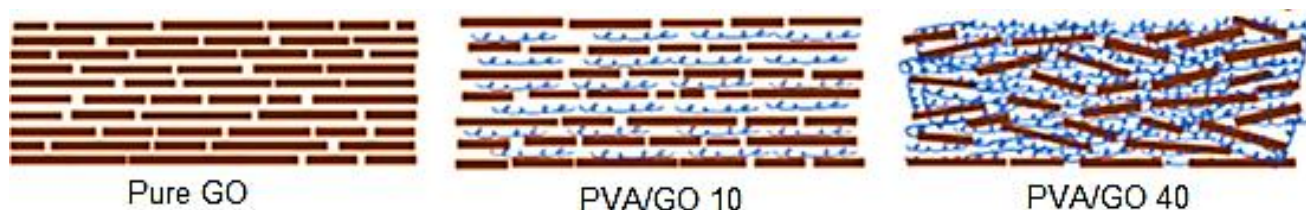


Figure 8. The brick–mortar model of pure GO and PVA/GO intercalated membranes [115]. GO—graphene oxide; PVA/GO—poly (vinyl alcohol)/graphene oxide. Reproduced with permission from ref. [115]. Copyright 2020 Elsevier.

Castro-Muñoz et al. [116] fabricated a PVA/GO nanocomposite membrane through the solution method. The membranes were used for the dehydration of ethanol. Figure 9 demonstrates the water permeation mechanism through the PVA/GO nanocomposite

membrane. The GO nanosheet possessed a d-spacing of $\sim 5 \text{ \AA}$, which was larger than the ethanol molecule diameter of $4.5 \text{ \AA}$. Therefore, the nanosheet allowed the passage and permeation of ethanol molecules. Consequently, the separation process was promoted. The 1 wt.% GO-loaded membrane revealed a permeate flux of $\sim 0.137 \text{ kg m}^{-2} \text{ h}^{-1}$. The PVA/graphene nanocomposite membranes revealed a successful enhancement of water flux and salt rejection features.

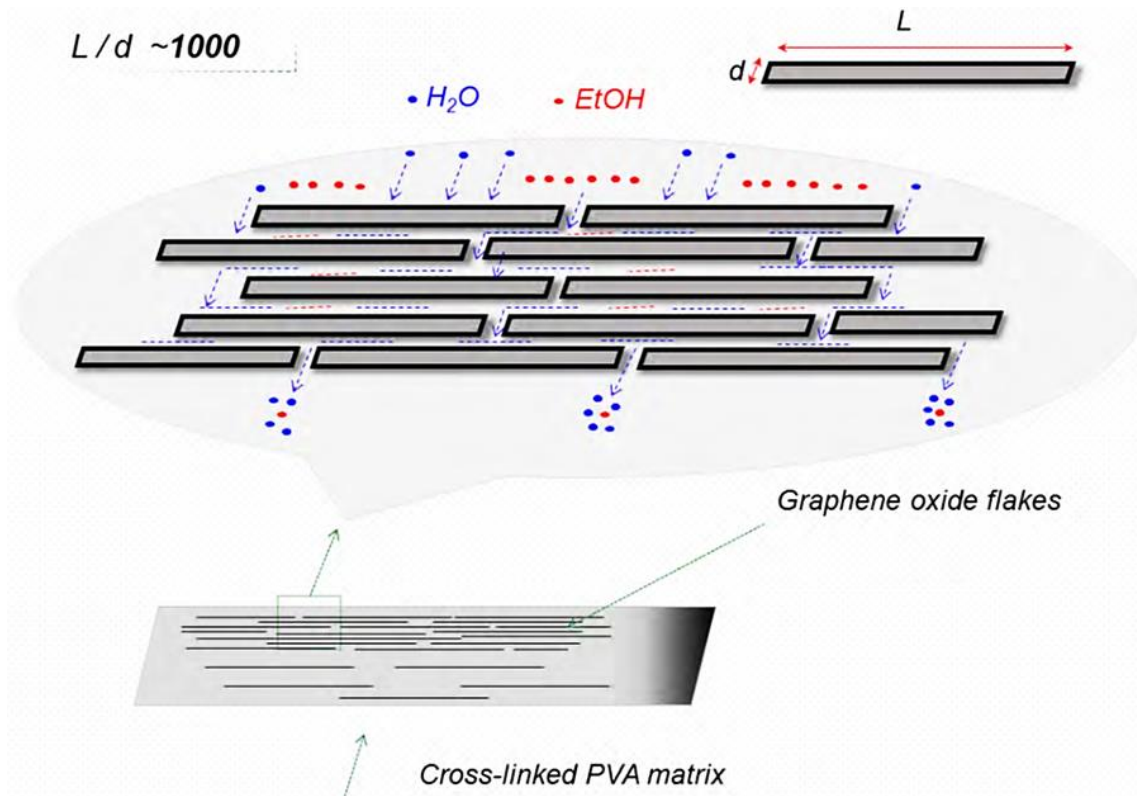


Figure 9. Schematic of water permeation mechanism through PVA/GO laminates [116]. PVA/GO—poly (vinyl alcohol)/graphene oxide. Reproduced with permission from ref. [116]. Copyright 2019 Elsevier.

5.2. Poly(Vinyl Acetate)/Graphene Nanocomposite Membranes

Poly(vinyl acetate) (PVAc) and graphene nanocomposite have previously been established [117,118]. Zhang et al. [119] fabricated PVAc and GO-derived nanocomposite membranes. Interactions between the PVAc matrix and GO nanosheets were observed. Kolya et al. [120] prepared PVAc, reduced graphene oxide (rGO), and a poly(diallyl dimethylammonium chloride) (PDADA)-derived nanocomposite membrane using the solution method. The hydrophobic properties of PVAc were enhanced by using PPDA-modified rGO. The contact angle of the PVAc/rGO/PPDA membrane was 188% higher than the neat PVAc (21%). More research efforts are desired in the field of PVAc and functional graphene membranes.

5.3. Poly(Vinyl Chloride)/Graphene Nanocomposite Membranes

The polyvinyl chloride (PVC) nanocomposites filled with graphene nanofillers have previously been reported on [121–123]. Zhao et al. [124] designed poly(vinyl chloride) (PVC) and GO-based PVC/GO nanocomposite membranes using the phase inversion technique. A finger-like macrovoid structure was observed in the morphology of PVC and PVC/GO. In nanocomposite membranes, the GO addition destroyed the macrovoid appearance. The membrane was used for the filtration of bovine serum albumin (BSA). Figure 10 shows the permeation flux of the neat PVC and PVC/GO nanocomposite membranes for water

and BSA filtration. The hydrophilic nature of the PVC/GO membranes prevented the absorption of BSA on the membrane's surface.

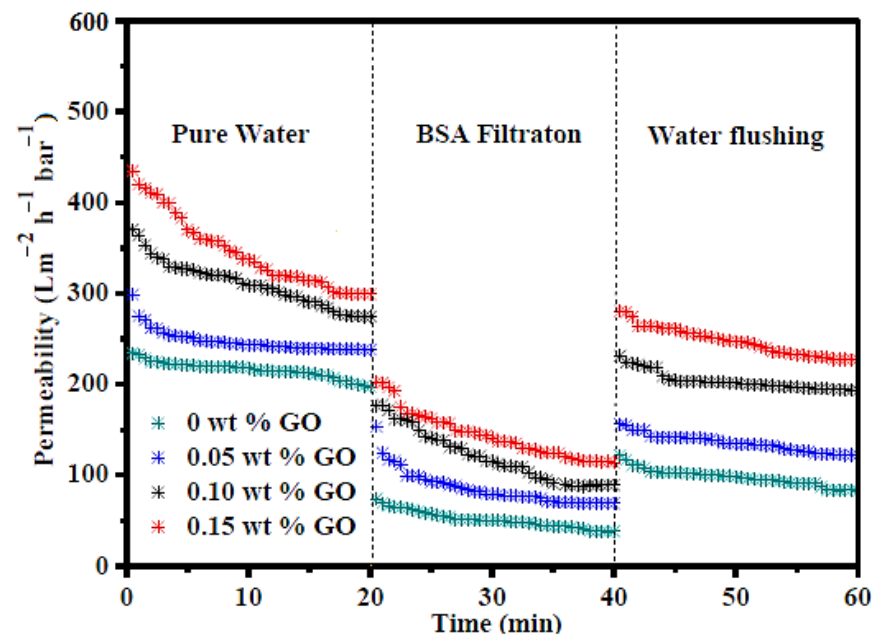


Figure 10. Permeation flux of fabricated PVC membranes incorporated with different amounts of GO before and after filtration of BSA solution [124]. PVC—poly (vinyl chloride); BSA—bovine serum albumin; GO—graphene oxide. Reproduced with permission from ref. [124]. Copyright 2016 Elsevier.

Namdar et al. [125] prepared PVC/GO membranes and studied their surface charge. The surface charge of neat PVC membrane was -8.72 mV, which changed to -33.17 mV with GO loading in the membrane. The electrostatic interaction between the functional GO and polymer caused this effect. Khakpour et al. [126] studied the roughness of PVC/GO membranes. This study revealed an enhancement in the surface roughness from 35 to 45 nm with an increasing nanofiller content from 0.05 to 0.15 wt.%. Subsequently, the polymer/graphene nanocomposite membranes have been effectively applied for water filtration and decontamination [127]. Nevertheless, polymer/graphene and polymer/graphene oxide nanocomposite membranes may suffer the shortcoming of membrane fouling. Moreover, the lifetime of these membranes needs to be improved.

5.4. Nylon 6/Graphene Nanocomposite Membranes

Nylon 6/graphene nanocomposites have gained much research attention [128,129]. Pant et al. [130] produced nylon 6/GO nanocomposite membranes using the solution route. A pore diameter of 14 nm was observed. The hydrogen bonding interaction was conducted between the nylon 6 and GO. Gong et al. [131] prepared the nylon 6/GO nanocomposite membranes through solution phase processing. A homogeneous dispersion of GO was observed in nylon 6. Li et al. [132] used in situ polymerization for the formation of the nylon 6/graphene nanocomposite membrane. The 0.7 wt.% graphene addition heightened the mechanical, tribological, and membrane properties of the nylon 6 membrane. Mehrani et al. [133] prepared the nylon 6/GO with poly(m-aminophenol) through the use of the electrospinning method. These membranes had the capability to separate a milk and water solution up to 88–101%.

5.5. Polysulfone/Graphene Nanocomposite Membranes

Polysulfone (PSF) and graphene-based nanocomposites have previously been reported on [134–136]. Ammar et al. [137] industrialized PSF and GO-derived nanocomposite membranes. The morphology of the membranes was studied by using microscopic techniques.

The water flux of the nanocomposite membranes was enhanced with the addition of GO due to the hydrophilic nature and hydrogen bonding between the matrix and nanofiller [138]. Rezaee et al. [139] fabricated polysulfone/graphene oxide (PSF/GO) membranes through the use of the solution casting method. The membranes had up to a 2 wt.% GO content. Atomic force microscopy (AFM) was employed to study the membrane morphology (Figure 11). The deep dark areas in the three-dimensional images revealed the existence of nanopores in the membranes. The bright bulging areas indicated the polymer matrix. The mean surface roughness of the neat polymer was 2.9 ± 0.23 nm, which was decreased to 2.5 ± 0.30 nm with 1 wt.% GO loading. The graphene loading revealed an electrostatic interaction and a good compatibility with the membrane matrix, and so the roughness was decreased [140–142]. Moreover, the GO loading of up to 1 wt.% increased the charge and zeta potential of the membranes. Figure 12 shows the influence of pH on the rejection rate of arsenate (As). The rejection rate was enhanced with increasing pH values (Table 1). Ganesh et al. [143] formed polysulfone and graphene oxide-based PSF/GO nanocomposite membranes. They used the wet phase inversion technique to fabricate the membranes [144]. Figure 13 depicts the change in the water uptake of PSF/GO nanocomposite membranes with a growing pH. The water uptake was enhanced with the level of GO loading. This effect was observed due to the hydrophilic nature of GO.

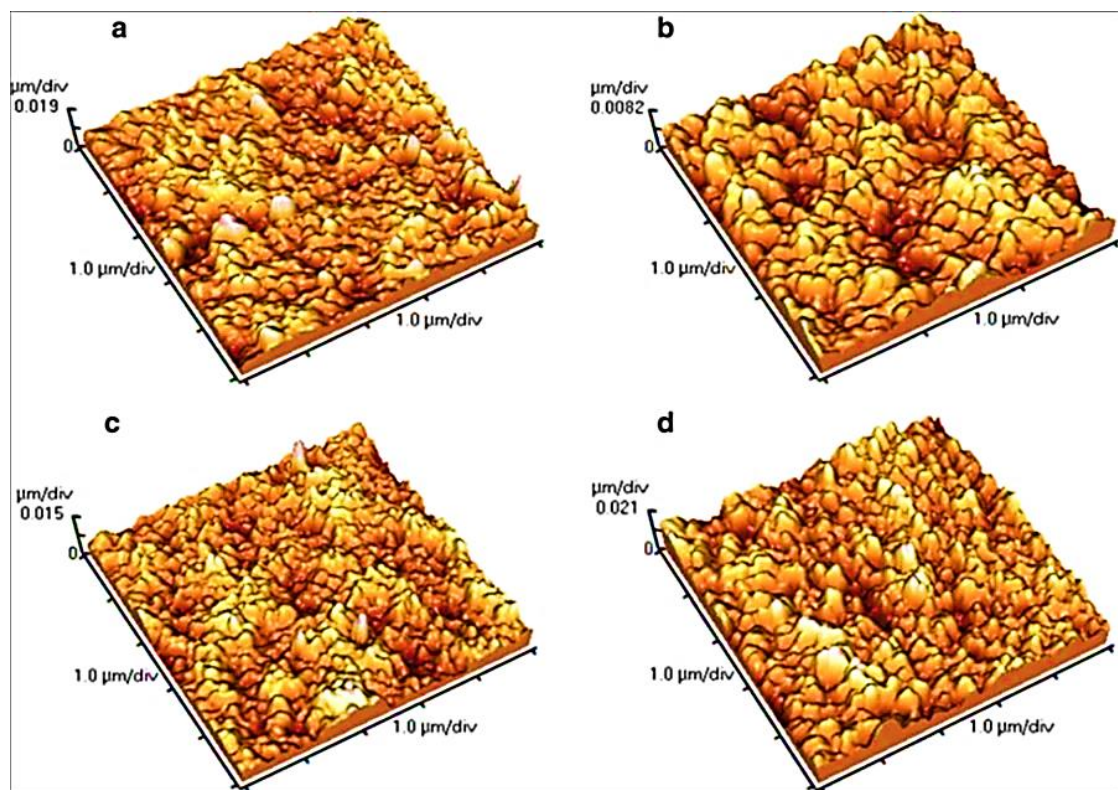


Figure 11. AFM three-dimensional surface morphology of prepared membranes (a) pure PSF; (b) PSF/GO 0.5; (c) PSF/GO 1; (d) PSF/GO 2 membranes [139]. PSF—polysulfone; PSF/GO—polysulfone/graphene oxide; AFM—atomic force microscopy. Reproduced with permission from ref. [139]. Copyright 2015 Springer.

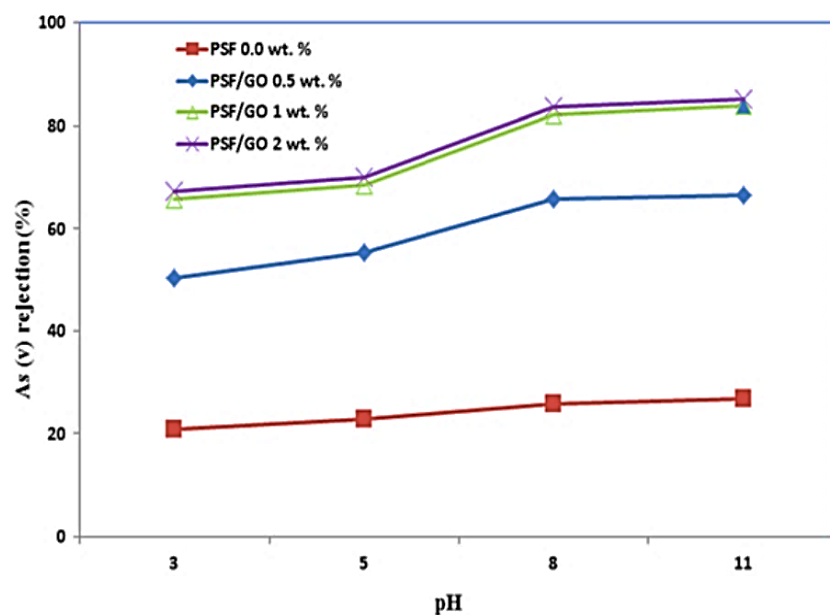


Figure 12. Percentage rejection of As (V) at different pH by prepared membranes with various GO contents (operating pressure = 4 bar; initial As (V) concentration = 300 ± 10 $\mu\text{g/L}$; feed temperature = 25 ± 0.5 $^{\circ}\text{C}$) [139]. As—arsenate; PSF—polysulfone; PSF/GO—polysulfone/graphene oxide. Reproduced with permission from ref. [139]. Copyright 2015 Springer.

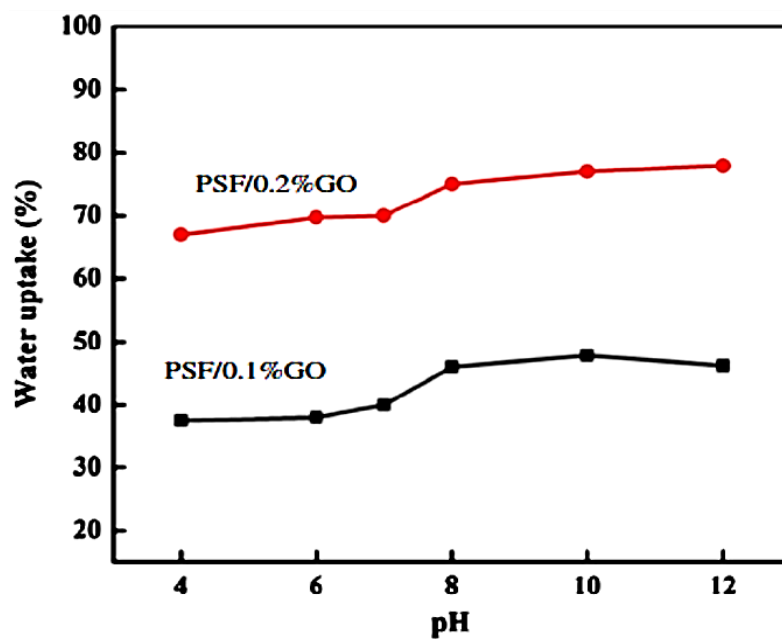


Figure 13. The effect of pH on water uptake for PSF/GO membranes [143]. PSF/GO—polysulfone/graphene oxide. Reproduced with permission from ref. [143]. Copyright 2013 Elsevier.

Table 1. Effect of GO content on water contact angle, pure water flux, and pore structure parameters of the prepared membranes [139]. PSF—polysulfone; PSF/GO—polysulfone/graphene oxide. Reproduced with permission from ref. [139]. Copyright 2015 Springer.

Membrane	Contact Angle	Pure Water Flux (L/m ² h)	Porosity (%)	Pore Diameter (nm)
Pure PSF	73.5 ± 2.1	19.7 ± 3.2	48.3 ± 2.6	6.9 ± 0.56
PSF/GO 0.5	66.7 ± 1.6	32.3 ± 3.5	77.9 ± 2.2	8.3 ± 0.31
PSF/GO 1	51.3 ± 1.2	49.9 ± 2.6	86.5 ± 1.8	9.1 ± 0.63
PSF/GO 2	54.8 ± 1.4	46.4 ± 2.0	82.1 ± 2.6	8.7 ± 0.42

Lai et al. [145] prepared thin film nanocomposite membranes of crosslinked polysulfone and polyamide using interfacial polymerization. The GO nanosheets were embedded in the matrices. TEM images of the polysulfone/polyamide membrane and polysulfone/polyamide/graphene oxide membranes are given in Figure 14. The GO nanosheets could be obviously seen in the 0.02 wt.% GO-loaded membrane, whereas these nanosheets were not perceived in the neat polymer membrane.

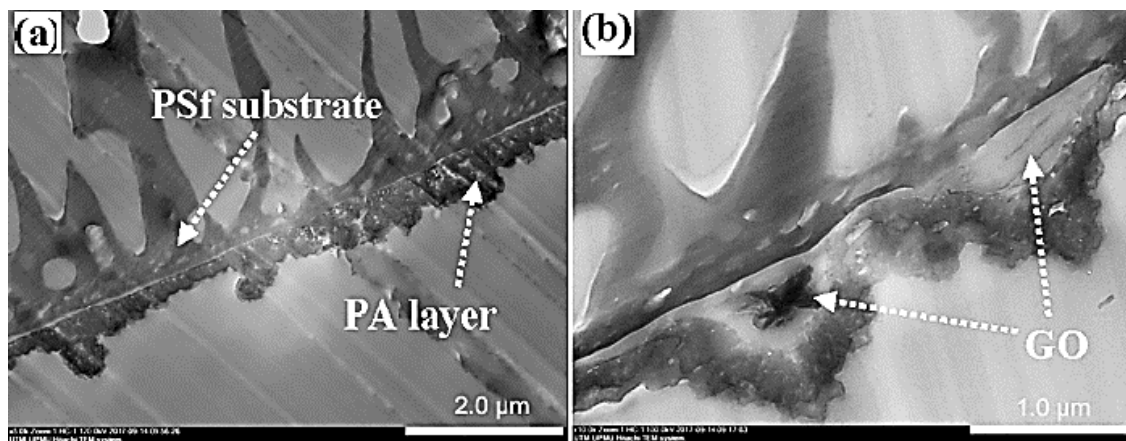


Figure 14. TEM cross-sectional images of (a) polysulfone/polyamide and (b) polymer with 0.02 wt.% GO membranes [145]. Reproduced from ref. [145]. Copyright 2018 Elsevier.

6. Compensations/Shortcomings of Graphene Nanocomposites in Membrane Technology

The use of polymeric membranes with nanofillers, such as carbon nanotubes and metal oxides, is preferred, since other inorganic nanoparticles may involve a high toxicity, cost, processability issues, etc. [146–148]. Conversely, graphene nanocomposites have the advantages of flexibility, stability, environmental friendliness, and no involvement of harmful or toxic solvents. Such nanocomposites have a high dispersion and alignment properties of graphene materials, promoting a better diffusion, water flux, and barrier features of the membranes. Moreover, polymer/graphene nanocomposite membranes have a fine structural flexibility, high flux, high permeation, salt rejection, and high ion or desired species-related separation properties. Nevertheless, graphene nanocomposites may have several shortcomings. Most importantly, polymer/graphene nanomaterials may possess the problem of graphene nanoflake aggregation. The surface of graphene needs to be functionalized for a better dispersal in polymers and well-matched interfaces in the matrix–nanofiller. Some graphene oxide and modified graphene nanostructures have been developed to design functional membrane nanomaterials. Still, up till now, very few amalgamations of graphene and polymer-based membranes have been identified. The crucial thoughtfulness of the structure–property relationships of polymer/graphene membranes has been found to be essential for future developments. Thus, research concerning

polymer/graphene-derived membranes has been an emerging field, expecting further research attention in the future [149].

7. Future and Summary

The essential features of graphene-based nanocomposite membranes were investigated [150]. Polymer/graphene nanocomposite membranes such as PVC/graphene, PVAc/graphene, PVA/graphene, PSF/graphene, and nylon 6/graphene were studied for their morphology, high barrier, water uptake, flux, toxins removal, desalination, and permeation characteristics. The initial function of graphene is to offer membranes mechanical features such as strength, toughness, and flexibility. Graphene dispersion and interactions with polymers have been found to augment membrane properties. The matrix–nanofiller associations and compatibility have been found to be indispensable for the enhancement of membrane performance. The dispersal and alignment of graphene and graphene oxide develop the aligned nanostructure for the diffusion and permeation of the membranes. In these membranes, the pore structure, wettability, and nanoparticle scattering may promote the transmission and purification of water. Graphene-dispersed nanofibers have also been used to develop membranes for filtration and permeation purposes. Consequently, the barrier properties of polymer/graphene and polymer graphene oxide membranes may affect the membrane properties. The morphology and pore structure of the membranes may fluently transport molecules through the graphene-dispersed membranes.

The major limitations in membrane separation processes were identified as fouling, shrinkage, and hydrophobicity [151]. Fouling is the phenomena of the deposition of particles/colloids, salts, or other molecules inside the pores of membranes during filtration. This leads to a decrease in the permeation flux, membrane life, durability, and selectivity properties during filtration. The main reason for fouling was recognized as the hydrophobicity of the membranes. Most of the polymeric membranes are hydrophobic due to the lack of a functional group in the backbone [152]. To overcome these drawbacks, the inclusion of graphene and graphene derivatives may impart important features onto the membranes such as hydrophilicity to prevent antifouling and enhance the durability and self-cleaning properties.

Hence, the potential of polymer/graphene membranes, including nanofibrous membranes, was explored in this article. Graphene and its derivatives may overcome challenges in the way of the promising future of membrane nanomaterials.

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References

1. Nunes, S.P.; Peinemann, K.-V. *Membrane Technology: In the Chemical Industry*; John Wiley & Sons: Hoboken, NJ, USA, 2006.
2. Singh, R.; Singh, M.; Kumari, N.; Janak; Maharana, S.; Maharana, P. A Comprehensive Review of Polymeric Wastewater Purification Membranes. *J. Compos. Sci.* **2021**, *5*, 162. [\[CrossRef\]](#)
3. Kausar, A. Conjugated Polymer/Graphene Oxide Nanocomposites—State-of-the-Art. *J. Compos. Sci.* **2021**, *5*, 292. [\[CrossRef\]](#)
4. Kumar, S.R.; Wang, J.-J.; Wu, Y.-S.; Yang, C.-C.; Lue, S.J. Synergistic role of graphene oxide-magnetite nanofillers contribution on ionic conductivity and permeability for polybenzimidazole membrane electrolytes. *J. Power Sources* **2020**, *445*, 227293. [\[CrossRef\]](#)
5. Choi, J.-Y.; Park, H.-B. Separation Membrane Including Graphene. EP2511002B1, 14 May 2014.

6. Yang, H.-C.; Hou, J.; Chen, V.; Xu, Z.-K. Surface and interface engineering for organic-inorganic composite membranes. *J. Mater. Chem. A* **2016**, *4*, 9716–9729. [\[CrossRef\]](#)
7. Mohammad, A.W.; Teow, Y.; Ang, W.L.; Chung, Y.T.; Oatley-Radcliffe, D.; Hilal, N. Nanofiltration membranes review: Recent advances and future prospects. *Desalination* **2015**, *356*, 226–254. [\[CrossRef\]](#)
8. Murthy, Z.; Gaikwad, M.S. Preparation of chitosan-multiwalled carbon nanotubes blended membranes: Characterization and performance in the separation of sodium and magnesium ions. *Nanoscale Microscale Thermophys. Eng.* **2013**, *17*, 245–262. [\[CrossRef\]](#)
9. Dai, X.; Wu, S.; Li, S. Progress on electrochemical sensors for the determination of heavy metal ions from contaminated water. *J. Chin. Adv. Mater. Soc.* **2018**, *6*, 91–111. [\[CrossRef\]](#)
10. Szeluga, U.; Kumanek, B.; Trzebicka, B. Synergy in hybrid polymer/nanocarbon composites. A review. *Compos. Part A Appl. Sci. Manuf.* **2015**, *73*, 204–231. [\[CrossRef\]](#)
11. Wu, Z.Y.; Liang, H.-W.; Hu, B.-C.; Yu, S.-H. Emerging Carbon-Nanofiber Aerogels: Chemosynthesis versus Biosynthesis. *Angew. Chem. Int. Ed.* **2018**, *57*, 15646–15662. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Miculescu, M.; Thakur, V.K.; Miculescu, F.; Voicu, S.I. Graphene-based polymer nanocomposite membranes: A review. *Polym. Adv. Technol.* **2016**, *27*, 844–859. [\[CrossRef\]](#)
13. Kobylukh, A.; Olszowska, K.; Szeluga, U.; Pusz, S. Iron oxides/graphene hybrid structures—Preparation, modification, and application as fillers of polymer composites. *Adv. Colloid Interface Sci.* **2020**, *285*, 102285. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Dhand, V.; Rhee, K.; Kim, H.J.; Jung, D.H. A comprehensive review of graphene nanocomposites: Research status and trends. *J. Nanomater.* **2013**, *2013*, 763953. [\[CrossRef\]](#)
15. Yin, J.; Deng, B. Polymer-matrix nanocomposite membranes for water treatment. *J. Membr. Sci.* **2015**, *479*, 256–275. [\[CrossRef\]](#)
16. Bae, T.-H.; Tak, T.-M. Preparation of TiO₂ self-assembled polymeric nanocomposite membranes and examination of their fouling mitigation effects in a membrane bioreactor system. *J. Membr. Sci.* **2005**, *266*, 1–5. [\[CrossRef\]](#)
17. Souza, V.; Quadri, M. Organic-inorganic hybrid membranes in separation processes: A 10-year review. *Braz. J. Chem. Eng.* **2013**, *30*, 683–700. [\[CrossRef\]](#)
18. Song, J.; Wu, X.; Zhang, M.; Liu, C.; Yu, J.; Sun, G.; Si, Y.; Ding, B. Highly flexible, core-shell heterostructured, and visible-light-driven titania-based nanofibrous membranes for antibiotic removal and *E. coli* inactivation. *Chem. Eng. J.* **2020**, *379*, 122269. [\[CrossRef\]](#)
19. Pi, Y.; Li, X.; Xia, Q.; Wu, J.; Li, Y.; Xiao, J.; Li, Z. Adsorptive and photocatalytic removal of Persistent Organic Pollutants (POPs) in water by metal-organic frameworks (MOFs). *Chem. Eng. J.* **2018**, *337*, 351–371. [\[CrossRef\]](#)
20. Wang, D.K.; Elma, M.; Motuzas, J.; Hou, W.-C.; Xie, F.; Zhang, X. Rational design and synthesis of molecular-sieving, photocatalytic, hollow fiber membranes for advanced water treatment applications. *J. Membr. Sci.* **2017**, *524*, 163–173. [\[CrossRef\]](#)
21. Shen, L.; Huang, Z.; Liu, Y.; Li, R.; Xu, Y.; Jakaj, G.; Lin, H. Polymeric membranes incorporated with ZnO nanoparticles for membrane fouling mitigation: A brief review. *Front. Chem.* **2020**, *8*. [\[CrossRef\]](#)
22. Alian, A.; Dewapriya, M.; Meguid, S. Molecular dynamics study of the reinforcement effect of graphene in multilayered polymer nanocomposites. *Mater. Des.* **2017**, *124*, 47–57. [\[CrossRef\]](#)
23. Gao, X.; Li, Y.; Yang, X.; Shang, Y.; Wang, Y.; Gao, B.; Wang, Z. Highly permeable and antifouling reverse osmosis membranes with acidified graphitic carbon nitride nanosheets as nanofillers. *J. Mater. Chem. A* **2017**, *5*, 19875–19883. [\[CrossRef\]](#)
24. Li, C.; Chou, T.-W. Elastic moduli of multi-walled carbon nanotubes and the effect of van der Waals forces. *Compos. Sci. Technol.* **2003**, *63*, 1517–1524. [\[CrossRef\]](#)
25. Jeffrey, G.A.; Saenger, W. *Hydrogen Bonding in Biological Structures*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 1991.
26. De Andres, P.; Ramírez, R.; Vergés, J.A. Strong covalent bonding between two graphene layers. *Phys. Rev. B* **2008**, *77*, 045403. [\[CrossRef\]](#)
27. Xie, M.; Shon, H.K.; Gray, S.R.; Elimelech, M. Membrane-based processes for wastewater nutrient recovery: Technology, challenges, and future direction. *Water Res.* **2016**, *89*, 210–221. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Liu, G.; Jin, W.; Xu, N. Two-dimensional-material membranes: A new family of high-performance separation membranes. *Angew. Chem. Int. Ed.* **2016**, *i*, 13384–13397. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Yoo, B.M.; Shin, H.J.; Yoon, H.W.; Park, H.B. Graphene and graphene oxide and their uses in barrier polymers. *J. Appl. Polym. Sci.* **2014**, *131*. [\[CrossRef\]](#)
30. Novoselov, K.S.; Geim, A.K.; Morozov, S.V.; Jiang, D.; Zhang, Y.; Dubonos, S.V.; Grigorieva, I.V.; Firsov, A.A. Electric field effect in atomically thin carbon films. *Science* **2004**, *306*, 666–669. [\[CrossRef\]](#)
31. Cai, D.; Song, M. Recent advance in functionalized graphene/polymer nanocomposites. *J. Mater. Chem.* **2010**, *20*, 7906–7915. [\[CrossRef\]](#)
32. Wang, Y.; Yang, G.; Wang, W.; Zhu, S.; Guo, L.; Zhang, Z.; Li, P. Effects of different functional groups in graphene nanofiber on the mechanical property of polyvinyl alcohol composites by the molecular dynamic simulations. *J. Mol. Liq.* **2019**, *277*, 261–268. [\[CrossRef\]](#)
33. Gao, Y.; Zhang, Y.; Chen, P.; Li, Y.; Liu, M.; Gao, T.; Ma, D.; Chen, Y.; Cheng, Z.; Qiu, X.; et al. Toward single-layer uniform hexagonal boron nitride-graphene patchworks with zigzag linking edges. *Nano Lett.* **2013**, *13*, 3439–3443. [\[CrossRef\]](#)

34. Huang, P.Y.; Ruiz-Vargas, C.S.; van der Zande, A.M.; Whitney, W.S.; Levendorf, M.P.; Kevek, J.W.; Garg, S.; Alden, J.S.; Hustedt, C.J.; Zhu, Y.; et al. Grains and grain boundaries in single-layer graphene atomic patchwork quilts. *Nature* **2011**, *469*, 389–392. [[CrossRef](#)] [[PubMed](#)]
35. Berger, C.; Song, Z.; Li, X.; Wu, X.; Brown, N.; Naud, C.; Mayou, D.; Li, T.; Hass, J.; Marchenkov, A.N.; et al. Electronic confinement and coherence in patterned epitaxial graphene. *Science* **2006**, *312*, 1191–1196. [[CrossRef](#)]
36. Hong, N.; Kireev, D.; Zhao, Q.; Chen, D.; Akinwande, D.; Li, W. Roll-to-Roll Dry Transfer of Large-Scale Graphene. *Adv. Mater.* **2022**, *34*, 2106615. [[CrossRef](#)]
37. Chen, X.; Fan, K.; Liu, Y.; Li, Y.; Liu, X.; Feng, W.; Wang, X. Recent advances in fluorinated graphene from synthesis to applications: Critical review on functional chemistry and structure engineering. *Adv. Mater.* **2022**, *34*, 2101665. [[CrossRef](#)] [[PubMed](#)]
38. Fadil, Y.; Thickett, S.C.; Agarwal, V.; Zetterlund, P.B. Synthesis of graphene-based polymeric nanocomposites using emulsion techniques. *Prog. Polym. Sci.* **2022**, *125*, 101476. [[CrossRef](#)]
39. Narayanam, P.K.; Botcha, V.D.; Ghosh, M.; Major, S.S. Growth and Photocatalytic Behaviour of Transparent Reduced GO-ZnO Nanocomposite Sheets. *Nanotechnology* **2019**, *30*, 485601. [[CrossRef](#)] [[PubMed](#)]
40. Liang, J.; Li, L.; Tong, K.; Ren, Z.; Hu, W.; Niu, X.; Chen, Y.; Pei, Q. Silver nanowire percolation network soldered with graphene oxide at room temperature and its application for fully stretchable polymer light-emitting diodes. *ACS Nano* **2014**, *8*, 1590–1600. [[CrossRef](#)]
41. Zandiatashbar, A.; Lee, G.-H.; An, S.J.; Lee, S.; Mathew, N.; Terrones, M.; Hayashi, T.; Picu, C.R.; Hone, J.; Koratkar, N. Effect of defects on the intrinsic strength and stiffness of graphene. *Nat. Commun.* **2014**, *5*, 3186. [[CrossRef](#)]
42. Kausar, A. Potential of Polymer/Graphene Nanocomposite in Electronics. *Am. J. Nanosci. Nanotechnol. Res.* **2018**, *6*, 55–63.
43. Shen, X.J.; Zeng, X.L.; Dang, C.Y. Graphene Composites. In *Handbook of Graphene*; Wiley: Hoboken, NJ, USA, 2019; Volume 1, pp. 1–25.
44. Yang, S.-T.; Chang, Y.; Wang, H.; Liu, G.; Chen, S.; Wang, Y.; Liu, Y.; Cao, A. Folding/aggregation of graphene oxide and its application in Cu²⁺ removal. *J. Colloid Interface Sci.* **2010**, *351*, 122–127. [[CrossRef](#)]
45. Wang, W.-N.; Jiang, Y.; Biswas, P. Evaporation-induced crumpling of graphene oxide nanosheets in aerosolized droplets: Confinement force relationship. *J. Phys. Chem. Lett.* **2012**, *3*, 3228–3233. [[CrossRef](#)]
46. Zhou, Q.; Xia, G.; Du, M.; Lu, Y.; Xu, H. Scotch-tape-like exfoliation effect of graphene quantum dots for efficient preparation of graphene nanosheets in water. *Appl. Surf. Sci.* **2019**, *483*, 52–59. [[CrossRef](#)]
47. Pei, S.; Cheng, H.-M. The reduction of graphene oxide. *Carbon* **2012**, *50*, 3210–3228. [[CrossRef](#)]
48. Lee, H.; Lee, K.S. Interlayer Distance Controlled Graphene, Supercapacitor and Method of Producing the Same. US20150103469A1, 26 February 2019.
49. Omran, B.; Baek, K.-H. Graphene-derived antibacterial nanocomposites for water disinfection: Current and future perspectives. *Environ. Pollut.* **2022**, *298*, 118836. [[CrossRef](#)]
50. Wu, T.; Yang, Y.; Sun, W.; Yang, Z.; Wang, L.; Wang, J.; Liu, G. Unfolding graphene nanosheets towards high barrier performance of epoxy/graphene nanocomposite coating. *Compos. Part A Appl. Sci. Manuf.* **2022**, *153*, 106732. [[CrossRef](#)]
51. Ding, J.; Zhao, H.; Yu, H. Bio-inspired Multifunctional Graphene–Epoxy Anticorrosion Coatings by Low-Defect Engineered Graphene. *ACS Nano* **2022**, *16*, 710–720. [[CrossRef](#)] [[PubMed](#)]
52. Han, J.T.; Jang, J.I.; Cho, J.; Hwang, J.Y.; Woo, J.S.; Jeong, H.J.; Jeong, S.Y.; Seo, S.H.; Lee, G.-W. Synthesis of nanobelt-like 1-dimensional silver/nanocarbon hybrid materials for flexible and wearable electronics. *Sci. Rep.* **2017**, *7*, 1–9. [[CrossRef](#)]
53. Panwar, N.; Soehartono, A.M.; Chan, K.K.; Zeng, S.; Xu, G.; Qu, J.; Coquet, P.; Yong, K.-T.; Chen, X. Nanocarbons for biology and medicine: Sensing, imaging, and drug delivery. *Chem. Rev.* **2019**, *119*, 9559–9656. [[CrossRef](#)]
54. Kumar, R.; del Pino, A.P.; Sahoo, S.; Singh, R.K.; Tan, W.K.; Kar, K.K.; Matsuda, A.; Joanni, E. Laser processing of graphene and related materials for energy storage: State of the art and future prospects. *Prog. Energy Combust. Sci.* **2022**, *90*, 100981. [[CrossRef](#)]
55. Zhang, M.; Shan, Y.; Kong, Q.; Pang, H. Applications of Metal–Organic Framework–Graphene Composite Materials in Electrochemical Energy Storage. *FlatChem* **2022**, *32*, 100332. [[CrossRef](#)]
56. Obraztsov, I.; Bakandritsos, A.; Šedajová, V.; Langer, R.; Jakubec, P.; Zoppellaro, G.; Pykal, M.; Presser, V.; Otyepka, M.; Zbořil, R. Graphene Acid for Lithium-Ion Batteries—Carboxylation Boosts Storage Capacity in Graphene. *Adv. Energy Mater.* **2022**, *12*, 2103010. [[CrossRef](#)]
57. Aiswaria, P.; Mohamed, S.N.; Singaravelu, D.L.; Brindhadevi, K.; Pugazhendhi, A. A review on graphene/graphene oxide supported electrodes for microbial fuel cell applications: Challenges and prospects. *Chemosphere* **2022**, *15*, 133983.
58. Yang, Y.; Cheng, Y.; Yang, M.; Qian, G.; Peng, S.; Qi, F.; Shuai, C. Semicoherent strengthens graphene/zinc scaffolds. *Mater. Today Nano* **2022**, *17*, 100163. [[CrossRef](#)]
59. Yuan, M.; Teng, Z.; Wang, S.; Xu, Y.; Wu, P.; Zhu, Y.; Wang, C.; Wang, G. Polymeric carbon nitride modified polyacrylonitrile fabrics with efficient self-cleaning and water disinfection under visible light. *Chem. Eng. J.* **2020**, *391*, 123506. [[CrossRef](#)]
60. Huang, Y.H.; Huang, S.-H.; Chao, W.-C.; Li, C.-L.; Hsieh, Y.-Y.; Hung, W.-S.; Liaw, D.-J.; Hu, C.-C.; Lee, K.-R.; Lai, J.-Y. A study on the characteristics and pervaporation performance of polyamide thin-film composite membranes with modified polyacrylonitrile as substrate for bioethanol dehydration. *Polym. Int.* **2014**, *63*, 1478–1486. [[CrossRef](#)]
61. von Reitzenstein, N.H.; Baghirzade, B.S.; Pruitt, E.; Hristovski, K.; Westerhoff, P.; Apul, O.G. Comparing the morphologies and adsorption behavior of electrospun polystyrene composite fibers with 0D fullerenes, 1D multiwalled carbon nanotubes and 2D graphene oxides. *Chem. Eng. J. Adv.* **2022**, *9*, 100199. [[CrossRef](#)]

62. Kumar, T.S.M.; Kumar, K.S.; Rajini, N.; Siengchin, S.; Ayrilmis, N.; Rajulu, A.V. A comprehensive review of electrospun nanofibers: Food and packaging perspective. *Compos. Part B Eng.* **2019**, *175*, 107074. [\[CrossRef\]](#)
63. Akampumuza, O.; Gao, H.; Zhang, H.; Wu, D.; Qin, X. Raising nanofiber output: The progress, mechanisms, challenges, and reasons for the pursuit. *Macromol. Mater. Eng.* **2018**, *303*, 1700269. [\[CrossRef\]](#)
64. Lhotáková, Y.; Plíštil, L.; Morávková, A.; Kubát, P.; Lang, K.; Forstová, J.; Mosinger, J. Virucidal nanofiber textiles based on photosensitized production of singlet oxygen. *PLoS ONE* **2012**, *7*, e49226. [\[CrossRef\]](#) [\[PubMed\]](#)
65. Pham, Q.P.; Sharma, U.; Mikos, A.G. Electrospinning of polymeric nanofibers for tissue engineering applications: A review. *Tissue Eng.* **2006**, *12*, 1197–1211. [\[CrossRef\]](#) [\[PubMed\]](#)
66. El-Newehy, M.H.; Al-Deyab, S.S.; Kenawy, E.-R.; Abdel-Megeed, A. Fabrication of electrospun antimicrobial nanofibers containing metronidazole using nanospider technology. *Fibers Polym.* **2012**, *13*, 709–717. [\[CrossRef\]](#)
67. Wu, K.; Wang, J.; Liu, D.; Lei, C.; Liu, D.; Lei, W.; Fu, Q. Highly Thermoconductive, Thermostable, and Super-Flexible Film by Engineering 1D Rigid Rod-Like Aramid Nanofiber/2D Boron Nitride Nanosheets. *Adv. Mater.* **2020**, *32*, 1906939. [\[CrossRef\]](#)
68. Wang, J.; Long, Y.; Sun, Y.; Zhang, X.; Yang, H.; Lin, B. Enhanced energy density and thermostability in polyimide nanocomposites containing core-shell structured BaTiO₃@SiO₂ nanofibers. *Appl. Surf. Sci.* **2017**, *426*, 437–445. [\[CrossRef\]](#)
69. Le Petit, L.; Rabiller-Baudry, M.; Touin, R.; Chataignier, R.; Thomas, P.; Connan, O.; Périon, R. Efficient and rapid multiscale approach of polymer membrane degradation and stability: Application to formulation of harmless non-oxidative biocide for polyamide and PES/PVP membranes. *Sep. Purif. Technol.* **2020**, *259*, 118054. [\[CrossRef\]](#)
70. Morales-Zamudio, L.; Lozano, T.; Caballero-Briones, F.; Zamudio, M.A.; Martin, M.E.A.-S.; de Lira-Gomez, P.; Martinez-Colunga, G.; Rodriguez-Gonzalez, F.; Neira, G.; Sanchez-Valdes, S. Structure and Mechanical Properties of Graphene Oxide-Reinforced Polycarbonate. *Mater. Chem. Phys.* **2020**, *261*, 124180. [\[CrossRef\]](#)
71. Boroojeni, F.R.; Mashayekhan, S.; Abbaszadeh, H.A.; Ansarizadeh, M.; Khoramgah, M.S.; Rahimi Movaghar, V. Bioinspired Nanofiber Scaffold for Differentiating Bone Marrow-Derived Neural Stem Cells to Oligodendrocyte-Like Cells: Design, Fabrication, and Characterization. *Int. J. Nanomed.* **2020**, *15*, 3903–3920. [\[CrossRef\]](#) [\[PubMed\]](#)
72. Gupta, N.; Kaur, G.; Sharma, V.; Nagraik, R.; Shandilya, M. Increasing the efficiency of reduced graphene oxide obtained via high temperature electrospun calcination process for the electrochemical detection of dopamine. *J. Electroanal. Chem.* **2022**, *904*, 115904. [\[CrossRef\]](#)
73. Cojocaru, E.; Ghitman, J.; Pircalabioru, G.G.; Stavarache, C.; Serafim, A.; Vasile, E.; Iovu, H. Electrospun Nanofibrous Membranes Based on Citric Acid-Functionalized Chitosan Containing rGO-TEPA with Potential Application in Wound Dressings. *Polymers* **2022**, *14*, 294. [\[CrossRef\]](#) [\[PubMed\]](#)
74. Alshrah, M.; Naguib, H.E.; Park, C.B. Reinforced resorcinol formaldehyde aerogel with Co-assembled polyacrylonitrile nanofibers and graphene oxide nanosheets. *Mater. Des.* **2018**, *151*, 154–163. [\[CrossRef\]](#)
75. Zhang, Y.; Zhu, B.; Cai, X.; Yuan, X.; Zhao, S.; Yu, J.; Qiao, K.; Qin, R. Rapid In Situ Polymerization of Polyacrylonitrile/Graphene Oxide Nanocomposites as Precursors for High-Strength Carbon Nanofibers. *ACS Appl. Mater. Interfaces* **2021**, *13*, 16846–16858. [\[CrossRef\]](#)
76. Pinto, A.M.; Cabral, J.; Tanaka, D.A.P.; Mendes, A.M.; Magalhães, F.D. Effect of incorporation of graphene oxide and graphene nanoplatelets on mechanical and gas permeability properties of poly (lactic acid) films. *Polym. Int.* **2013**, *62*, 33–40. [\[CrossRef\]](#)
77. Chen, J.; Peng, H.; Wang, X.; Shao, F.; Yuan, Z.; Han, H. Graphene oxide exhibits broad-spectrum antimicrobial activity against bacterial phytopathogens and fungal conidia by intertwining and membrane perturbation. *Nanoscale* **2014**, *6*, 1879–1889. [\[CrossRef\]](#)
78. Greiner, A.; Wendorff, J.H. Electrospinning: A fascinating method for the preparation of ultrathin fibers. *Angew. Chem. Int. Ed.* **2007**, *46*, 5670–5703. [\[CrossRef\]](#)
79. Ding, W.; Zhu, H.; Lu, L.; Zhang, J.; Yu, H.; Zhao, H. Three-dimensional layered Fe-N/C catalysts built by electrospinning and the comparison of different active species on oxygen reduction reaction performance. *J. Alloys Compd.* **2020**, *848*, 156605. [\[CrossRef\]](#)
80. Chou, W.-J.; Wang, C.-C.; Chen, C.-Y. Characteristics of polyimide-based nanocomposites containing plasma-modified multi-walled carbon nanotubes. *Compos. Sci. Technol.* **2008**, *68*, 2208–2213. [\[CrossRef\]](#)
81. Jirsak, O.; Sanetrik, F.; Lukas, D.; Kotek, V.; Martinova, L.; Chaloupek, J. Method of Nanofibres Production from a Polymer Solution Using Electrostatic Spinning and a Device for Carrying Out the Method. US7585437B2, 8 September 2009.
82. Francis, L.; Ahmed, F.E.; Hilal, N. Electrospun membranes for membrane distillation: The state of play and recent advances. *Desalination* **2022**, *526*, 115511. [\[CrossRef\]](#)
83. Huang, T.; Marshall, L.R.; Armantrout, J.E.; Yembrick, S.; Dunn, W.H.; Oconnor, J.M.; Mueller, T.; Avgousti, M.; Wetzel, M.D. Production of Nanofibers by Melt Spinning. US827711B2, 2 October 2012.
84. Jeong, K.; Kim, D.H.; Chung, Y.S.; Hwang, S.K.; Hwang, H.Y.; Kim, S.S. Effect of processing parameters of the continuous wet spinning system on the crystal phase of PVDF fibers. *J. Appl. Polym. Sci.* **2018**, *135*, 45712. [\[CrossRef\]](#)
85. Liu, Y.-L.; Li, Y.; Xu, J.-T.; Fan, Z.-Q. Cooperative effect of electrospinning and nanoclay on formation of polar crystalline phases in poly (vinylidene fluoride). *ACS Appl. Mater. Interfaces* **2010**, *2*, 1759–1768. [\[CrossRef\]](#)
86. Park, S.; Park, K.; Yoon, H.; Son, J.; Min, T.; Kim, G. Apparatus for preparing electrospun nanofibers: Designing an electrospinning process for nanofiber fabrication. *Polym. Int.* **2007**, *56*, 1361–1366. [\[CrossRef\]](#)

87. Badoei-Dalfard, A.; Tahami, A.; Karami, Z. Lipase immobilization on glutaraldehyde activated graphene oxide/chitosan/cellulose acetate electrospun nanofibrous membranes and its application on the synthesis of benzyl acetate. *Colloids Surf. B Biointerfaces* **2022**, *209*, 112151. [[CrossRef](#)] [[PubMed](#)]
88. Gulino, E.F.; Citarrella, M.C.; Maio, A.; Scaffaro, R. An innovative route to prepare in situ graded crosslinked PVA graphene electrospun mats for drug release. *Compos. Part A Appl. Sci. Manuf.* **2022**, *155*, 106827. [[CrossRef](#)]
89. de Farias, L.M.; Ghislandi, M.G.; de Aguiar, M.F.; Silva, D.B.R.S.; Leal, A.N.R.; Silva, F.d.O.; Fraga, T.J.M.; de Melo, C.P.; Alves, K.G.B. Electrospun polystyrene/graphene oxide fibers applied to the remediation of dye wastewater. *Mater. Chem. Phys.* **2022**, *276*, 125356. [[CrossRef](#)]
90. Ali, I.H.; Ouf, A.; Elshishiny, F.; Taskin, M.B.; Song, J.; Dong, M.; Chen, M.; Siam, R.; Mamdouh, W. Antimicrobial and Wound-Healing Activities of Graphene-Reinforced Electrospun Chitosan/Gelatin Nanofibrous Nanocomposite Scaffolds. *ACS Omega* **2022**, *7*, 1838–1850. [[CrossRef](#)] [[PubMed](#)]
91. Lin, Y.-Z.; Zhong, L.-B.; Dou, S.; Shao, Z.-D.; Liu, Q.; Zheng, Y.-M. Facile synthesis of electrospun carbon nanofiber/graphene oxide composite aerogels for high efficiency oils absorption. *Environ. Int.* **2019**, *128*, 37–45. [[CrossRef](#)]
92. Kumar, S.R.; Gopinath, P. Dual applications of silver nanoparticles incorporated functionalized MWCNTs grafted surface modified PAN nanofibrous membrane for water purification. *RSC Adv.* **2016**, *6*, 109241–109252. [[CrossRef](#)]
93. Li, L.; Ma, Z.; Xua, P.; Zhoua, B.; Lia, Q.; Mab, J.; Hec, C.; Fenga, Y.; Liua, C. Flexible and alternant-layered cellulose nanofiber/graphene film with superior thermal conductivity and efficient electromagnetic interference shielding. *Compos. Part A Appl. Sci. Manuf.* **2020**, *139*, 106134. [[CrossRef](#)]
94. Yilmaz, E.; Soylak, M. Nanotechnological Developments in Nanofiber-Based Membranes Used for Water Treatment Applications. In *Environmental Nanotechnology*; Springer: Berlin/Heidelberg, Germany, 2021; Volume 5, pp. 205–259.
95. Danayat, S.; Nayal, A.S.; Tarannum, F.; Annam, R.; Muthaiah, R.; Garg, J. Role of solvent in enhancement of thermal conductivity of epoxy/graphene nanocomposites. *arXiv* **2022**, arXiv:2201.03527.
96. Boyko, E.; Kostogrud, I.A.; Pilnik, A.A.; Smovzh, D.V. Thermoacoustics and Temperature Distribution on the Surface of a Polymer-Graphene Composite. *Int. J. Thermophys.* **2022**, *43*, 1–10. [[CrossRef](#)]
97. Lian, T.; Yang, K.; Sun, S.; Zhu, M.; Yue, J.; Lin, B.; Sun, X.; Wang, X.; Zhang, D. Polarization-independent electro-absorption optical modulator based on trapezoid polymer-graphene waveguide. *Opt. Laser Technol.* **2022**, *149*, 107815. [[CrossRef](#)]
98. Muthaiah, R.; Tarannum, F.; Danayat, S.; Annam, R.S.; Nayal, A.S.; Yedukondalu, N.; Garg, J. Superior effect of edge relative to basal plane functionalization of graphene in enhancing polymer-graphene nanocomposite thermal conductivity-A combined molecular dynamics and Greens functions study. *arXiv* **2022**, arXiv:2201.01011.
99. Fu, G.; Sun, F.; Sun, F.; Huo, D.; Shyha, I.; Fang, C.; Gao, Q. Finite element and experimental studies on the machining process of polymer/graphene nanoplatelet nanocomposites. *Compos. Part B Eng.* **2022**, *230*, 109545. [[CrossRef](#)]
100. Linares, R.V.; Li, Z.; Sarp, S.; Bucs, S.; Amy, G.; Vrouwenvelder, J. Forward osmosis niches in seawater desalination and wastewater reuse. *Water Res.* **2014**, *66*, 122–139. [[CrossRef](#)]
101. Saraswathi, M.S.S.A.; Nagendran, A.; Rana, D. Tailored polymer nanocomposite membranes based on carbon, metal oxide and silicon nanomaterials: A review. *J. Mater. Chem. A* **2019**, *7*, 8723–8745. [[CrossRef](#)]
102. Moradi-Dastjerdi, R.; Behdian, K. Stability analysis of multifunctional smart sandwich plates with graphene nanocomposite and porous layers. *Int. J. Mech. Sci.* **2020**, *167*, 105283. [[CrossRef](#)]
103. Ganguly, S. Preparation/processing of polymer-graphene composites by different techniques. In *Polymer Nanocomposites Containing Graphene*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 45–74.
104. Rozelle, L.; Gadotte, J.; Corneliussen, R.; Erickson, E.; Cobian, K.; Kopp, J.R.C. Phase inversion membranes. In *Encyclopedia of Separation Science*; Mulder, M., Ed.; Academic Press: Cambridge, MA, USA, 2000; pp. 3331–3346.
105. Yang, C.; Jin, C.; Chen, F. Micro-tubular solid oxide fuel cells fabricated by phase-inversion method. *Electrochem. Commun.* **2010**, *12*, 657–660. [[CrossRef](#)]
106. Yuan, X.; Zhang, Y.; Dong, C.; Sheng, J. Morphology of ultrafine polysulfone fibers prepared by electrospinning. *Polym. Int.* **2004**, *53*, 1704–1710. [[CrossRef](#)]
107. Cho, J.; Paul, D. Nylon 6 nanocomposites by melt compounding. *Polymer* **2001**, *42*, 1083–1094. [[CrossRef](#)]
108. Sato, Y.; Takikawa, T.; Takishima, S.; Masuoka, H. Solubilities and diffusion coefficients of carbon dioxide in poly (vinyl acetate) and polystyrene. *J. Supercrit. Fluids* **2001**, *19*, 187–198. [[CrossRef](#)]
109. Zhao, X.; Zhang, Q.; Chen, D.; Lu, P. Enhanced mechanical properties of graphene-based poly (vinyl alcohol) composites. *Macromolecules* **2010**, *43*, 2357–2363. [[CrossRef](#)]
110. Duraikkannu, S.L.; Castro-Muñoz, R.; Figoli, A. A review on phase-inversion technique-based polymer microsphere fabrication. *Colloid Interface Sci. Commun.* **2021**, *40*, 100329. [[CrossRef](#)]
111. Nguyen Thi, H.Y.; Nguyen, B.T.D.; Kim, J.F. Sustainable fabrication of organic solvent nanofiltration membranes. *Membranes* **2021**, *11*, 19. [[CrossRef](#)]
112. Cheng, H.K.F.; Sahoo, N.G.; Tan, Y.P.; Pan, Y.; Bao, H.; Li, L.; Chan, S.H.; Zhao, J. Poly (vinyl alcohol) nanocomposites filled with poly (vinyl alcohol)-grafted graphene oxide. *ACS Appl. Mater. Interfaces* **2012**, *4*, 2387–2394. [[CrossRef](#)] [[PubMed](#)]
113. Das, S.; Wajid, A.S.; Bhattacharia, S.K.; Wilting, M.D.; Rivero, I.V.; Green, M.J. Electrospinning of polymer nanofibers loaded with noncovalently functionalized graphene. *J. Appl. Polym. Sci.* **2013**, *128*, 4040–4046. [[CrossRef](#)]

114. You, Y.; Jin, X.; Wen, X.; Sahajwalla, V.; Chen, V.; Bustamante, H.; Joshi, R. Application of graphene oxide membranes for removal of natural organic matter from water. *Carbon* **2018**, *129*, 415–419. [\[CrossRef\]](#)
115. Sun, J.; Qian, X.; Wang, Z.; Zeng, F.; Bai, H.; Li, N. Tailoring the microstructure of poly (vinyl alcohol)-intercalated graphene oxide membranes for enhanced desalination performance of high-salinity water by pervaporation. *J. Membr. Sci.* **2020**, *599*, 117838. [\[CrossRef\]](#)
116. Castro-Muñoz, R.; Buera-González, J.; de la Iglesia, Ó.; Galiano, F.; Fila, V.; Malankowska, M.; Rubio, C.; Figoli, A.; Téllez, C.; Coronas, J. Towards the dehydration of ethanol using pervaporation cross-linked poly (vinyl alcohol)/graphene oxide membranes. *J. Membr. Sci.* **2019**, *582*, 423–434. [\[CrossRef\]](#)
117. Khan, U.; May, P.; Porwal, H.; Nawaz, K.; Coleman, J. Improved adhesive strength and toughness of polyvinyl acetate glue on addition of small quantities of graphene. *ACS Appl. Mater. Interfaces* **2013**, *5*, 1423–1428. [\[CrossRef\]](#)
118. Sabzi, M.; Babaahmadi, M.; Rahnama, M. Thermally and electrically triggered triple-shape memory behavior of poly (vinyl acetate)/poly (lactic acid) due to graphene-induced phase separation. *ACS Appl. Mater. Interfaces* **2017**, *9*, 24061–24070. [\[CrossRef\]](#) [\[PubMed\]](#)
119. Zhang, B.; Zhang, Y.; Peng, C.; Yu, M.; Li, L.; Deng, B.; Hu, P.; Fan, C.; Li, J.; Huang, Q. Preparation of polymer decorated graphene oxide by γ -ray induced graft polymerization. *Nanoscale* **2012**, *4*, 1742–1748. [\[CrossRef\]](#) [\[PubMed\]](#)
120. Kolya, H.; Kang, C.-W. Polyvinyl acetate/reduced graphene oxide-poly (diallyl dimethylammonium chloride) composite coated wood surface reveals improved hydrophobicity. *Prog. Org. Coat.* **2021**, *156*, 106253. [\[CrossRef\]](#)
121. Deshmukh, K.; Khatake, S.; Joshi, G.M. Surface properties of graphene oxide reinforced polyvinyl chloride nanocomposites. *J. Polym. Res.* **2013**, *20*, 1–11. [\[CrossRef\]](#)
122. Wang, H.; Xie, G.; Fang, M.; Ying, Z.; Tong, Y.; Zeng, Y. Electrical and mechanical properties of antistatic PVC films containing multi-layer graphene. *Compos. Part B Eng.* **2015**, *79*, 444–450. [\[CrossRef\]](#)
123. Akhina, H.; Nair, M.R.G.; Kalarikkal, N.; Pramoda, K.; Ru, T.H.; Kailas, L.; Thomas, S. Plasticized PVC graphene nanocomposites: Morphology, mechanical, and dynamic mechanical properties. *Polym. Eng. Sci.* **2018**, *58*, E104–E113. [\[CrossRef\]](#)
124. Zhao, Y.; Lu, J.; Liu, X.; Wang, Y.; Lin, J.; Peng, N.; Li, J.; Zhao, F. Performance enhancement of polyvinyl chloride ultrafiltration membrane modified with graphene oxide. *J. Colloid Interface Sci.* **2016**, *480*, 1–8. [\[CrossRef\]](#) [\[PubMed\]](#)
125. Namdar, H.; Akbari, A.; Yegani, R.; Roghani-Mamaqani, H. Influence of aspartic acid functionalized graphene oxide presence in polyvinylchloride mixed matrix membranes on chromium removal from aqueous feed containing humic acid. *J. Environ. Chem. Eng.* **2021**, *9*, 104685. [\[CrossRef\]](#)
126. Khakpour, S.; Jafarzadeh, Y.; Yegani, R. Incorporation of graphene oxide/nanodiamond nanocomposite into PVC ultrafiltration membranes. *Chem. Eng. Res. Des.* **2019**, *152*, 60–70. [\[CrossRef\]](#)
127. Xu, Y.; Bai, H.; Lu, G.; Li, C.; Shi, G. Flexible graphene films via the filtration of water-soluble noncovalent functionalized graphene sheets. *J. Am. Chem. Soc.* **2008**, *130*, 5856–5857. [\[CrossRef\]](#)
128. Li, C.; Xiang, M.; Zhao, X.; Ye, L. In situ synthesis of monomer casting nylon-6/graphene-polysiloxane nanocomposites: Intercalation structure, synergistic reinforcing, and friction-reducing effect. *ACS Appl. Mater. Interfaces* **2017**, *9*, 33176–33190. [\[CrossRef\]](#) [\[PubMed\]](#)
129. Zhang, F.; Peng, X.; Yan, W.; Peng, Z.; Shen, Y. Nonisothermal crystallization kinetics of in situ nylon 6/graphene composites by differential scanning calorimetry. *J. Polym. Sci. Part B Polym. Phys.* **2011**, *49*, 1381–1388. [\[CrossRef\]](#)
130. Pant, H.R.; Park, C.H.; Tijing, L.D.; Amarjargal, A.; Lee, D.-H.; Kim, C.S. Bimodal fiber diameter distributed graphene oxide/nylon-6 composite nanofibrous mats via electrospinning. *Colloids Surf. A Physicochem. Eng. Asp.* **2012**, *407*, 121–125. [\[CrossRef\]](#)
131. Gong, L.; Yin, B.; Li, L.-P.; Yang, M.-B. Nylon-6/Graphene composites modified through polymeric modification of graphene. *Compos. Part B Eng.* **2015**, *73*, 49–56. [\[CrossRef\]](#)
132. Li, C.; Xiang, M.; Ye, L. Intercalation structure and highly enhancing tribological performance of monomer casting nylon-6/graphene nano-composites. *Compos. Part A Appl. Sci. Manuf.* **2017**, *95*, 274–285. [\[CrossRef\]](#)
133. Mehrani, Z.; Ebrahimzadeh, H.; Moradi, E. Poly m-aminophenol/nylon 6/graphene oxide electrospun nanofiber as an efficient sorbent for thin film microextraction of phthalate esters in water and milk solutions preserved in baby bottle. *J. Chromatogr. A* **2019**, *1600*, 87–94. [\[CrossRef\]](#) [\[PubMed\]](#)
134. Ionita, M.; Vasile, E.; Crica, L.E.; Voicu, S.I.; Pandele, A.M.; Dinescu, S.; Predoiu, L.; Galateanu, B.; Hermenean, A.; Costache, M. Synthesis, characterization and in vitro studies of polysulfone/graphene oxide composite membranes. *Compos. Part B Eng.* **2015**, *72*, 108–115. [\[CrossRef\]](#)
135. Sali, S.; Mackey, H.R.; Abdala, A.A. Effect of graphene oxide synthesis method on properties and performance of polysulfone-graphene oxide mixed matrix membranes. *Nanomaterials* **2019**, *9*, 769. [\[CrossRef\]](#)
136. Voicu, S.I.; Pandele, M.A.; Vasile, E.; Rughinis, R.; Crica, L.; Pitan, L.; Ionita, M. The impact of sonication time through polysulfone-graphene oxide composite films properties. *Dig. J. Nanomater. Biostruct.* **2013**, *8*, 1389–1394.
137. Ammar, A.; Al-Enizi, A.M.; AlMaadeed, M.A.; Karim, A. Influence of graphene oxide on mechanical, morphological, barrier, and electrical properties of polymer membranes. *Arab. J. Chem.* **2016**, *9*, 274–286. [\[CrossRef\]](#)
138. Ayyaru, S.; Ahn, Y.-H. Application of sulfonic acid group functionalized graphene oxide to improve hydrophilicity, permeability, and antifouling of PVDF nanocomposite ultrafiltration membranes. *J. Membr. Sci.* **2017**, *525*, 210–219. [\[CrossRef\]](#)

139. Rezaee, R.; Nasser, S.; Mahvi, A.H.; Nabizadeh, R.; Mousavi, S.A.; Rashidi, A.; Jafari, A.; Nazmara, S. Fabrication and characterization of a polysulfone-graphene oxide nanocomposite membrane for arsenate rejection from water. *J. Environ. Health Sci. Eng.* **2015**, *13*, 1–11. [[CrossRef](#)] [[PubMed](#)]
140. Chu, L.; Grouve, W.J.B.; van Drongelen, M.; Guha, Y.; de Vries, E.G.; Akkerman, R.; de Rooij, M.B. Influence of the polymer interphase structure on the interaction between metal and semicrystalline thermoplastics. *Adv. Eng. Mater.* **2021**, *23*, 2000518. [[CrossRef](#)]
141. Pathak, A.K.; Sharma, L.; Garg, H.; Yokozeki, T.; Dhakate, S.R. In situ cross-linking capability of novel amine-functionalized graphene with epoxy nanocomposites. *J. Appl. Polym. Sci.* **2022**, 52249. [[CrossRef](#)]
142. Javidi, Z.; Nazockdast, H.; Ghasemi, I. Effect of graphene/graphene oxide on microstructure development and its impact on electrical conductivity and shape recovery behavior of plasticized starch-based nano-biocomposites. *J. Polym. Res.* **2022**, *29*, 1–14. [[CrossRef](#)]
143. Ganesh, B.; Isloor, A.M.; Ismail, A.F. Enhanced hydrophilicity and salt rejection study of graphene oxide-polysulfone mixed matrix membrane. *Desalination* **2013**, *313*, 199–207. [[CrossRef](#)]
144. Sizov, V.E.; Kondratenko, M.S.; Gallyamov, M.O.; Stevenson, K.J. Advanced porous polybenzimidazole membranes for vanadium redox batteries synthesized via a supercritical phase-inversion method. *J. Supercrit. Fluids* **2018**, *137*, 111–117. [[CrossRef](#)]
145. Lai, G.; Lau, W.; Goh, P.; Ismail, A.F.; Tan, Y.; Chong, C.; Krause-Rehberg, R.; Awad, S. Tailor-made thin film nanocomposite membrane incorporated with graphene oxide using novel interfacial polymerization technique for enhanced water separation. *Chem. Eng. J.* **2018**, *344*, 524–534. [[CrossRef](#)]
146. Karki, S.; Gohain, M.B.; Yadav, D.; Ingole, P.G. Nanocomposite and bio-nanocomposite polymeric materials/membranes development in energy and medical sector: A review. *Int. J. Biol. Macromol.* **2021**, *193*, 2121–2139. [[CrossRef](#)] [[PubMed](#)]
147. Pires, J.; de Paula, C.D.; Souza, V.G.L.; Fernando, A.L.; Coelho, I. Understanding the barrier and mechanical behavior of different nanofillers in chitosan films for food packaging. *Polymers* **2021**, *13*, 721. [[CrossRef](#)]
148. Iravani, S. Nanomaterials and nanotechnology for water treatment: Recent advances. *Inorg. Nano-Met. Chem.* **2021**, *51*, 1615–1645. [[CrossRef](#)]
149. Mahdavi Far, R.; Van der Bruggen, B.; Verliefde, A.; Cornelissen, E. A review of zeolite materials used in membranes for water purification: History, applications, challenges and future trends. *J. Chem. Technol. Biotechnol.* **2021**, *97*, 575–596. [[CrossRef](#)]
150. Qalyoubi, L.; Al-Othman, A.; Al-Asheh, S. Recent progress and challenges of adsorptive membranes for the removal of pollutants from wastewater. *Part II Environ. Appl. Case Stud. Chem. Environ. Eng.* **2021**, *3*, 100102. [[CrossRef](#)]
151. Jhaveri, J.H.; Murthy, Z. A comprehensive review on anti-fouling nanocomposite membranes for pressure driven membrane separation processes. *Desalination* **2016**, *379*, 137–154. [[CrossRef](#)]
152. Junaidi, N.F.D.; Othman, N.H.; Shahrudin, M.Z.; Alias, N.H.; Lau, W.J.; Ismail, A.F. Effect of graphene oxide (GO) and polyvinylpyrrolidone (PVP) additives on the hydrophilicity of composite polyethersulfone (PES) membrane. *Malays. J. Fundam. Appl. Sci.* **2019**, *15*, 361–366. [[CrossRef](#)]