



Review

# Recent Progress on Nanomaterial-Based Membranes for Water Treatment

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**Abstract:** Nanomaterials have emerged as the new future generation materials for high-performance water treatment membranes with potential for solving the worldwide water pollution issue. The incorporation of nanomaterials in membranes increases water permeability, mechanical strength, separation efficiency, and reduces fouling of the membrane. Thus, the nanomaterials pave a new pathway for ultra-fast and extremely selective water purification membranes. Membrane enhancements after the inclusion of many nanomaterials, including nanoparticles (NPs), two-dimensional (2-D) layer materials, nanofibers, nanosheets, and other nanocomposite structural materials, are discussed in this review. Furthermore, the applications of these membranes with nanomaterials in water treatment applications, that are vast in number, are highlighted. The goal is to demonstrate the significance of nanomaterials in the membrane industry for water treatment applications. It was found that nanomaterials and nanotechnology offer great potential for the advancement of sustainable water and wastewater treatment.

**Keywords:** nanomaterials; membrane separation; water and wastewater treatment; membrane enhancements; nano sheets; nano composites



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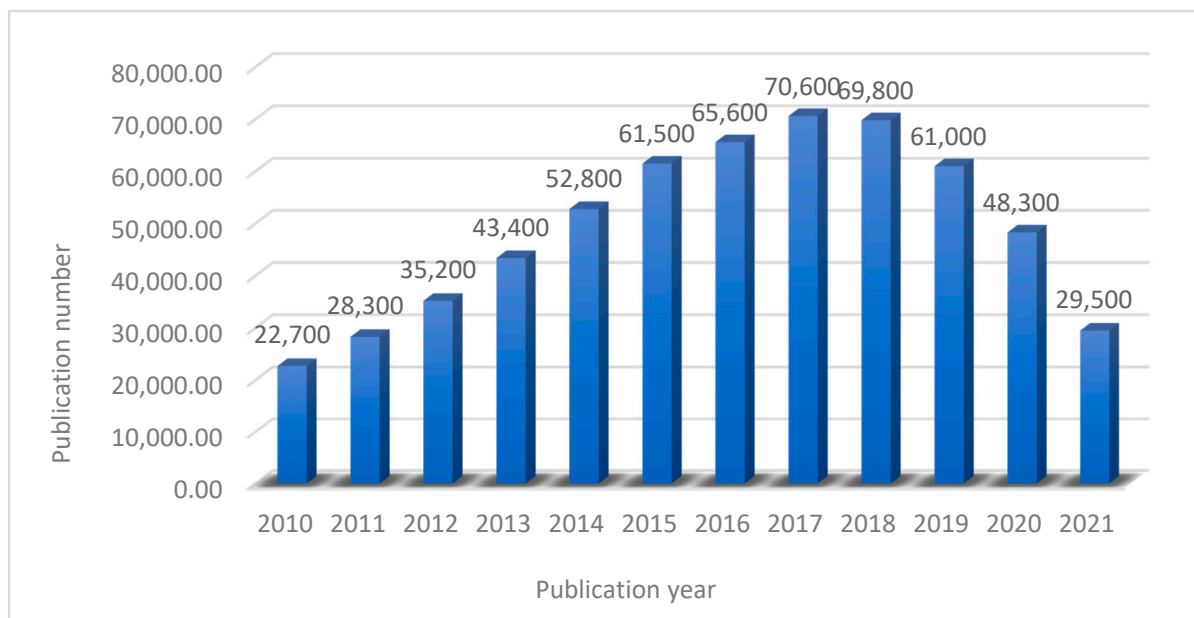
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## 1. Introduction

Water scarcity is presently a major area of concern for the entire world [1–3]. Rapid industrial development and global population growth are increasing the demand for several water resources. Based on UN Water ORG, 1.8 billion people are estimated to be living in areas with absolute water scarcity, and two-thirds of the global population will live under water stress conditions by the year 2025 [4]. Thus, highly efficient water treatment technologies with great sustainability are required to tackle the worldwide water scarcity issue. Membrane technology stands out to be the best technology for water treatment compared to other technologies such as distillation [5–7], electrolysis [8–10], adsorption [11–13], and photodegradation [14–16]. The reason for this is that membrane technology requires less energy to operate, attains a high separation efficiency, and is capable of operating in a continuous mode. Several studies have been conducted to increase the overall performance of membranes. Nanotechnology plays a vital role in accelerating the performance of membranes. The use of nanomaterials increases water permeability, mechanical strength, and reduces the fouling phenomenon of the membrane [17].

Nanotechnology is thought to be the cure-all for the majority of problems involved with water contamination remediation. In the past few decades, the urgent need for novel membranes, made up of nanomaterials with well-defined nanostructures, has transformed traditional membrane concepts, resulting in groundbreaking water treatment methods

that exceed state-of-the-art performance. The nanomaterials used in the membranes include nanoparticles (NPs), two-dimensional (2-D) layer materials, nanofibers, and other nanocomposite structural materials. Furthermore, a huge array of water treatment equipment, including those incorporating nanotechnology, are presently available in the market, with several more on the way. Figure 1 shows the number of publications about the use of nanomaterial-based membranes for water treatment.



**Figure 1.** A short post-2010 timeline showing the number of water treatment nanomaterial-based membrane related academic publications.

It is clearly seen from Figure 1 that the number of publications about the use of nanomaterials-based membranes in the water treatment field has a general increasing trend. This proves the importance of the nanomaterials in the membrane field for water treatment.

Several types of research and studies have been conducted to examine the use of nanomaterials in the advancement of membrane performance. This review focuses on membrane modifications following the implementation of new nanomaterials, including nanoparticles (NPs), two-dimensional (2-D) layer materials, nanofibers, nanosheets, and other nanocomposite structural materials. In addition, the applicability of these membranes containing nanomaterials in various water treatment applications are highlighted. The purpose is to prove the significance of nanomaterials in the membrane industry for water treatment applications.

## 2. Traditional Membrane Materials

Membrane technology has advanced at a breakneck pace over the last few decades [18,19]. The membranes used in industrial and laboratory separation processes are mainly made up of polymeric [20–23] and inorganic materials [24]. Generally speaking, ceramic membranes are artificial membranes synthesized by the deposition of metal hydroxides colloidal suspensions on porous supports [25]. Ceramic membranes are greatly employed in separation processes that involve strong media such as acids and strong solvents or extreme conditions such as high temperature and pressure. As a result of the accelerated chemical inertness and mechanical thermal resistance of ceramic membranes, the flux through the membrane can be recovered easily after fouling [26]. Ceramics, however, are excessively brittle, and their high production costs severely limit their application in large-scale industries [27].

Polymeric membranes, on the other hand, are the leaders in the membrane separation processes in industries due to their high performance and viable cost [28]. Porous polymer membranes are traditionally synthesized using mechanical stretching and/or a phase-

inversion technique. The advantages of polymeric membranes rely upon their superb separation performance, high permeation rate, and perm-selectivity. The disadvantages include low tolerance to high-temperature levels, corrosive environments, and organic solvents [29].

Thin-film composite membranes, a significant breakthrough in the field of membranes, presently have a more flexible structure that combines a number of higher selective layers and porous support layers for a more complex separation environment [30]. Under pressure, nevertheless, the multilayer structure has significant compaction repercussions [31]. When the loading pressure is increased, the polymers rearrange into a smaller structure, resulting in a decrease in porosity and, as a result, a loss in separation efficiency. Compaction often increases with increasing pressure [32,33].

### 3. Nanomaterial-Based Membranes

Despite the domination of the water purification market by conventional membranes, it is difficult to choose the most preferable membrane depending on usage, because each membrane type is bounded by a tradeoff, such as selectivity, permeability, flux, stability, or high manufacturing cost [1]. In addition, fouling is a serious issue that constrains the application of ceramic and polymeric membranes. Several pathways have been taken to chemically modify the membrane surface for better performance and less fouling. Among the wide variety of the proposed technologies and pathways, nanotechnology stands out to be the most promising membrane technology. There are several nanomaterials used in membranes. Figure 2 below shows the most widely used membrane-based nanomaterial structures.

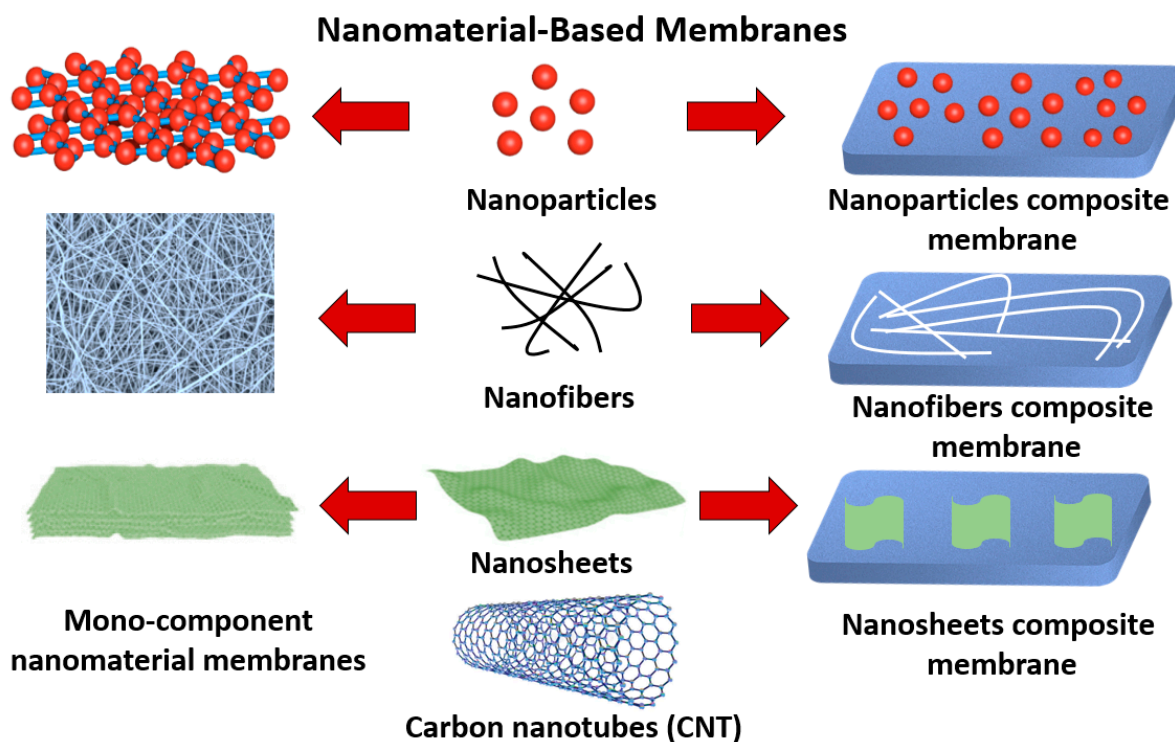


Figure 2. The most commonly used nanomaterial-based membrane structures.

#### 3.1. Nanoparticle Composed Membranes

##### 3.1.1. Freestanding Nanoparticle Membrane

Nanoparticle membranes are synthesized by assembling the nanoparticles into free-standing ultrathin membranes. Nanoparticle membranes are generated utilizing filtering, a drying-mediated self-assembly method, and blown-film extrusion, as well as nano film segregation over a two-dimensional interface created within a hole. At present, mono-

component nanomaterial membranes that are entirely made up of nanoparticles such as close-packed gold nanoparticle mono-layers, are not much available. Freestanding ultrathin nano-membranes (FUN-membranes) are two-dimensional membrane materials with a nanoscale thickness of <100 nm and with very little, or almost no, substrate support. In the past few years, there has been a surge of interest in rationally designing such membranes for a wide range of applications, from electronic devices to water remediation systems [34]. However, there are few studies available in the market about the use of freestanding ultrathin nano-membranes (FUN-membranes). Zhang, et al. [35] prepared freestanding cross-linked polystyrene nanoparticle membranes that have a thickness of 80 nm and very precise pores. The membrane was synthesized by the authors via polystyrene nanoparticle filtration over a microfiltration membrane via a sacrificial layer of metal hydroxide nano strands. The synthesized membranes exhibited very interesting properties along with a quick separation of gold nanoparticles and small proteins [35]. Membrane filtration has been proposed as a viable option to remediate the environment by incorporating it into a modern oxidation processes to reduce energy and cost consumption. Ye, et al. [36] successfully synthesized a freestanding 2-D confinement graphene oxide (GO) composite membrane. The fabricated membrane had excellent capabilities of pollutant catalytic degradation. Hence, these features demonstrate great potential for the fabricated 2-D confinement catalytic membranes with enriched oxygen vacancies in wastewater purification [36].

### 3.1.2. Nanoparticles as Filler for Composite Membrane

Filling membrane composites with nanoparticles involves the addition of nanoparticles to the ceramic or polymeric membrane during the synthesis process. The concept behind the addition of inorganic or organic materials into a polymer matrix is commonly used in the fabrication of mixed matrix membranes. In recent years, the incorporation of nanoparticles into membranes has emerged as a new focus. However, the use of these small nanosize particles in the membranes is followed by some advantages and disadvantages. The advantages include a better interaction between the two phases in the membrane which leads to higher selectivity, permeability, mechanical stability, hydrophilicity, and less fouling. In addition, some nanoparticles provide the membranes with antibacterial and catalytic properties. On the other hand, the disadvantages rely on the fact that some properties of the polymeric membranes are rendered in the presence of the nanoparticles. The most commonly used nanoparticles in the polymeric and ceramic membranes include the following: alumina, TiO<sub>2</sub>, silica, zinc oxide, zeolite, and attapulgite (APT) into polymeric membranes, which have shown to enhance the membrane water permeability, surface hydrophilicity, resistance to fouling, and functionalization. Table 1 below shows the membrane enhancements after the addition of some widely used nanoparticles in membranes.

**Table 1.** Three-dimensional structures and membrane enhancements for some widely used nanoparticles in membranes.

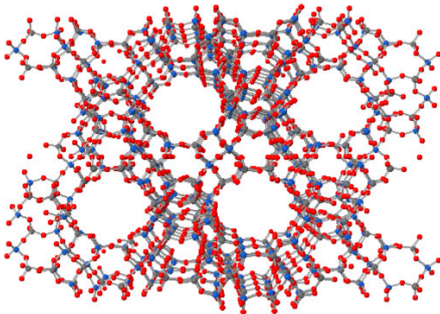
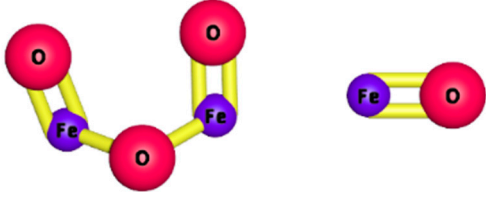


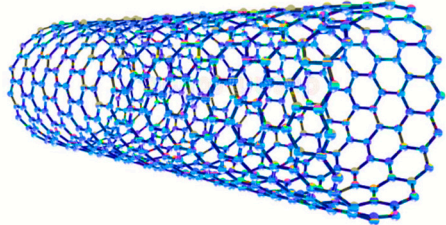
Nanoparticle	Three-Dimensional Structure (3-D)	Enhancements in Membrane after the Addition of the Nanoparticle
Zeolites		Hydrophilicity, filtration, tunable chemistry molecular sieve, and high permeability

Table 1. Cont.

Nanoparticle	Three-Dimensional Structure (3-D)	Enhancements in Membrane after the Addition of the Nanoparticle
Magnetite		Superparamagnetic and tunable chemistry
Silver		Anti-biofouling and antimicrobial
TiO <sub>2</sub>		Chemical stability, reactivity, photocatalysis, and hydrophilicity
Carbon nanotubes (CNTs)		Chemical stability, tunable chemistry, antimicrobial, high mechanical strength, and anti-biofouling

Several studies have analyzed membrane efficiency enhancement after the incorporation of the most commonly used nanoparticles in several industries. Ghaemi [37] studied the improvements that occurred in the removal efficiency of copper in PES membranes after the incorporation of alumina (Al<sub>2</sub>O<sub>3</sub>) nanoparticles. The authors prepared mixed matrix membranes by a phase inversion method while using PES and various amounts of alumina nanoparticles. The results of the authors' study show that the water permeation of the mixed matrix membranes was elevated after the addition of the alumina nanoparticles compared with the pristine PES. The increased water permeability was responsible for the increase in the porosity and hydrophilicity of the mixed matrix membrane after the incorporation of alumina nanoparticles into the matrix of the membrane. In addition, the copper ion removal efficiency of the alumina mixed membranes was also enhanced [37]. Hosseini, et al. [38] studied the enhancement effects of TiO<sub>2</sub> nanoparticles on the physicochemical properties of a mixed matrix membrane. The authors used a solution casting technique to prepare polyvinylchloride-co-TiO<sub>2</sub> nanoparticle mixed matrix heterogeneous cation exchange membranes. The results of the study show that the membrane ion exchange capacity, flux, mechanical strength, and selectivity were all improved after the addition of TiO<sub>2</sub> into the matrix of the membrane [38]. Furthermore, in a study that included TiO<sub>2</sub> nanoparticles, Mobarakabad, et al. [39] revealed the effect of titanium dioxide (TiO<sub>2</sub>) nanoparticles as an inorganic filler additive on the membrane physico-chemical properties. The authors used a phase inversion method to prepare asymmetric poly (1,4-phenylene ether-ether-sulfone) (PPEES)-blend-polyethylene glycol nanocomposite nanofiltration membranes with titanium dioxide (TiO<sub>2</sub>) nanoparticles as the inorganic filler additive and N-methyl pyrrolidone as the solvent. The results of this study revealed that there was an enhancement in the membrane water flux (WF), tensile strength, hydrophilicity, and salt rejection after the addition of TiO<sub>2</sub> nanoparticles as the inorganic filler in the membrane [39]. Ayyaru, et al. [40] studied the effect of different GO-ZnO loadings on a polyvinylidene fluoride (PVDF) membrane. The addition of GO-ZnO nanocomposite significantly improved membrane porosity, wettability, water flux, and anti-fouling properties. This proves that the overall properties of the GO-ZnO/PVDF are improved compared to the bare PVDF membrane after the addition of the nanocomposite GO-ZnO [40]. Borjigin, et al. [41] studied the

effect of incorporating Beta ( $\beta$ ) zeolite in a polyamide (PA) thin-film nanocomposite (TFN) membrane. The authors found that after the modification of the TFN membrane by the Beta ( $\beta$ ) zeolite the water flux, and the separation of the membrane significantly increased [41]. Attapulgitte (APT) is a very promising highly hydrophilic mineral additive in nature that is used to modify ultrafiltration (UF) membranes. Zhang, et al. [42] used attapulgitte (APT) as an additive for a polyvinylidene fluoride (PVDF) matrix to prepare a hybrid membrane using the phase inversion method. The results of the study show that the APT particle blended membranes had greater hydrophilicity, better thermal stability, higher water permeability, smaller pore size when, and enhanced antifouling performance compared with the pure PVDF sample [42]. Tables 2–4 show the enhancements in membranes after the incorporation of  $\text{TiO}_2$ ,  $\text{SiO}_2$ , and other nanoparticles in the membranes.

**Table 2.** A summary of key elements of  $\text{TiO}_2$  nanoparticle-based nanocomposite membranes.

Membrane Application	Modification Technique	Membrane Modification Enhancement	Reference
Study of Escherichia coli membrane bioreactor system	Dipped coating	Anti-bio-fouling property was improved.	[43]
activated sludge filtration	Dipped coating	Higher anti-fouling properties	[44]
Treatment of emulsified oil wastewater	Dipped coating and Phase inversion	Increase in composite membrane porosity, and a higher anti-fouling properties.	[45]
Enhancement of PES/PI nanofiltration membranes	Phase inversion method	Higher water permeability, hydrophilicity, mechanical strength and anti-fouling ability	[46]
Study of the performance of PVDF membrane	Phase inversion method	High flux recovery	[47]
The synthesized membrane can be used as an advanced filtration system	Dipped coating under UV	Enhanced antifouling properties of PVDF (polyvinylidene fluoride) membrane	[48]
Alkaline fuel cells (AFC)	Sol-gel method/Deep coating method	Higher mechanical strength and structural stability.	[49]
Study of the morphology and properties of poly(phthalazine ether sulfone ketone) (PPESK)	Phase inversion method	Greater thermal properties, thermal resistance and enhanced water take.	[50]
Removal of harsh organic solvents	Phase inversion method	Enhanced antifouling properties, increase in tensile mechanical properties, higher membrane hydrophilicity and wettability.	[51]
Study of poly (vinylidene fluoride) (PVDF)/sulfonated polyethersulfone (SPES) blend membrane	Phase inversion method	Higher antifouling property, thermal stability, and flux recovery.	[52]
Study of Polyethersulfone ultrafiltration membranes	Dipped coating	Higher long-term flux stability and antifouling property.	[53]
Study of PES/ $\text{TiO}_2$ composite membranes	Surface deposition in presence and absence of UV	Reduction in membrane fouling.	[54]
Study of the polysulfonamide/nano titanium dioxide (PSA/nano- $\text{TiO}_2$ ) composite	Phase inversion method	Improvement in thermal stability, hydrophilicity, mechanical strength and anti-fouling property.	[55]
Membrane can be used in guided bone regeneration (GBR)	Phase inversion using a spinning technique	Better thermal stability and greater ultraviolet resistance	[56]
	Casting method	Greater mechanical strength, and higher antimicrobial activity	[57]

Table 2. Cont.

Membrane Application	Modification Technique	Membrane Modification Enhancement	Reference
Study the photo-bactericidal effect on <i>Escherichia coli</i> ( <i>E. coli</i> )	Phase inversion method	Better antibacterial property, higher hydrophilicity, greater flux recovery and enhanced antifouling property.	[58]
Study of titania nanocomposite polyethersulfone ultrafiltration membranes	The sol-gel surface coating method	Higher stability, durability, hydrophilicity, and antifouling property	[59]
Degradation of dyes	Phase inversion using electro-spinning	Greater photocatalytic activity	[60]
Improving fouling resistance	Phase inversion method	Greater permeability, higher antifouling property and improved hydrophilicity	[61]
Study of sulfonated-polyethersulfone (SPES)/nano-TiO <sub>2</sub> composite UF membrane	Casting method	Greater antifouling property, improved photocatalytic activity and binding strength	[62]
Study of polyamide thin film nanocomposite (TFN) nanofiltration membrane	Surface coating	Higher salt rejection, permeability, thermal stability, and selectivity.	[63]
Study of photocatalytic polyvinyl alcohol (PVA)/TiO <sub>2</sub> composite polymer membrane	Phase inversion method using electro-spinning	Higher photocatalytic activity, and enhanced tensile strength	[64]
Study of PVDF membrane	Dipped coating	Higher antifouling property	[65]
Study of microporous PES membrane	Phase inversion method	Greater thermal stability, and permeation. In addition, the pore size of the membrane surface layer and the breaking strength was increased.	[66]

Table 3. A summary of key elements of SiO<sub>2</sub> nanoparticle-based nanocomposite membranes.

Membrane Application	Modification Technique	Membrane Modification Enhancement	Reference
Polyethersulfone-mesoporous silica nanocomposite ultrafiltration membranes	Phase inversion casting method	Greater hydrophilicity, thermal stability, porosity, water uptake and antifouling properties.	[67]
Polysulfone/silica nanoparticle mixed-matrix membranes used for gas separation	Phase inversion method	Enhanced gas permeability of the PS (polysulfone) membrane	[68]
Ce-doped nonstoichiometric nanosilica/polysulfone composite membranes used in wastewater treatment	Phase inversion method	Greater tensile strength, antifouling property, and hydrophilicity.	[69]
Poly(vinylidene fluoride) composite membranes applied in the electro-driven separation processes	Phase inversion method	Higher conductivity, selectivity, and physical stability.	[70]
Organic/inorganic composite membranes	Solution casting method	Higher chemically stability and tensile strength. In addition, the membrane proton conductivity was also improved	[71]
PDMS nanocomposite membranes used for gas separation	Casting method	Greater permeability	[72]

Table 3. Cont.

Membrane Application	Modification Technique	Membrane Modification Enhancement	Reference
PSf/SiO <sub>2</sub> nanocomposite membrane applied in oil-in-water emulsion separation	Phase inversion method	Higher permeability and antifouling property.	[73]
Silica nanocomposite membranes	Phase inversion method	Increase in water diffusivity and fractional free-volume.	[74]
Nanocomposite membranes for gas separation	Phase inversion method	Higher diffusivity, gas permeability, solubility, and selectivity.	[75]
Nano silica/Nafion composite membrane applied in proton exchange membrane fuel cells	Phase inversion method	Higher proton conductivity.	[76]
Polymer Nanocomposite Electrolyte Membrane used for High Performance Lithium/Sulfur Batteries	Casting method	Higher electrochemical stability, and ionic conductivity.	[77]
PBI and PBI/ZIF-8 nanocomposite membranes	Phase inversion method	Improved solubility, degree of swelling, and selectivity	[78]
PVA/nano silica composite membranes	Phase inversion method	Higher hydrophilicity and flux.	[79]

Table 4. A summary of key elements of several nanoparticle-based nanocomposite membranes.

Nanoparticle	Membrane Application	Modification Technique	Membrane Modification Enhancement	Reference
Zeolite	Polymer-Zeolite Nanocomposites as Mixed-Matrix Membranes used for Gas Separation	Casting method	Greater permeability for CH <sub>4</sub> , N <sub>2</sub> , and CO <sub>2</sub> .	[80]
ZIF-8	Polybenzimidazole (PBI) and PBI/zeolitic imidazolate framework (ZIF-8) nanocomposite membranes	Phase inversion method	Increase in permeability, sorption diffusion coefficient, pervaporation, and swelling characteristics.	[78]
ZnO	Chitosan/ZnO nanoparticle composite membranes	Phase inversion	Higher antibacterial property and mechanical stability.	[81]
Al <sub>2</sub> O <sub>3</sub>	Al <sub>2</sub> O <sub>3</sub> /PES membrane applied in wastewater filtration	Phase inversion	The composite membrane had a decline in the fouling effect and a decrease in flux.	[82]
SiO <sub>2</sub> -Al <sub>2</sub> O <sub>3</sub>	Nanocomposite SiO <sub>2</sub> -Al <sub>2</sub> O <sub>3</sub> membrane	Surface coating	Higher structural stability and hydrogen selectivity.	[83]
Zirconia	Poly(arylene ether sulfone)/Nano-ZrO <sub>2</sub> Composite Anion Exchange Membranes applied in Alkaline Fuel Cells	Phase inversion	Improved water uptake, hydroxide ion conductivity, dimension stability, mechanical properties, thermal stability and chemical stability.	[84]
ZrO <sub>2</sub> , Al <sub>2</sub> O <sub>3</sub> , and TiO <sub>2</sub>	Nano-structured ceramic-metallic composite microporous membranes for gas separation application	Spray assisted surface coating	Enhanced thermal and chemical stability.	[85]



Table 4. Cont.

Nanoparticle	Membrane Application	Modification Technique	Membrane Modification Enhancement	Reference
Al <sub>2</sub> O <sub>3</sub>	Hybrid Composite Membranes used for Lithium-Ion Batteries	Dipped Coating	Greater thermal stability and enhanced wettability.	[86]
Fe/Pd	Microfiltration Membrane	Ion-exchange pore diffusion technique	Higher reactivity.	[87]
ZnO	PVDF microfiltration membranes used for water treatment	Phase inversion	The composite membrane had greater water flux, breaking strength, and pore size distribution.	[88]

### 3.1.3. Applications of Nanoparticle Membranes in Water Treatment

The pollution of water by contaminants is a worldwide issue that must be addressed efficiently to overcome the drastic consequences of water contamination. Nanotechnology offers a wide range of applications in the field of water and wastewater treatment (Table 5).

Table 5. Summary of nanomaterials used in membranes for water/wastewater treatment.

Nanomaterial	Application in Water/Waste Treatment	Process Applied	Enhancement in Membrane after the Incorporation of the Nanomaterial
CNTs, zeolites, metal-oxides and chitosan	Pollutant removal	Adsorption	High surface area, high accessible adsorption sites, fine-tuning of compound to pollutant, easy to reuse
nZVI, Au, and TiO <sub>2</sub>	Pollutant degradation	Photocatalysis or chemical reduction	Catalytic reduction and photocatalysis not seen in bulk materials, unique quantum effects
Chitosan, Ag, TiO <sub>2</sub> and MgO, and CNTs	Removal of contaminants from drinking water or wastewater	Disinfection	Cell membrane damage, metal chelation in cells, reactive oxygen species (ROS) production, chemical stability

Figure 3 represents the adsorption process of a nanoparticle-based membrane in the removal of several heavy metals and dyes for water treatment. Several studies have reported the use of nanoparticles in membranes to enhance the removal efficiency of pollutants from water. Figure 4 below shows the most commonly used nanoparticles for water treatment.

Zhao, et al. [89] added a series of defective ZIF-8 (dZIF-8) nanoparticles into polyamide-based thin-film nanocomposite (TFN) membranes for the desalination of seawater and brackish water. The authors studied the incorporation of dZIF-8 with several loadings on membrane separation performance and properties. The authors found that the separation performance and the properties of the membrane were greatly enhanced as the loadings of the nanoparticles increased [89]. The main target of Bose, et al. [90] was to fabricate a polymeric nanocomposite membrane with a low-budget nanoparticle for an effective oil-water separation process. The authors used a cellulose acetate (CA) polymer to fabricate the membrane and silicon carbide (SiC) nanoparticles to modify the membrane. The effect of silicon carbide (SiC) nanoparticle addition on membrane properties was analyzed by the authors. The results of the authors' study show that the addition of silicon carbide (SiC) nanoparticles increased membrane hydrophilicity, pore size, water flux, porosity, and water content. An 89% increment of the pure water flux occurred after using the modified membrane. Furthermore, the antifouling properties of the membrane was enhanced as

well. Besides, reasonable improvement in the antifouling attributes of the membranes were also observed. Thus, the modified membrane by the SiC nanoparticles is more efficient for the oil-water separation process than the unmodified membrane [90].

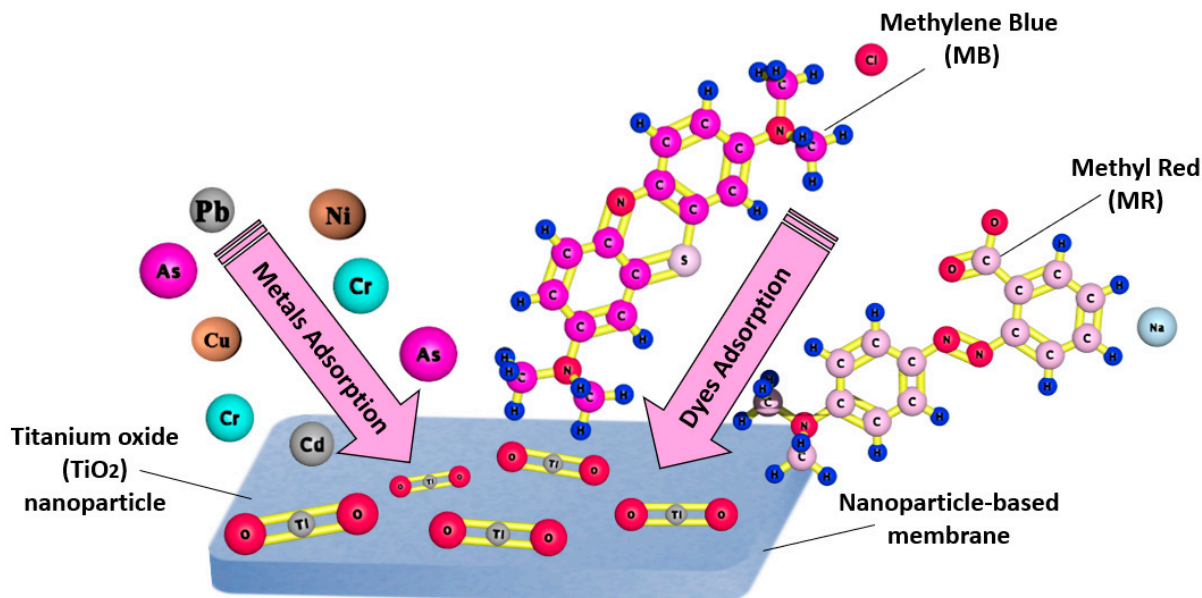


Figure 3. Schematic representation of heavy metals and dye adsorption by a nanoparticle-based membrane for water treatment.

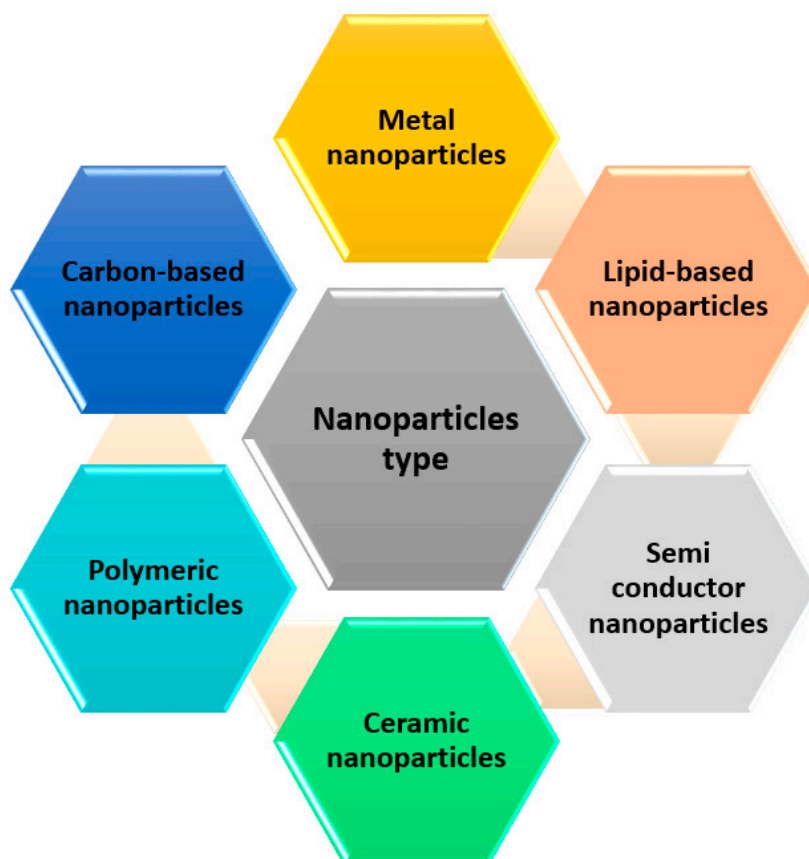


Figure 4. Most commonly used types of nanoparticles in water treatment.

Wen, et al. [91] successfully modified a graphene oxide membrane (GOM) by superhydrophobic modification using fluorinated silica nanoparticles layers on the membrane

surface to improve the surface adhesion and decrease the surface energy. The authors used light/heavy water as a model and an air gap membrane distillation (AGMD) apparatus to evaluate the separation performance of the isotopic hydrogen of this composite membrane. The results of the authors' study demonstrate that the selectivity of the membrane was enhanced by the addition of the fluorinated silica nanoparticles [91]. Membrane fouling is considered the main limitation to the performance of membranes. Kazemi, et al. [92] aimed to enhance the antifouling properties of a PVC membrane by incorporating GO and GO-ZnO nanoparticles into the PVC membrane in oily wastewater treatment. The results of the study revealed that increasing the nanoparticle content of the membranes improved the membrane's hydrophilicity. In addition, the water flux, and mechanical strength of the membrane were also increased. Furthermore, the PVC/GO-ZnO membranes showed a greater turbidity removal efficiency and less flux reduction compared to the PVC and PVC/GO membranes [92]. There is a wide range of emerging technologies for the treatment of oily wastewater using ultrafiltration membranes that use hydrophilic nanoparticles for improving membrane efficiency. De Guzman, et al. [93] fabricated cellulose acetate (CA) mixed-matrix membranes with zwitterionic nanoparticles (polydopamine-sulfobetaine methacrylate P(DA-SBMA)) via a wet-phase inversion method for treating oily wastewater. The authors' found that the addition of the nanoparticles improved membrane porosity, hydrophilicity, water flux, flux recovery, and reversible fouling. The authors used several oil-in-water emulsions in their study, including containing diesel oil, toluene, hexane, dodecane, and food-grade oil. The study revealed that oil-water separation efficiencies from 95% up to 99% were achieved. Thus, nanoparticles were successful in improving the performance of membranes for oily wastewater treatment [93].

The design and fabrication of polymeric membranes with high rejection and outstanding permeability remains a major issue. Zhang, et al. [94] synthesized and used metal-organic framework nanoparticles that are soluble in water to modify a polyether-sulfone membrane forming a uniform porous membrane. The results of the authors' study showed that the permeability of the modified membrane was enhanced considerably. In addition, the water flux was also significantly enhanced. Furthermore, the modified membrane had a high rejection of approximately 100% for bovine serum albumin. Thus, the modification of the membrane with the nanoparticles significantly improved its separation performance [94]. Zhao, et al. [95] incorporated UiO-66-NH<sub>2</sub> nanoparticles into polyamide-based thin-film nanocomposite (TFN) RO membranes. The outstanding properties of the UiO-66-NH<sub>2</sub> nanoparticles enhanced the membrane surface hydrophilicity and decreased the preferential pathways and degree of cross-linking for the water molecules across the selective layers. In addition, the TFN membranes showed a higher salt rejection and water flux compared to the benchmark membranes [95]. Kotp [96] reported a new method containing high flux thin-film nanocomposite (TFN) nanofiltration (NF) membranes. The authors synthesized the membranes by incorporating camphor-Al<sub>2</sub>O<sub>3</sub>NPs (CA.TFN) and commercial-Al<sub>2</sub>O<sub>3</sub> (CO.TFN) into polyamide layers using an interfacial polymerization method. The results of the study revealed that the addition of the camphor-Al<sub>2</sub>O<sub>3</sub> NPs into the TFC membrane improved membrane water flux, salt rejection, and hydrophilicity [96]. In a further study, Matindi, et al. [97] fabricated polyethersulfone (PES)/sulfonated polysulfone (SPSf)/TiO<sub>2</sub> mixed matrix membranes (MMMs) for the oil/water emulsion separation process. The authors analyzed the membrane performance by various loadings of TiO<sub>2</sub> nanoparticles (NPs) and polymer concentrations. The results of the authors' study exhibited that adding small concentrations of TiO<sub>2</sub> NPs into the membrane led to an outstanding improvement in the separation performance of membranes applied in oil/water emulsion filtration [97]. Barati, et al. [98] used in situ grown iron oxide nanoparticles (NPs) study to impregnate commercial ceramic membranes via a facile technique to treat produced water. The results of the authors' study revealed that membrane hydrophilicity, organic rejection, and antifouling behavior were improved significantly after the addition of the iron oxide nanoparticles (NPs) [98].

The use of nanocomposite adsorptive membranes that incorporate nanosorbents is a very promising option for water treatment from heavy metals; however, the aggregation of nano-sorbents in the membrane matrix has hampered their practical uses. He, et al. [99] prepared an adsorptive membrane made up of homogenous in-situ generated ferrihydrite nanoparticles (NPs)/polyethersulfone (PES), and strived to remove lead from water containing heavy metals. The synthesized membrane had high surface hydrophilicity and water flux. In addition, it also showed high adsorption capacity and selectivity of  $Pb^{2+}$ , and outstanding reusability without significant loss of  $Pb^{2+}$  adsorption. Consequently, the reported membrane in this study with the ferrihydrite nanoparticles (NPs) is a very promising present material for the removal of heavy metals from water [99].

There have been huge advancements using inorganic membranes in the treatment of marginal water containing hydrocarbon contaminants. Liu, et al. [100] incorporated silica nanoparticles into an alumina matrix to achieve hydrophilic modification of alumina microfiltration membranes. The alumina membrane incorporating silica nanoparticles was intended to separate cyclohexane from water. The study demonstrated that the added silica nanoparticles significantly increased membrane hydrophilicity, water flux, and oil rejection. This study proved that the addition of nanoparticles in the membrane enhances the overall performance of the membrane with respect to oil-water separation processes [100]. The separation of oil-water emulsions can be successfully achieved by using porous ceramic membranes with great mechanical strength. However, the preparation of ceramic membranes that have small pore sizes and remarkable antifouling properties is quite hard to attain. Zhang, et al. [101] modified  $\beta$ -SiAlON ceramic membranes with  $SiO_2$  nanoparticles for the removal of oil droplets from an oil-water emulsion. The modified membranes had a very small pore size, and water fluxes that were outstanding for the oil-water separation process. Furthermore, the membrane displayed a high oil rejection rate and remarkable antifouling ability. Thus the synthesized membrane in this study with the nanoparticle can be considered as a promising material for oil-contaminated wastewater treatment [101]. Rowley and Abu-Zahra [102] used  $Fe_3O_4$  nanoparticles (NPs) to modify polyethersulfone (PES) nanocomposite membranes for the removal of arsenic from water. The fabricated PES membranes with A- $Fe_3O_4$  NPs showed a high adsorption capacity of arsenic from water using only small concentrations of the A- $Fe_3O_4$  NPs. The results prove that the synthesized membrane in this study with the incorporated A- $Fe_3O_4$  NPs is a very efficient candidate for the treatment of water from arsenic [102]. Table 6 below shows the applications of several nanoparticles for the removal of contaminants from water.

**Table 6.** Application of nanoparticles in the removal of contaminants from water.

Nanoparticle	Contaminants	Removal Capacities	Rejection (%)	Process Used	pH	Contact Time	Reference
Aluminium substituted goethite (Al-FeOOH)	Ni	94.52 mg·g <sup>-1</sup>	-	-	5	6 h	[103]
SiO <sub>2</sub>	Oil/water emulsion	-	99%	Microfiltration	-	-	[104]
ZnO and montmorillonite	Cu(II)	-	-	-	4	90 min	[105]
AgNps	<i>E. coli</i> , <i>B. subtilis</i>		94%	Microfiltration	-	-	[106]
Iron nanoparticles modified micro fibrillated cellulose	As(V)	2.460 mmol·g <sup>-1</sup>	-	-	2	75 min	[103]

Table 6. Cont.

Nanoparticle	Contaminants	Removal Capacities	Rejection (%)	Process Used	pH	Contact Time	Reference
Hematite	As(III) and As(V)	2899 ± 71.09 $\mu\text{g}\cdot\text{g}^{-1}$ and 4122 ± 62.79 $\mu\text{g}\cdot\text{g}^{-1}$	-	-	6–8	8 h	[107]
Nanoscale zero valent iron (NZVI)	Cr(VI)	100%	-	-	2	10–30 min	[108]
TiO <sub>2</sub> @g-C <sub>3</sub> N <sub>4</sub>	tetracycline	-	97%	Photocatalysis	-	-	[109]
Magnetite Fe <sub>3</sub> O <sub>4</sub> /Chitosan nanoparticles (Fe <sub>3</sub> O <sub>4</sub> /CSNPs)	Pb(II)	79.29 $\text{mg}\cdot\text{g}^{-1}$	-	-	6	12 h	[110]
MWCNTs, Graphene, TiO <sub>2</sub>	Cadmium	-	100%	Adsorption	-	-	[109]
MgO	Pb(II)	2614 $\text{mg}\cdot\text{g}^{-1}$	-	-	-	180 min	[111]
Zerovalent iron and reduced graphene oxide	Cd(II)	425.72 $\text{mg}\cdot\text{g}^{-1}$	-	-	5	50 min	[112]
CNTS	TOC	-	30.5%	Microfiltration	-	-	[113]
Ascorbic acid-stabilized zero valent iron Nps	Cd(II)	79.58%	-	-	7	60 min	[114]
Copper oxide	Cr(VI)	15.62 $\text{mg}\cdot\text{g}^{-1}$	-	-	3	180 min	[115]
Ag Nps	AZG dye	-	85%	Photocatalysis	-	-	[116]
Graphene oxide-Cobalt oxide	Cr(VI)	208.8 $\text{mg}\cdot\text{g}^{-1}$	-	-	3	12 h	[117]
$\gamma$ -Al <sub>2</sub> O <sub>3</sub> NPs	Cd(II)	17.22 $\text{mg}\cdot\text{g}^{-1}$	-	-	5	30 min	[118]
Manganese ferrite and cobalt	As(III)	24.17 and 24.81 $\text{mg}\cdot\text{g}^{-1}$	-	-	2	4 h	[119]
ZnO Nps	Oil, <i>E. coli</i>	-	-	Microfiltration, Antimicrobial	-	-	[120]
Sulfonated magnetic NPs	Pb(II)	108.93 $\text{mg}\cdot\text{g}^{-1}$	-	-	7	24 h	[121]
$\gamma$ -alumina NPs and MWCNTs	Ni	99.41% and 87.65%	-	-	10	30 min	[122]
Titanate nanotubes	Th(I) and Th(III)	709.2 $\text{mg}\cdot\text{g}^{-1}$	-	-	-	10 min	[123]
OMWCNTs	Indigo	-	98%	Microfiltration	-	-	[124]
Modified henna with Fe <sub>3</sub> O <sub>4</sub>	Cu(II)	99.11%	-	-	4	85 min	[125]
SiO <sub>2</sub>	Oil/water	-	98%	Microfiltration	-	-	[126]

Table 6. Cont.

Nanoparticle	Contaminants	Removal Capacities	Rejection (%)	Process Used	pH	Contact Time	Reference
$\gamma$ -alumina	Cu(II)	31.3 mg·g <sup>-1</sup>	-	-	5	4 h	[127]
Fe <sub>3</sub> O <sub>4</sub>	Ni	209.205 to 362.318 mg·g <sup>-1</sup>	-	-	8	35 min	[107]
GO	Oil/water; Methylene Blue dye	-	99%, 95.38%, 92.45%	Microfiltration, Adsorption	-	-	[128]
Nanoscale zero valent iron (nZVI)	Pb(II), Cd(II), Cu(II), Ni(II)	-	-	-	2–7	30 min (Pb), 20 min (Cd, Cu, Ni)	[129]

### 3.2. Nanofiber-Composed Membrane

#### 3.2.1. Freestanding Nanofiber Membrane

Nanofibers are traditionally stated as fibers with diameters less than 100 nm. Nanofibers are known for having a high weight ratio, and highly porous structure with remarkable pore interconnectivity [130]. The ratio of the nanofibers is very high, which makes it easier for them to interlock and form a freestanding porous membrane. The distinguishable properties of the nanofibers allow them to be used in various applications in several industries.

Cellulose fiber-modified membranes have been used for a long time ago in various water treatment applications. A new cellulose form was discovered in the last century that allows the design of new liquid separation membranes. Cellulose has outstanding film-forming and mechanical properties that enable it to be used in several industries. In addition, the cellulose surface is easy to modify and very safe to use, which eases the process of surface modification.

In many separation processes, there is an increasing demand for solvent-resistant and highly efficient nanoporous membranes. It is common for membranes to have a low permeation flux as a result of a low resistance to solvent and a thick membrane layer. The synthesis of ultrathin nanometer pore size membranes for rapid organic filtering is now the most difficult issue. Zhang, et al. [131] prepared ultrafine cellulose nanofibers via a facile method for the fabrication of ultrathin nano-porous membranes. The synthesized nanofibers had a diameter of  $7.5 \pm 2.5$  nm, and the cellulose nanoporous membranes had an adjustable thickness down to 23 nm. In addition, the cellulose nano-porous membranes had very narrow pore sizes that ranged from 2.5 to 12 nm. The resultant nanocellulose membrane had rapid permeation of water and several organic compounds in a pressure-driven filtration process. In addition, the prepared cellulose nanofibers in this study were easy to use in the production of novel syringe filters with less than 10 nm pore size, which has a wide range of applications in the rapid separation and purification process [131].

The fabrication of other biopolymer-based nanofiber ultrathin membranes was the main aim of several studies. Ling, et al. [132] synthesized a new ultrathin filtration membrane made of silk nanofibrils (SNFs), which were exfoliated from natural *Bombyx mori* silk fibers, for the separation of various dyes, proteins, and colloids of nanoparticles. The synthesized membranes had a thickness down to 40 nm and pore sizes ranging from 8 to 12 nm. The SNF-based ultrathin membrane synthesized in this study showed a water flux of  $13,000 \text{ L}\cdot\text{h}^{-1}\cdot\text{m}^{-2}\cdot\text{bar}^{-1}$ , which is greater than 1000 times of the most commercial ultrathin filtration membranes at present. In addition, the SNF-based ultrathin membranes exhibited very high efficiency for dyes, colloids of nanoparticles, and proteins, with a minimum of 64% rejection for Rhodamine B. Thus, the reported SNF-based ultrathin membrane in this study is a promising material for a broad range of applications in water and wastewater treatment.

Various techniques can be used in the preparation of nanofibers, including melt-blowing, flash-spinning, splitting of bicomponent fibers, physical drawing, phase separa-

tion [5], self-assembling [6], centrifugal spinning, solvent dispersion [7,8], hydrothermal [9], and electrospinning. Electrospinning is the best method of nanofiber preparation among all the mentioned methods. Electrospinning surpasses the mentioned methods by its high versatility in the preparation of nanofibers using a wide range of materials, and the capability of controlling the nanofiber diameter, morphology, and structure. In addition, it is easy to modify by the addition of several nanomaterials or soluble substances to the electrospinning solution. However, the application of electrospinning is hindered by its high cost, since it needs massive-scale solvent recovery from a dilute air stream, making the process uneconomical. Several studies reported the use of electrospinning for the preparation of nanofiber membranes for water treatment applications. Du, et al. [133] prepared via one-step electrostatic spinning of a polyvinylpyrrolidone (PVP), polyvinylidene fluoride (PVDF), and an inorganic titanium dioxide ( $\text{TiO}_2$ ) nanoparticles blend nanofiber membrane. The presence of PVDF increases the strength and chemical resistance of the membrane. In addition, the PVP enhances the hydrophilicity and the mechanical strength of the membrane. The synthesized membrane in this study showed a high separation efficiency (98.4%) for various emulsions, great antifouling properties with a remarkable flux recovery rate (FRR 95.68%), and a low total fouling ratio (15.18%) after many cycles. Thus, the electrospinning method is a remarkable method for the preparation of nanofiber membranes to be used in water treatment processes [133].

### 3.2.2. Nanofibers as Filler for Composite Membranes

In the water purification field, thin-film composite membranes (TFC) have received a lot of researchers' attention. Using a one-step procedure, a unique TFC membrane was created based on a layer of polyvinylidene fluoride (PVDF) that formed tree-like electrospun nanofiber membranes (TENMs) [134]. The TENMs were characterized by a high-proportion of interconnect pores, high surface porosity, a pore size less than 200 nm, and low tortuosity, compared to the traditional support membranes. Thus, this is very promising for the fabrication of high-performance TFC nanofiltration (NF) membranes. The results of the authors' study revealed that the rejection rate was greater than 97% against the  $\text{MgSO}_4$  solution and 76% against NaCl solution, showing great potentials in the water purification field [134].

As a result of the remarkable sieving performance for small molecules and ions, lower energy requirements, and high permeation flux, nanofiltration plays a major role in a wide range of processes. On the other hand, current nanofiltration membranes (NFMs) face significant difficulties in improving permeability while keeping a high rejection rate for divalent (or multivalent) ions. Lv, et al. [135] used an electrospun polyacrylonitrile nanofiber membrane as a support for a fabricated thin-film composite (TFC) nanofiltration membrane. The resulting NFMs had high water flux along with an excellent rejection rate for divalent anions and cations. This study opens the door for highly efficient methods for the preparation of NFMs to be used in various separation applications [135].

### 3.2.3. Applications of Nanofiber Membranes in Water Treatment

Catastrophic oily discharges into water are a huge concern for environmental pollution. Effective electrospun nanofiber membranes have attracted great interest due to their high surface area, high porosity, customizable wettability, and uniform pore distribution [136]. However, the most frequently used nanofiber membrane modification methods, including grafting and surface coating, are strictly limited, and thus reduce their use in several applications. Thus, Du, Wang, Liu, Wang and Yu [133] used a one-step electrostatic spinning technique to fabricate a polyvinylpyrrolidone (PVP), polyvinylidene fluoride (PVDF), and inorganic titanium dioxide ( $\text{TiO}_2$ ) nanoparticle blend nanofiber membrane. The addition of these chemicals increased the nanofiber membrane mechanical strength, hydrophilicity, and chemical resistance. In addition, the membrane appeared to be oleophobic in water and hydrophilic in air. The results of this study show that the produced membrane attained a separation efficiency of 98.4% for several emulsions, distinguishable antifouling

properties with a high flux recovery rate reaching 95.68%, and a low total fouling ratio up to 15.18%, after its use in several cycles. Thus, the fabricated membrane is an excellent choice for oil/water separation applications [133]. Xu, et al. [137] synthesized a unique tubular polyvinyl chloride (PVC) hybrid nanofiber membrane using hydrophobic nanosilica ( $\text{SiO}_2$ ) as the inorganic additive and a polyester (PET) hollow braided tube as the support. The fabricated membrane appeared to be very efficient in the separation of liquid, because of its remarkable separation efficiency for various water/oil emulsions. Furthermore, the membrane showed a distinguishable superhydrophobicity and lipophilicity under oil. In addition, the membrane had a high permeation flux and a remarkable separation efficiency greater than 95% under gravity. In addition, the three-dimensional tubular nanofiber membrane showed excellent porosity, mechanical properties, thermal stability, and hydrophobic stability. All of the above-mentioned properties of the synthesized three-dimensional tubular nanofiber membrane allow it to be effectively used in oily wastewater remediation processes [137]. As a continuation to oily wastewater separation methods, Su, et al. [138] fabricated a poly (vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP) nanofiber (PNF) membrane via a solution blow spinning technology. The fabricated membrane had high membrane roughness, super hydrophobicity and super lipophilicity. In addition, the membrane was capable of separating various oil/water mixtures including toluene, n-hexane, dichloromethane, and kerosene by gravity with a high (toluene/water) separation efficiency up to 99.99. Furthermore, the membrane had the capability of degrading organic pollutants in oily wastewater. Thus, the synthesized membrane is fully capable of being used as an efficient candidate for oil/water treatment processes [138]. Zhang, et al. [139] fabricated a PVDF/graphene (GE) composite membrane (TPGCM) covered with micro/nanospheres and tubular nanofibers. The membrane showed high superoleophilicity in air, remarkable separation efficiency, and outstanding recyclability. Thus, it can be efficiently used in oily water treatment industries [139]. Obaid, et al. [140] fabricated an electrospun nanofiber membrane (ENM) that is super-hydrophilic and, underwater, superoleophobic. The nanocoated-ENMs synthesized in this study showed excellent oil/water emulsion separation performance. In addition, the nanocoated-ENMs had high flux and separation efficiency for a surfactant-stabilized oil-in-water emulsion up to 97.5%. Furthermore, the nanocoated-ENMs showed outstanding chemical stability, reusability, and durability in harsh environments. Thus, the synthesized nanocoated-ENMs are promising candidates for oil/water emulsion separation [140].

Superwetting interfacial porous membranes with several wettabilities can be widely used in wastewater treatment. Several factors control membrane wettability including pH, temperature, and pressure. Yin, et al. [141] used a calcining-spraying method to prepare a novel electrospun SiNPs/ZnNPs- $\text{SiO}_2$ /TiO<sub>2</sub> (SZST) nanofiber membrane. The resultant membrane had the capability of changing its wettability in several environments. The membrane showed a high separation efficiency up to 99% for an oil/water emulsion. Furthermore, the membrane had excellent chemical stability and corrosion resistance. Consequently, the synthesized SZST nanofiber membrane in this study can be efficiently used in various water treatment processes [141]. Venkatesh, et al. [142] fabricated a DTPA/MWCNT/TiO<sub>2</sub>-polyvinylidene difluoride (PVDF) nanofiber membrane for oil-in-water emulsion separation. This showed a good underwater oleophobicity and hydrophilicity, and high separation efficiency for oil-water emulsions. Thus the synthesized nanofiber membrane in this study has great potential in oil-water treatment processes [142]. Wang, et al. [143] synthesized a deacetylated cellulose acetate (d-CA) nanofiber membrane for oil/water separation. The fabricated membrane was super-hydrophilic in oil and oleophobic in water and showed high separation efficiency of 99.97% and separation flux of 38,000 L/m<sup>2</sup>·h. The d-CA nanofiber membranes showed outstanding self-cleaning and antipollution abilities. Thus, the synthesized nanofiber membrane in this study can be efficiently used in the separation of oil from water [143]. The usage of electrostatic spinning to fabricate nanofiber membranes (NFMs) has gained great interest in the treatment of wastewater due to these membranes having a large specific surface area and high porosity.



However, the large-scale application of nanofiber membranes (NFMs) is limited by fouling and their incapability of removing very small molecular weight dyes. Thus, Li, et al. [144] fabricated polyacrylonitrile (PAN)-ZnO NFM for efficient dye removal. The results of the study demonstrated that the (PAN)-ZnO NFM exhibited a very high removal rate of more than 95% for sunset yellow (YS), methylene blue (MB), Congo red (CR), rhodamine B (RhB), and methyl orange (MO) with an outstanding water flux ( $1016 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}\cdot\text{Bar}^{-1}$ ). In addition, the PAN-ZnO NFM had remarkable mechanical properties and antifouling abilities. As a result of the excellent abilities that the PAN-ZnO NFM holds, it is fully capable to be used in dye removal from wastewater [144]. Ozbey-Unal, et al. [145] synthesized hydrophobic nanofiber membranes to remove salt and boron from geothermal water using air gap membrane distillation (AGMD). The results of the study showed that the permeate flux and the mechanical strength of the membrane were improved. Hence, the membrane was capable of removing salt and boron from geothermal water [145]. Wang, et al. [146] synthesized a multifunctional polyvinylidene fluoride-co-hexafluoropropylene (PVDF-HFP)/catechol-polyethyleneimine (CA-PEI)/Ag/3-glycidyloxy propyltrimethoxysilane (KH560) tubular nanofiber membrane (TNM) for oil/water separation and dye degradation. The results of the study show that the fabricated membrane had a high separation rate and separation efficiency along with a catalytic ability for the degradation of several dyes. Thus, the membrane is efficient for oil/water separation and water treatment processes [146].

The development of a cost-effective and fast-paced oil/water separation process has become necessary due to an increase in oil spills and significant organic contamination of the marine environment. Moatmed, et al. [147] introduced flexible and freestanding hybrid polystyrene nanofibers as a hybrid membrane for ultrafast oil/water separation. The authors used several loadings of  $\text{Fe}_3\text{O}_4$  nanoparticles and added them to the polystyrene nanofibers to synthesize a superhydrophobic/super-oleophilic membrane. The results of the study show that the addition of ( $\text{Fe}_3\text{O}_4$ ) nanoparticles to the membrane improved the separation efficiency and superhydrophobic properties of light and heavy oils. The synthesized membrane had a very high flux ( $5000 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ ), along with a separation efficiency of up to 99.8% for hexane. Thus, the nanofiber membrane synthesized in the current study can be efficiently used in oil/water separation industries [147]. Choi, et al. [148] aimed to adsorb heavy metal ions from water by synthesizing a thiol-functionalized cellulose nanofiber membrane. The membrane showed a high adsorption rate for Cd(II), Cu(II), and Pb(II) ions. Thus, the synthesized membrane can be used in the remediation of water from heavy metal ions [148]. Zhang, et al. [149] fabricated an alkali lignin/poly (vinyl alcohol) (lignin/PVA) composite nanofiber membrane for the adsorption of Safranin T (ST). The nanofiber membrane showed excellent adsorption ability for Safranin T (ST) from water. Hence, the synthesized alkali lignin/poly (vinyl alcohol) (lignin/PVA) composite nanofiber membrane can be used as an efficient adsorbent for dyes from wastewater [149].

The fabrication of highly porous super-hydrophobic and super-oleophilic materials is very important in the efficient removal of oils and dyes from wastewater. Gao, et al. [150] synthesized a hybrid nanofiber membrane (FHNM) containing  $\text{SiO}_2$ /polyvinylidene fluoride (PVDF) microspheres for oil separation from water. The results of the study showed that the FHNM was fully capable of separating oil, and corrosive solutions from water. Hence, FHNM is a promising candidate for oil remediation from water [150]. Cao, et al. [151] prepared a stellate poly(vinylidene fluoride) (PVDF)/polyethersulfone (PES) microsphere-nanofiber membrane for oil/water separation. The synthesized PES/PVDF membranes showed excellent ability in the separation of oils from water. Hence, the PES/PVDF membranes mentioned in this study can be successfully used in oil/water separation processes [151]. Zhang, et al. [152] synthesized a  $\text{TiO}_2$  nanofiber membrane for water treatment. The  $\text{TiO}_2$  nanofiber membrane appeared to have a high Humic Acid removal reaching 90%. Thus, the synthesized  $\text{TiO}_2$  nanofiber membrane is a promising candidate for water treatment [152]. Tables 7 and 8 below shows the application of several nanocellulose and nanofibrous membranes in the removal of contaminants from water.

**Table 7.** Application of modified nanocellulose membranes in the removal of contaminants for water treatment.

Modified Nanocellulose	Method Used	Application	Removal Efficiency	Reference
Amino-modified CNF	Infusion	Microfiltration of virus, bacteria, and metal ions adsorption	MS2: LRV 4; <i>E. coli</i> : LRV 6; Metal ions: -	[153]
TEMPO-oxidized CNC	Membrane coating	Metal ions adsorption	–	[154]
BTCA-functionalized CNC	Spray coating	Metal ions adsorption	58.05%	[155]
TEMPO-modified and Unmodified CNF	Membrane deposition	Oil-water separation	>99%	[156]
Meldrum's acid-modified CNF	Impregnation	Dye adsorption and Microfiltration of Fe <sub>2</sub> O <sub>3</sub> nanoparticles	>99% dye and nanoparticles	[157]
TiO <sub>2</sub> -modified CNC	In-situ growth	Oil-water separation	>99.5%	[158]
AgNP- and PtNP-grafted CNC	phase separation	wastewater treatment	92–94%	[159]
(tridecafluoro-1,1,2,2-tetrahydrooctyl)-trichlorosilane-modified BNC	Supercritical-drying	Desalination using DCMD	>99.8%	[160]
Thiol-modified CNF	Infusion	Metal ions adsorption	>93%	[161]
Alkoxysilanes-modified BNC	Conventional drying	Water-oil separation	>99%	[162]
Ag-modified CNF	Immobilizations	Dye degradation	98%	[163]
(3-aminopropyl) triethoxysilane-modified BNC	Freeze-drying	Metal ion adsorption	5–100%	[164]
Fe <sub>3</sub> O <sub>4</sub> modified CNF	In-situ synthesis	Dye degradation	94.9%	[165]

**Table 8.** Application of various nanofibrous membranes in the removal of heavy metals from water for water treatment.

Nano Fibrous Membrane	Heavy Metal Ion	Adsorption Capacity (Mg/G)	Reference
Chitosan	As(V)	11.2	[166]
Multiwalled carbon nanotube-Polyethyleneimine/Polyacrylonitrile	Pb(II), Cu(II)	232.7, 112.5	[167]
Polyindole	Cd(II)	140.36	[168]
Polyvinyl alcohol/Silica	Cu(II)	489.12	[169]
Silk fibroin/Cellulose acetate	Cu(II)	22.8	[170]
Polyvinyl alcohol/Titanium dioxide/Zinc oxide	Th(IV)	333.3	[171]
Chitosan	As(V)	30.8	[172]
Polyacrylonitrile/Titanium dioxide	Pb(II), Cd(II)	193, 91	[173]
Chitosan/Cellulose acetate	Cd(II)	110.48	[174]
Polyvinylpyrrolidone/Silica/3-Aminopropyltriethoxysilane	Cd(II), Pb(II), Ni(II)	157.4, 158.3, 63.0	[175]
Chitosan	Cr(VI)	20.5	[176]

Table 8. Cont.

Nano Fibrous Membrane	Heavy Metal Ion	Adsorption Capacity (Mg/G)	Reference
Polyamide 6/Fe <sub>3</sub> O <sub>4</sub> /Oxidized multiwalled carbon nanotubes	Pb(II)	49.3	[177]
Wool keratose/Silk fibroin	Cu(II)	2.88	[178]
Polyvinylpyrrolidone/Silica	Cr(III)	97	[179]
Chitosan/poly(L-lactic acid)	Cu(II)	111.66 ± 3.22	[180]
Polyvinyl alcohol/Titanium dioxide	Th(IV)	238.1	[181]
polyethersulfone-poly (dimethyl amino) ethyl methacrylate	Cu(II)	161.3	[182]
Chitosan/Polyvinyl alcohol	Cu(II)	90.3	[183]
Polyacrylonitrile/Fe <sub>2</sub> O <sub>3</sub> /Sodium dodecyl sulfate	Cu(II), Pb(II), Cd(II)	11.8, 30, 7.5	[184]
Chitosan/Poly(ethylene oxide)/Permutit	Cr(VI)	208	[185]
Polyacrylonitrile/γ-AlOOH	Pb(II), Cu(II), Cd(II)	180.83, 48.68, 114.94	[186]
Polyethyleneimine/Polyvinyl alcohol	Cr(VI)	150	[187]
Polyacrylic acid/Polyvinyl alcohol/Zero-valent iron	Cu(II)	107.8	[188]
Chitosan/Graphene oxide	Cu(II), Pb(II), Cr(VI)	461.3, 423.8, 310.4	[189]
Polyethyleneimine/Polydopamine	Cu(II)	33.59	[190]
Polyetherimide-Fe <sub>3</sub> O <sub>4</sub> /Polyacrylonitrile	Cr(VI)	684.93	[191]
Chitosan/Sodium polyacrylate	Cr(VI)	78.92	[192]
Polyvinyl alcohol/Chitosan/ZnO	Cd(II), Ni(II)	138.77, 50.21	[193]
Polyindole	Cu(II)	121.95	[194]
Poly(vinylidene fluoride)/Polydopamine	Cu(II)	26.7	[195]
Wool keratin/Nylon 6	Cu(II)	103.5	[196]
Polyacrylonitrile/Cellulose acetate/ZIF-67	Cu(II), Cr(VI)	18.9, 14.5	[197]
Chitosan/Poly(ethylene oxide)	Ni(II)	227.27	[198]
Polyvinyl alcohol/NaX zeolite	Ni(II), Cd(II)	342.8, 838.7	[199]
Polyacrylic acid/Polyvinyl alcohol	Pb(II)	288	[200]
Polyvinyl alcohol/Sb-TBC		91	
Polyvinyl alcohol/Sr-TBC	Pb(II)	124	[201]
Polyvinyl alcohol/La-TBC		194	
Polyacrylonitrile/Polypyrrole	Cr(VI)	74.91	[202]
Cellulose acetate/Polymethacrylic acid	Pb(II)	146.21	[203]
Polyacrylic acid/Sodium alginate	Cu(II)	591.7	[204]
Polystyrene/Titanium dioxide	Cu(II)	522	[205]
Chitosan/Titanium dioxide	Cu(II), Pb(II)	710.3, 579.1	[206]
Polyacrylonitrile/Zinc oxide	Pb(II), Cd(II)	322, 166	[207]
Polyacrylonitrile@γ-AlOOH	Cr(VI)	5	[208]
Ethyl cellulose/Al <sub>2</sub> O <sub>3</sub>	Pb(II)	134.5	[209]

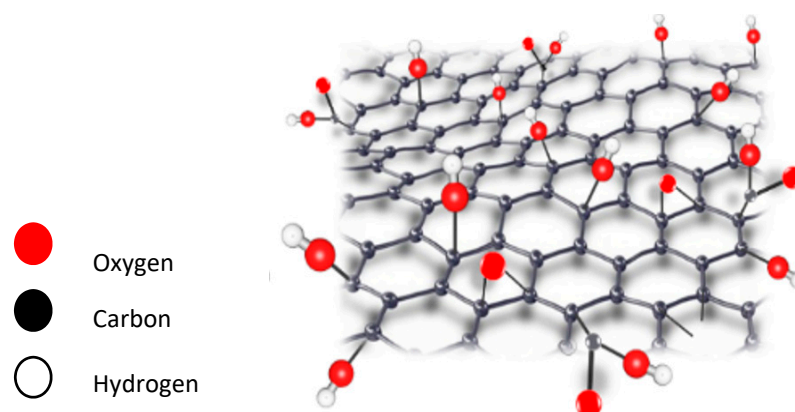
Table 8. Cont.

Nano Fibrous Membrane	Heavy Metal Ion	Adsorption Capacity (Mg/G)	Reference
Silica@Polyvinylidene fluoride-hexafluoropropylene	Cu(II)	21.9	[210]
Polyacrylonitrile/Chitosan	Cr(III)	116.5	[211]
MgAl-EDTH-LDH@Polyacrylonitrile	Cu(II)	120.77	[212]
Polyvinyl alcohol/Silica	Mn(II), Ni(II)	234.7, 229.9	[213]
Polyvinylpyrrolidone/Silica	Hg(II)	852	[214]
Chitosan/Poly (ethylene oxide)/Activated carbon	Cr(VI), Fe(III), Cu(II), Zn(II), Pb(II)	261.1, 217.4, 195.3, 186.2, 176.9	[215]
Poly (ethylene oxide)/Graphene oxide	Cu(II), Cd(II)	44.7, 59.1	[216]
Cellulose/Graphene oxide	Hg(II)	13.73	[217]
Polyacrylonitrile/F300	Hg(II), Pb(II)	53.09, 30.19	[218]
Polyacrylonitrile/MOF808		50.88, 23.98	
Poly(vinylidene fluoride)/MOF808		42.60, 17.19	
Polyacrylonitrile/MOF-808	Cd(II), Zn(II)	225.05, 287.06	[219]
Chitosan/Polyvinyl alcohol/Zeolite	Cr(VI)	450	[220]
Chitosan/Fe	As(III)	36.1	[221]
Chitosan/Fe <sub>3</sub> O <sub>4</sub> /Oxidized multiwalled carbon nanotubes	Cr(VI)	358	[222]

### 3.3. Two-Dimensional Layer Materials Composed Membrane

In today's society, studies in the fields of the chemical industry, energy conservation, and environmental remediation are all confronting significant hurdles in terms of the usefulness, durability, and performance of essential main materials. It is well known that complex and advanced carbon-based nanomaterials, such as graphene, will keep on evolving and accelerating over time. These carbon-based nanomaterials are predicted to play a key role in resolving several important difficulties and achieving advances in engineering and technology. These carbon nanomaterials are used in several water treatment applications such as dye removal, oil separation from water, and heavy metal ions removal.

In the membrane field, two-dimensional materials (2-D) have evolved rapidly in chemical engineering research and water treatment applications. It all started in the year 2010 when Geim and Novoselov were awarded the Nobel Prize in Physics for their groundbreaking experiment in the two-dimensional graphene [223]. Graphene and other two-dimensional materials are the main focus of a wide number of studies in several research fields. According to Whitby [224], graphene has a honeycomb crystal structure made up of a monolayer of carbon atoms with a one-atomic thickness of  $sp^2$  linked carbon that forms a two-dimensional (2-D) array of carbon atoms arranged in a hexagonal structure. The unique characteristics of two-dimensional carbon-based materials, especially graphene, makes them the ultimate choice for membrane materials. These 2-D materials have a two-dimensional structure with a mono-atomic thickness, high chemical inertness, and mechanical strength. Typically, graphene has been regarded as an ideal membrane because of its monolayer structure with mono-atomic thickness. Figure 5 below shows the three-dimensional structure of graphene.



**Figure 5.** Graphene three-dimensional (3-D) structure.

The wide variation in 2-D materials opens the door for a lot of possibilities for the development of two-dimensional-material membranes (2DMMs). Porous graphene, zeolite nanosheets, and MOFs can all be used to produce nanosheet membranes. The strategic selection of the aperture size and porosity of in-plane nanopores can significantly improve the membrane's selectivity and permeation simultaneously. However, nonporous nanosheets, such as graphene oxide (GO), can be drawn into laminar membranes with ordered structures. Basically, defect-free graphene is an impenetrable material for all types of molecules, even for the tiniest ones, thus it is crucial to either drill nano-size pores in graphene nanosheets or construct the nanosheet into a laminar membrane to give it the size-sieving feature. Several molecular dynamics simulations and tests have proved the feasibility of using graphene ultrathin membranes with functionalized nanopores for the separation of various ions and liquids with a remarkable selectivity and a fast separation rate. However, large-scale production of graphene nanosheets functionalized with nanopores is very difficult, since it requires very precise control for correct membrane pore size and distribution. In addition, as the applied pressure exceeds the critical pressure, the produced nanopores may undergo a loss of mechanical strength and stability, leading to catastrophic ripping of the membrane. With the great number of challenges facing the use of graphene nanosheets functionalized with nanopores, most of the studies primarily focus on finding an explanation for the transport behavior and sieving mechanism of the membrane. On the other hand, graphene derivatives, including a graphene oxide (GO) membrane and reduced graphene, do not face the same problems as graphene nanosheets with functionalized nanopores. Because of the nanochannels in their membranes, the nanopores in their nanosheets, and their functional groups, graphene derivatives have strong selective separation capability.

The presence of the oxygen-containing functional groups in graphene oxide nanosheets enables them to be formed into a laminar structure membrane using several techniques such as vacuum filtration, and dip coating. Many studies have focused on improving the structural stability of graphene oxide nanosheets, such as the addition of metal ions or molecules to the nanosheets. Furthermore, controlling the graphene-based membranes pore sizes is a necessity for the exploration of their transport characteristics and their application in several water treatment fields, such as water desalination. Based on present research studies, graphene oxide (GO) membranes hold very promising desalination capabilities owing to their easy fabrication process, low cost of production, and great performance [225]. Chen, et al. [226] synthesized ultrathin graphene membranes with very precise control of subnanometer pores via coassembling a graphene oxide nanosheet and a polymer on a porous ceramic substrate. The results of the authors' study show that the synthesized graphene membranes have distinguishable molecular-sieving water evaporation properties that achieve a very high water evaporation flux compared to other conventional membranes. Thus, the graphene membrane fabricated in this study is a very promising material for water desalination and other separation processes [226]. The remediation of

detrimental heavy metals from the marine environment has become the focus of a wide number of studies as a result of the catastrophic implications that they have on the whole environment and human body.

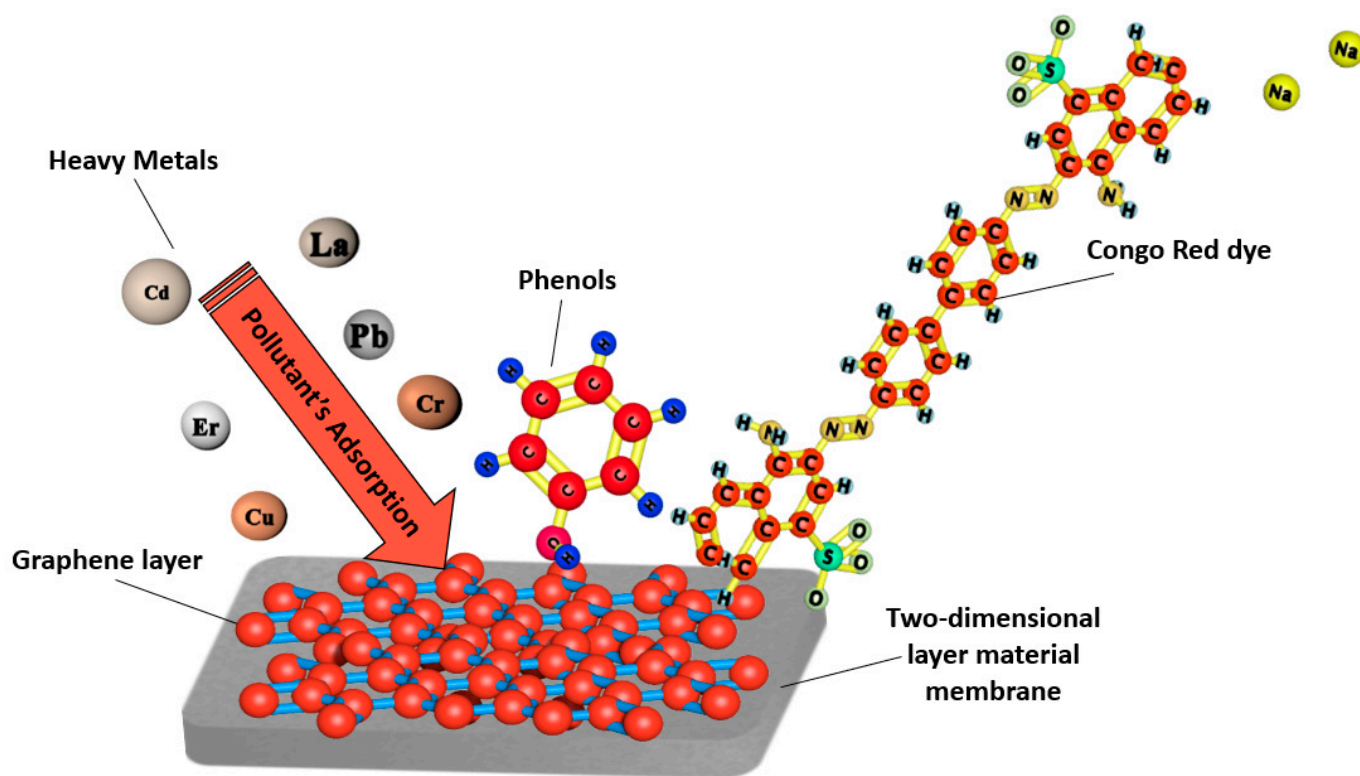
Modi and Bellare [227] fabricated a unique nanohybrid that comprises zeolitic imidazolate framework-67 nanoparticles-decorated carboxylated graphene oxide nanosheets (ZIF-67/cGO) incorporated in polyethersulfone (P) hollow fiber membranes (HFMs) to improve membrane separation efficacy. The results of the authors' study showed that the addition of ZIF-67/cGO nanohybrid in HFMs enhanced the physicochemical properties of the nanocomposite (ZcGP) HFMs, which led to a remarkably high pure water flux ( $346.4 \pm 11.2$  L/m<sup>2</sup>/h) and an outstanding flux recovery (95.7%). In addition, the membrane showed high adsorption capacity and removal of Cu<sup>2+</sup> and Pb<sup>2+</sup> heavy metal ions from contaminated water. Thus, the membrane provided in this study is an efficient material for the separation of heavy metals from water [227].

Current studies have used two-dimensional materials other than carbon-based 2-D materials, such as carbon nitride nanosheets (g-C<sub>3</sub>N<sub>4</sub>NSs), 2-D boron nitride nanosheets (BNNS), and metal-organic framework nanosheets in water treatment applications. In addition, a few studies have reported the use of mixed matrix membranes that comprise nanosheets in water remediation. Amid, et al. [228] fabricated ultrafiltration polycarbonate mixed matrix membranes (MMMs) for the separation of oil from water. Graphene oxide nanosheets and modified halloysite nanotubes were incorporated by the authors into the blank membrane. The result of the authors' study show that after the modification of the membrane, the oil rejection rate and oil removal efficiency were enhanced. Thus, the synthesized MMMs in this study are a promising candidate for oil/water separation processes [228].

#### Application of Two-Dimensional Layer Materials Composed Membrane in Water Treatment

Currently, two-dimensional layer materials composed of membranes are becoming new-generation materials for water treatment applications with high efficiency (Figure 6). Several studies have focused their search on graphene oxide (GO) membranes for a wide variety of water treatment applications. The unique two-dimensional GO membrane inter-layer nanostructure provides a base for a very precise and efficient molecular sieving for rapid water and ion transport applications. However, there are a few studies concerning the transport mechanism of water and ions through the GO membrane's 2-D interlayer nanochannels. In addition, the GO membrane application in several water treatment processes is limited by the tradeoff between selectivity and permeability. Li, et al. [229] investigated the water and ion transport mechanisms in the two-dimensional nanochannels of the GO membrane for the development of GO membranes for a desalination process. The authors found there was an interaction between the oxygen-containing groups in the GO nanosheets and the water/ion, which proved there was successful transport. Thus, GO membranes were efficiently used in the desalination process [229]. The major industrial effluent that pollutes the environment is oily wastewater. Membrane technology is widely used in the treatment of oily wastewater to limit its catastrophic effects on the environment. Zeng, et al. [230] synthesized Hal@MXene-PDA two-dimensional (2-D) composite membranes via vacuum filtration to investigate their application in oil/water separation. The Hal@MXene-PDA composite membrane showed higher hydrophilicity compared to the bare membrane. In addition, the membrane showed high pure water flux and high oil rejection (petroleum ether and lubricating oil) up to 99.8%. Furthermore, the modified membrane (M6) also had excellent anti-fouling abilities. Thus, the membrane fabricated in this study is a promising candidate for oil-water separation [230]. Feng, et al. [231] synthesized a reduced graphene oxide (RGO)/polydopamine (PDA)/titanium carbide (MXene) composite via a dopamine modification approach. The authors suction filtrated the RGO/PDA/MXene composites on a nylon membrane to fabricate a two-dimensional-two-dimensional (2D-2D) laminated composite membrane. The modified membrane demonstrated very high removal, greater than 96% for the following dyes:

Methylene Blue (MB), Methyl Red (MR), Methyl Orange (MO), Evans Blue (EB), and Congo Red (CO). In addition, the modified membrane also exhibited a very high oil/water separation greater than 97% on emulsions. Moreover, long-term cycle experiments conducted by the authors demonstrated the stability of RGO/PDA/MXene composite membranes. Thus, the RGO/PDA/MXene composite membranes synthesized in this study is a very promising applicant in the oil/water separation process and water treatment field [231]. Zhao, et al. [232] synthesized a graphitic carbon nitride nanosheet/reduced graphene oxide/cellulose acetate composite photocatalytic membrane (g-C<sub>3</sub>N<sub>4</sub> NS/RGO/CA) for water treatment applications. Under visible light irradiation the membrane exhibited an outstanding performance in water treatment. The membrane showed high removal efficiency of Rhodamine B and excellent anti-fouling property. The membrane also had high removal efficiency for COD<sub>Mn</sub>, UV<sub>254</sub>, TOC, and bacteria from the surface of the water. Thus, the synthesized membrane in this study can be successfully used in water treatment applications [232].



**Figure 6.** Schematic representation of heavy metals, dyes, and phenols adsorption by a graphene-based membrane for water treatment.

Small pollutants and organic molecules cause detrimental environmental effects that destroy the environment and human health. However, their removal from the environment is very difficult due to their narrow size. Yang, et al. [233] demonstrated single-layer nanoporous graphene (NPG) membranes for the removal of organic pollutants (methanol, ethanol, urea, n-nitrosodimethylamine (NDMA), 2-propanol, pyrrole, and phenol) from water. The nano porous graphene (NPG) membranes exhibited high water permeability and selectivity against the target organic pollutants. Thus, the proposed membrane in this study is a promising candidate for the removal of organic contaminants from water [233]. Nanomaterials are mainly incorporated into the membranes to enhance the membrane permeation flux and oil/water emulsion separation performance. Zhang, et al. [234] fabricated nanocomposite membranes graphene oxide/halloysite nanotubes (GO/HNTs) that consisted of GO nanosheets and HNTs. The fabricated membrane exhibited high permeation flux and rejection rate. In addition, the GO/HNTs composite membrane

was successfully used for oil-water separation experiments. Consequently, the proposed membrane in this study is a promising candidate for oil/water separation processes [234]. Table 9 below shows the application of some graphene and its derivatives in the removal of heavy metals and dyes from water.

**Table 9.** Application of graphene and its derivatives in the removal of heavy metals and dyes from water for water treatment.

Adsorbent	Pollutant	Adsorption Capacity (mg·g <sup>-1</sup> )	Kinetic Model	Reference
Reduced graphene oxide (rGO) decorated with molybdenum disulfide (MoS <sub>2</sub> )	Cr(III)	242	-	[235]
	Co(II)	112		
	Ni(II)	145		
	Cu(II)	417		
	Zn(II)	550		
	Pb(II)	498		
Chitosan reinforced graphene oxide-hydroxyapatite (CS@GO-Hap)	Congo Red (CR)	43.06	pseudo-second-order	[236]
	Acid Red 1 (AR1)	41.32		
	Reactive Red 2 (RR2)	40.03		
β-CD/PAA/GO nanocomposites	methylene blue (MB)	247.99	Langmuir	[237]
	safranin T (ST)	175.49		
MnO <sub>2</sub> nanotubes@reduced graphene oxide hydrogel (MNGH)	Pb <sup>2+</sup>	356.37	-	[238]
	Cd <sup>2+</sup>	177.4		
	Ag <sup>+</sup>	138.2		
	Cu <sup>2+</sup>	121.5		
	Zn <sup>2+</sup>	83.9		
Graphene oxide embedded calcium alginate (GOCA)	Pb(II)	602	Pseudo-second-order	[239]
	Hg(II)	374		
	Cd(II)	181		
Silica-decorated graphene oxide (SGO)	Cadmium(II)	43.45	pseudo-second-order	[240]
Thiosemicarbazide functionalized graphene oxide (GO-TSC-GO)	methylene blue (MB)	596.642	pseudo-second-order	[241]
Fe <sub>3</sub> O <sub>4</sub> /SiO <sub>2</sub> -GO	Cd(II)	128.2	-	[242]
	Pb(II)	385.1		
Poly(m-phenylenediamine)/reduced graphene oxide/nickle ferrite nanocomposite	Cr(VI)	502.5	pseudo-second-order	[243]
Graphene oxide–silica composite	Congo red (CR)	43.45	pseudo-second-order	[240]
	Cadmium(II)	333.33		
Graphene oxide-activated carbon (GO-AC) composite	methylene blue (MB)	147	pseudo-second-order	[244]
	crystal violet (CV)	70		
Graphene oxide (GO)	Pb <sup>2+</sup>	75.41	pseudo-second-order	[245]
	Ni <sup>2+</sup>	29.04		
	Cd <sup>2+</sup>	31.35		
Reduced graphene oxide (rGO)	malachite green (MG)	476.2	pseudo-second-order	[246]
GO@SiO <sub>2</sub> -MSP@SiO <sub>2</sub> NH <sub>2</sub>	Pb(II)	323.5	pseudo-second-order	[247]



Table 9. Cont.

Adsorbent	Pollutant	Adsorption Capacity (mg g <sup>-1</sup> )	Kinetic Model	Reference
Reduced graphene oxide/Lanthanum Alluminate nanocomposites (RGO-LaAlO <sub>3</sub> )	Methyl orange (MO)	702.2	Pseudo-second-order	[248]
Sulfonated graphene oxide (SGO)	Pb <sup>2+</sup>	415	Pseudo-second-order	[249]
MnFe <sub>2</sub> O <sub>4</sub> /rGO magnetic nanoparticles (MRGO)	methylene blue (MB)	105	Pseudo-second order	[250]
Graphene oxide functionalized chitosan-magnetite nanocomposite	Cu(II) Cr(VI)	111.11 142.85	Pseudo-second-order	[251]
Fe <sub>3</sub> O <sub>4</sub> /graphene nanocomposite	Cr(VI)	280.6	Pseudo-second-order	[252]
magnetic CoFe <sub>2</sub> O <sub>4</sub> /graphene oxide (GO)	methylene blue (MB) rhodamine B (RhB)	355.9 284.9	Pseudo-second-order	[253]
Graphene oxide (GO)	Pb(II)	555	Pseudo-second-order	[254]
Bimetal oxide decorated graphene oxide (Gd <sub>2</sub> O <sub>3</sub> /Bi <sub>2</sub> O <sub>3</sub> @GO) nanocomposite	Methyl orange (MO)	544	Pseudo-second-order	[255]
Thiosemicarbazide-grafted graphene oxide (GO-TSC)	Hg(II)	231	-	[256]
3D graphene nanoedges	methyl orange (MO)	27.932	-	[257]
Porous silica-graphene oxide nanocomposite(GO-SiO <sub>2</sub> )	Pb(II) As(III)	527 30	Pseudo-second-order	[258]
Magnetic CoF/GO	MB MV	157 122	Pseudo-second-order	[259]
GN-MnO <sub>2</sub>	Co(II) Cr(III)	403.4 491.98	Second-order-pseudo	[260]
Graphene oxide	Congo Red (CR)	120.20	second order	[261]
Bifunctionalized graphene oxide/MnFe <sub>2</sub> O <sub>4</sub> magnetic nanoparticles (PEHA-Phos-GO/MnFe <sub>2</sub> O <sub>4</sub> )	Pb(II)	366.4	Pseudo-second-order	[262]

#### 4. Conclusions

The fast pace of industrial development and the global population growth is increasing the demand for several water resources. Thus, high-performance water treatment technologies are required. Membrane technology is the best technology for water treatment compared to other conventional technologies. However, application is hindered by several factors including fouling, selectivity, and permeability. Consequently, the use of materials to improve the performance of membranes is required.

Nanomaterials have emerged as the new future generation materials for high-performance membranes that are expected to solve the water crisis issue. The use of nanomaterials increases water permeability and mechanical strength, and reduces fouling of the membrane.

This review paper highlights the incorporation of several nanomaterials in membranes in various water treatment fields. It is recommended that researchers and scientists should apply more effort in the field of nanomaterials and try to reduce the overall cost of the process. Issues related to the scale up of the production of nanomaterials and their derivatives, and applications in situ, are also important aspects for future development. In addition, the toxicity of the nanomaterials themselves may need further investigation.

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editing, all authors; visualization, all authors; supervision, M.K.; project administration, M.K.; funding acquisition, M.K. All authors have read and agreed to the published version of the manuscript.

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## References

- Huang, Z.; Liu, X.; Sun, S.; Tang, Y.; Yuan, X.; Tang, Q. Global assessment of future sectoral water scarcity under adaptive inner-basin water allocation measures. *Sci. Total Environ.* **2021**, *783*, 146973. [[CrossRef](#)] [[PubMed](#)]
- Müller, A.B.; Avellán, T.; Schanze, J. Risk and sustainability assessment framework for decision support in 'water scarcity—Water reuse' situations. *J. Hydrol.* **2020**, *591*, 125424. [[CrossRef](#)]
- Swain, S.S.; Mishra, A.; Sahoo, B.; Chatterjee, C. Water scarcity-risk assessment in data-scarce river basins under decadal climate change using a hydrological modelling approach. *J. Hydrol.* **2020**, *590*, 125260. [[CrossRef](#)]
- Navarro-Ortega, A.; Acuña, V.; Bellin, A.; Burek, P.; Cassiani, G.; Choukr-Allah, R.; Dolédec, S.; Elozegi, A.; Ferrari, F.; Ginebreda, A.; et al. Managing the effects of multiple stressors on aquatic ecosystems under water scarcity. The GLOBAQUA project. *Sci. Total Environ.* **2015**, *503*, 3–9. [[CrossRef](#)] [[PubMed](#)]
- Saïdi, S.; Macedonio, F.; Russo, F.; Hannachi, C.; Hamrouni, B.; Drioli, E.; Figoli, A. Preparation and characterization of hydrophobic P(VDF-HFP) flat sheet membranes using Tamisolve®NxG solvent for the treatment of saline water by direct contact membrane distillation and membrane crystallization. *Sep. Purif. Technol.* **2021**, *275*, 119144. [[CrossRef](#)]
- Santos, P.G.; Scherer, C.M.; Fisch, A.G.; Rodrigues, M.A.S. Petrochemical wastewater treatment: Water recovery using membrane distillation. *J. Clean. Prod.* **2020**, *267*, 121985. [[CrossRef](#)]
- Nawaz, M.S.; Son, H.S.; Jin, Y.; Kim, Y.; Soukane, S.; Al-Hajji, M.A.; Abu-Ghdaib, M.; Ghaffour, N. Investigation of flux stability and fouling mechanism during simultaneous treatment of different produced water streams using forward osmosis and membrane distillation. *Water Res.* **2021**, *198*, 117157. [[CrossRef](#)]
- Yao, Q.-S.; Huang, C.; Wang, M.-K.; Xiong, L.; Chen, X.-D. Treatment of water hyacinth anaerobic fermentation wastewater by combining Fe-C micro-electrolysis with Fenton reaction. *J. Environ. Chem. Eng.* **2020**, *8*, 104157. [[CrossRef](#)]
- Chen, L.; Xue, Y.; Luo, T.; Wu, F.; Alshwabkeh, A.N. Electrolysis-assisted UV/sulfite oxidation for water treatment with automatic adjustments of solution pH and dissolved oxygen. *Chem. Eng. J.* **2021**, *403*, 126278. [[CrossRef](#)]
- Chen, Y.; Lin, T.; Chen, W. Enhanced removal of organic matter and typical disinfection byproduct precursors in combined iron-carbon micro electrolysis-UBAF process for drinking water pre-treatment. *J. Environ. Sci.* **2019**, *78*, 315–327. [[CrossRef](#)] [[PubMed](#)]
- Jamil, S.; Loganathan, P.; Khan, S.J.; McDonald, J.A.; Kandasamy, J.; Vigneswaran, S. Enhanced nanofiltration rejection of inorganic and organic compounds from a wastewater-reclamation plant's micro-filtered water using adsorption pre-treatment. *Sep. Purif. Technol.* **2021**, *260*, 118207. [[CrossRef](#)]
- Wang, B.; Xiong, M.; Shi, B.; Li, Z.; Zhang, H. Treatment of shale gas flowback water by adsorption on carbon-nanotube-nested diatomite adsorbent. *J. Water Process Eng.* **2021**, *42*, 102074. [[CrossRef](#)]
- Shinde, P.A.; Ukarde, T.M.; Gogate, P.R.; Pawar, H.S. An integrated approach of adsorption and membrane separation for treatment of sewage water and resource recovery. *J. Water Process Eng.* **2021**, *40*, 101795. [[CrossRef](#)]
- Xu, H.; Wang, S.; Wang, M.; Ge, B.; Ren, G.; Li, W.; Zhao, L. Application of superhydrophobic ZnO rod composites with environmentally-friendly and photodegradation properties in water environment treatment. *Colloids Surf. A Physicochem. Eng. Asp.* **2021**, *618*, 126437. [[CrossRef](#)]
- Chenab, K.K.; Sohrabi, B.; Jafari, A.; Ramakrishna, S. Water treatment: Functional nanomaterials and applications from adsorption to photodegradation. *Mater. Today Chem.* **2020**, *16*, 100262. [[CrossRef](#)]
- Telegang Chekem, C.; Goetz, V.; Richardson, Y.; Plantard, G.; Blin, J. Modelling of adsorption/photodegradation phenomena on AC-TiO<sub>2</sub> composite catalysts for water treatment detoxification. *Catal. Today* **2019**, *328*, 183–188. [[CrossRef](#)]
- Yadav, S.; Saleem, H.; Ibrar, I.; Naji, O.; Hawari, A.A.; Alanezi, A.A.; Zaidi, S.J.; Altaee, A.; Zhou, J. Recent developments in forward osmosis membranes using carbon-based nanomaterials. *Desalination* **2020**, *482*, 114375. [[CrossRef](#)]
- Mamah, S.C.; Goh, P.S.; Ismail, A.F.; Suzaimi, N.D.; Yogarathinam, L.T.; Raji, Y.O.; El-badawy, T.H. Recent development in modification of polysulfone membrane for water treatment application. *J. Water Process Eng.* **2021**, *40*, 101835. [[CrossRef](#)]

19. Eray, E.; Candelario, V.M.; Boffa, V.; Safafar, H.; Østedgaard-Munck, D.N.; Zahrtmann, N.; Kadrispahic, H.; Jørgensen, M.K. A roadmap for the development and applications of silicon carbide membranes for liquid filtration: Recent advancements, challenges, and perspectives. *Chem. Eng. J.* **2021**, *414*, 128826. [[CrossRef](#)]
20. Li, C.; Huang, Y.; Feng, X.; Zhang, Z.; Gao, H.; Huang, J. Silica-assisted cross-linked polymer electrolyte membrane with high electrochemical stability for lithium-ion batteries. *J. Colloid Interface Sci.* **2021**, *594*, 1–8. [[CrossRef](#)]
21. Valappil, R.S.K.; Ghasem, N.; Al-Marzouqi, M. Current and future trends in polymer membrane-based gas separation technology: A comprehensive review. *J. Ind. Eng. Chem.* **2021**, *98*, 103–129. [[CrossRef](#)]
22. Han, Y.; Ho, W.S.W. Polymeric membranes for CO<sub>2</sub> separation and capture. *J. Membr. Sci.* **2021**, *628*, 119244. [[CrossRef](#)]
23. Kianfar, E.; Cao, V. Polymeric membranes on base of PolyMethyl methacrylate for air separation: A review. *J. Mater. Res. Technol.* **2021**, *10*, 1437–1461. [[CrossRef](#)]
24. Masmoudi, S.; Ben Amar, R.; Larbot, A.; El Feki, H.; Salah, A.B.; Cot, L. Elaboration of inorganic microfiltration membranes with hydroxyapatite applied to the treatment of wastewater from sea product industry. *J. Membr. Sci.* **2005**, *247*, 1–9. [[CrossRef](#)]
25. Asif, M.B.; Zhang, Z. Ceramic membrane technology for water and wastewater treatment: A critical review of performance, full-scale applications, membrane fouling and prospects. *Chem. Eng. J.* **2021**, *418*, 129481. [[CrossRef](#)]
26. Gu, Q.; Ng, T.C.A.; Bao, Y.; Ng, H.Y.; Tan, S.C.; Wang, J. Developing Better Ceramic Membranes for Water and Wastewater Treatment: Where Microstructure Integrates with Chemistry and Functionalities. *Chem. Eng. J.* **2021**, *428*, 130456. [[CrossRef](#)]
27. Arumugham, T.; Kaleekkal, N.J.; Gopal, S.; Nambikkattu, J.; Rambabu, K.; Aboulella, A.M.; Ranil Wickramasinghe, S.; Banat, F. Recent developments in porous ceramic membranes for wastewater treatment and desalination: A review. *J. Environ. Manag.* **2021**, *293*, 112925. [[CrossRef](#)]
28. Ravi, J.; Othman, M.H.D.; Matsuura, T.; Ro'il Bilad, M.; El-badawy, T.H.; Aziz, F.; Ismail, A.F.; Rahman, M.A.; Jaafar, J. Polymeric membranes for desalination using membrane distillation: A review. *Desalination* **2020**, *490*, 114530. [[CrossRef](#)]
29. Keskin, B.; Zeytuncu-Gökoğlu, B.; Koyuncu, I. Polymer inclusion membrane applications for transport of metal ions: A critical review. *Chemosphere* **2021**, *279*, 130604. [[CrossRef](#)] [[PubMed](#)]
30. Mollahosseini, A.; Abdelrasoul, A. Recent advances in thin film composites membranes for brackish groundwater treatment with critical focus on Saskatchewan water sources. *J. Environ. Sci.* **2019**, *81*, 181–194. [[CrossRef](#)]
31. Goh, P.S.; Ismail, A.F. Chemically functionalized polyamide thin film composite membranes: The art of chemistry. *Desalination* **2020**, *495*, 114655. [[CrossRef](#)]
32. Karami, P.; Khorshidi, B.; McGregor, M.; Peichel, J.T.; Soares, J.B.P.; Sadrzadeh, M. Thermally stable thin film composite polymeric membranes for water treatment: A review. *J. Clean. Prod.* **2020**, *250*, 119447. [[CrossRef](#)]
33. Alihemati, Z.; Hashemifard, S.A.; Matsuura, T.; Ismail, A.F.; Hilal, N. Current status and challenges of fabricating thin film composite forward osmosis membrane: A comprehensive roadmap. *Desalination* **2020**, *491*, 114557. [[CrossRef](#)]
34. Cheng, W.; Campolongo, M.J.; Tan, S.J.; Luo, D. Freestanding ultrathin nano-membranes via self-assembly. *Nano Today* **2009**, *4*, 482–493. [[CrossRef](#)]
35. Zhang, Q.; Ghosh, S.; Samitsu, S.; Peng, X.; Ichinose, I. Ultrathin freestanding nanoporous membranes prepared from polystyrene nanoparticles. *J. Mater. Chem.* **2011**, *21*, 1684–1688. [[CrossRef](#)]
36. Ye, J.; Wang, Y.; Li, Z.; Yang, D.; Li, C.; Yan, Y.; Dai, J. 2D confinement freestanding graphene oxide composite membranes with enriched oxygen vacancies for enhanced organic contaminants removal via peroxymonosulfate activation. *J. Hazard. Mater.* **2021**, *417*, 126028. [[CrossRef](#)] [[PubMed](#)]
37. Ghaemi, N. A new approach to copper ion removal from water by polymeric nanocomposite membrane embedded with  $\gamma$ -alumina nanoparticles. *Appl. Surf. Sci.* **2016**, *364*, 221–228. [[CrossRef](#)]
38. Hosseini, S.M.; Nemati, M.; Jeddi, F.; Salehi, E.; Khodabakhshi, A.R.; Madaeni, S.S. Fabrication of mixed matrix heterogeneous cation exchange membrane modified by titanium dioxide nanoparticles: Mono/bivalent ionic transport property in desalination. *Desalination* **2015**, *359*, 167–175. [[CrossRef](#)]
39. Mobarakabad, P.; Moghadassi, A.R.; Hosseini, S.M. Fabrication and characterization of poly(phenylene ether-ether sulfone) based nanofiltration membranes modified by titanium dioxide nanoparticles for water desalination. *Desalination* **2015**, *365*, 227–233. [[CrossRef](#)]
40. Ayyaru, S.; Dinh, T.T.L.; Ahn, Y.-H. Enhanced antifouling performance of PVDF ultrafiltration membrane by blending zinc oxide with support of graphene oxide nanoparticle. *Chemosphere* **2020**, *241*, 125068. [[CrossRef](#)]
41. Borjigin, B.; Liu, L.; Yu, L.; Xu, L.; Zhao, C.; Wang, J. Influence of incorporating beta zeolite nanoparticles on water permeability and ion selectivity of polyamide nanofiltration membranes. *J. Environ. Sci.* **2020**, *98*, 77–84. [[CrossRef](#)]
42. Zhang, Y.; Zhao, J.; Chu, H.; Zhou, X.; Wei, Y. Effect of modified attapulgite addition on the performance of a PVDF ultrafiltration membrane. *Desalination* **2014**, *344*, 71–78. [[CrossRef](#)]
43. Kim, S.H.; Kwak, S.-Y.; Sohn, B.-H.; Park, T.H. Design of TiO<sub>2</sub> nanoparticle self-assembled aromatic polyamide thin-film-composite (TFC) membrane as an approach to solve biofouling problem. *J. Membr. Sci.* **2003**, *211*, 157–165. [[CrossRef](#)]
44. Bae, T.-H.; Tak, T.-M. Preparation of TiO<sub>2</sub> 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](#)]
45. Bae, T.-H.; Tak, T.-M. Effect of TiO<sub>2</sub> nanoparticles on fouling mitigation of ultrafiltration membranes for activated sludge filtration. *J. Membr. Sci.* **2005**, *249*, 1–8. [[CrossRef](#)]

46. Yang, Y.; Zhang, H.; Wang, P.; Zheng, Q.; Li, J. The influence of nano-sized TiO<sub>2</sub> fillers on the morphologies and properties of PSF UF membrane. *J. Membr. Sci.* **2007**, *288*, 231–238. [[CrossRef](#)]
47. Mansourpanah, Y.; Madaeni, S.S.; Rahimpour, A.; Farhadian, A.; Taheri, A.H. Formation of appropriate sites on nanofiltration membrane surface for binding TiO<sub>2</sub> photo-catalyst: Performance, characterization and fouling-resistant capability. *J. Membr. Sci.* **2009**, *330*, 297–306. [[CrossRef](#)]
48. Cao, X.; Ma, J.; Shi, X.; Ren, Z. Effect of TiO<sub>2</sub> nanoparticle size on the performance of PVDF membrane. *Appl. Surf. Sci.* **2006**, *253*, 2003–2010. [[CrossRef](#)]
49. Hong, H.-J.; Sarkar, S.K.; Lee, B.-T. Formation of TiO<sub>2</sub> nano fibers on a micro-channeled Al<sub>2</sub>O<sub>3</sub>-ZrO<sub>2</sub>/TiO<sub>2</sub> porous composite membrane for photocatalytic filtration. *J. Eur. Ceram. Soc.* **2012**, *32*, 657–663. [[CrossRef](#)]
50. Nonjola, P.T.; Mathe, M.K.; Modibedi, R.M. Chemical modification of polysulfone: Composite anionic exchange membrane with TiO<sub>2</sub> nano-particles. *Int. J. Hydrog. Energy* **2013**, *38*, 5115–5121. [[CrossRef](#)]
51. Li, J.-B.; Zhu, J.-W.; Zheng, M.-S. Morphologies and properties of poly(phthalazinone ether sulfone ketone) matrix ultrafiltration membranes with entrapped TiO<sub>2</sub> nanoparticles. *J. Appl. Polym. Sci.* **2007**, *103*, 3623–3629. [[CrossRef](#)]
52. Soroko, I.; Livingston, A. Impact of TiO<sub>2</sub> nanoparticles on morphology and performance of crosslinked polyimide organic solvent nanofiltration (OSN) membranes. *J. Membr. Sci.* **2009**, *343*, 189–198. [[CrossRef](#)]
53. Rahimpour, A.; Jahanshahi, M.; Mollahosseini, A.; Rajaeian, B. Structural and performance properties of UV-assisted TiO<sub>2</sub> deposited nano-composite PVDF/SPES membranes. *Desalination* **2012**, *285*, 31–38. [[CrossRef](#)]
54. Rahimpour, A.; Madaeni, S.S.; Taheri, A.H.; Mansourpanah, Y. Coupling TiO<sub>2</sub> nanoparticles with UV irradiation for modification of polyethersulfone ultrafiltration membranes. *J. Membr. Sci.* **2008**, *313*, 158–169. [[CrossRef](#)]
55. Wu, G.; Gan, S.; Cui, L.; Xu, Y. Preparation and characterization of PES/TiO<sub>2</sub> composite membranes. *Appl. Surf. Sci.* **2008**, *254*, 7080–7086. [[CrossRef](#)]
56. Xin, B.J.; Chen, Z.M.; Wu, X.J.; Wang, X.F.; Chen, W.J. Preparation and characterization of PSA/nano-TiO<sub>2</sub> composites and fibers. *J. Text. Inst.* **2013**, *104*, 164–169. [[CrossRef](#)]
57. Li, J.; Zuo, Y.; Man, Y.; Mo, A.; Huang, C.; Liu, M.; Jansen, J.A.; Li, Y. Fabrication and Biocompatibility of an Antimicrobial Composite Membrane with an Asymmetric Porous Structure. *J. Biomater. Sci. Polym. Ed.* **2012**, *23*, 81–96. [[CrossRef](#)]
58. Rahimpour, A.; Jahanshahi, M.; Rajaeian, B.; Rahimnejad, M. TiO<sub>2</sub> entrapped nano-composite PVDF/SPES membranes: Preparation, characterization, antifouling and antibacterial properties. *Desalination* **2011**, *278*, 343–353. [[CrossRef](#)]
59. Razmjou, A.; Mansouri, J.; Chen, V.; Lim, M.; Amal, R. Titania nanocomposite polyethersulfone ultrafiltration membranes fabricated using a low temperature hydrothermal coating process. *J. Membr. Sci.* **2011**, *380*, 98–113. [[CrossRef](#)]
60. Linh, N.T.B.; Lee, K.-H.; Lee, B.-T. A Novel Photoactive Nano-Filtration Module Composed of a TiO<sub>2</sub> Loaded PVA Nano-Fibrous Membrane on Sponge Al<sub>2</sub>O<sub>3</sub> Scaffolds and Al<sub>2</sub>O<sub>3</sub>-(m-ZrO<sub>2</sub>)/t-ZrO<sub>2</sub> Composites. *Mater. Trans.* **2011**, *52*, 1452–1456. [[CrossRef](#)]
61. Li, J.-H.; Xu, Y.-Y.; Zhu, L.-P.; Wang, J.-H.; Du, C.-H. Fabrication and characterization of a novel TiO<sub>2</sub> nanoparticle self-assembly membrane with improved fouling resistance. *J. Membr. Sci.* **2009**, *326*, 659–666. [[CrossRef](#)]
62. Luo, M.; Wen, Q.; Liu, J.; Liu, H.; Jia, Z. Fabrication of SPES/Nano-TiO<sub>2</sub> Composite Ultrafiltration Membrane and Its Anti-fouling Mechanism. *Chin. J. Chem. Eng.* **2011**, *19*, 45–51. [[CrossRef](#)]
63. Rajaeian, B.; Rahimpour, A.; Tade, M.O.; Liu, S. Fabrication and characterization of polyamide thin film nanocomposite (TFN) nanofiltration membrane impregnated with TiO<sub>2</sub> nanoparticles. *Desalination* **2013**, *313*, 176–188. [[CrossRef](#)]
64. Linh, N.T.B.; Lee, K.-H.; Lee, B.-T. Fabrication of photocatalytic PVA-TiO<sub>2</sub> nano-fibrous hybrid membrane using the electro-spinning method. *J. Mater. Sci.* **2011**, *46*, 5615–5620. [[CrossRef](#)]
65. Madaeni, S.S.; Zinadini, S.; Vatanpour, V. A new approach to improve antifouling property of PVDF membrane using in situ polymerization of PAA functionalized TiO<sub>2</sub> nanoparticles. *J. Membr. Sci.* **2011**, *380*, 155–162. [[CrossRef](#)]
66. Li, J.-F.; Xu, Z.-L.; Yang, H.; Yu, L.-Y.; Liu, M. Effect of TiO<sub>2</sub> nanoparticles on the surface morphology and performance of microporous PES membrane. *Appl. Surf. Sci.* **2009**, *255*, 4725–4732. [[CrossRef](#)]
67. Huang, J.; Zhang, K.; Wang, K.; Xie, Z.; Ladewig, B.; Wang, H. Fabrication of polyethersulfone-mesoporous silica nanocomposite ultrafiltration membranes with antifouling properties. *J. Membr. Sci.* **2012**, *423*, 362–370. [[CrossRef](#)]
68. Ahn, J.; Chung, W.-J.; Pinnau, I.; Guiver, M.D. Polysulfone/silica nanoparticle mixed-matrix membranes for gas separation. *J. Membr. Sci.* **2008**, *314*, 123–133. [[CrossRef](#)]
69. Zhang, Y.; Shan, L.; Tu, Z.; Zhang, Y. Preparation and characterization of novel Ce-doped nonstoichiometric nanosilica/polysulfone composite membranes. *Sep. Purif. Technol.* **2008**, *63*, 207–212. [[CrossRef](#)]
70. Yu, S.; Zuo, X.; Bao, R.; Xu, X.; Wang, J.; Xu, J. Effect of SiO<sub>2</sub> nanoparticle addition on the characteristics of a new organic-inorganic hybrid membrane. *Polymer* **2009**, *50*, 553–559. [[CrossRef](#)]
71. Pu, H.; Liu, L.; Chang, Z.; Yuan, J. Organic/inorganic composite membranes based on polybenzimidazole and nano-SiO<sub>2</sub>. *Electrochim. Acta* **2009**, *54*, 7536–7541. [[CrossRef](#)]
72. Farno, E.; Ghadimi, A.; Kasiri, N.; Mohammadi, T. Separation of heavy gases from light gases using synthesized PDMS nano-composite membranes: Experimental and neural network modeling. *Sep. Purif. Technol.* **2011**, *81*, 400–410. [[CrossRef](#)]
73. Ahmad, A.L.; Majid, M.A.; Ooi, B.S. Functionalized PSf/SiO<sub>2</sub> nanocomposite membrane for oil-in-water emulsion separation. *Desalination* **2011**, *268*, 266–269. [[CrossRef](#)]

74. Lue, S.J.; Lee, D.-T.; Chen, J.-Y.; Chiu, C.-H.; Hu, C.-C.; Jean, Y.C.; Lai, J.-Y. Diffusivity enhancement of water vapor in poly(vinyl alcohol)-fumed silica nano-composite membranes: Correlation with polymer crystallinity and free-volume properties. *J. Membr. Sci.* **2008**, *325*, 831–839. [[CrossRef](#)]
75. Kim, S.; Marand, E. High permeability nano-composite membranes based on mesoporous MCM-41 nanoparticles in a polysulfone matrix. *Microporous Mesoporous Mater.* **2008**, *114*, 129–136. [[CrossRef](#)]
76. Wang, K.; McDermid, S.; Li, J.; Kremliaikova, N.; Kozak, P.; Song, C.; Tang, Y.; Zhang, J.; Zhang, J. Preparation and performance of nano silica/Nafion composite membrane for proton exchange membrane fuel cells. *J. Power Sources* **2008**, *184*, 99–103. [[CrossRef](#)]
77. Jeddi, K.; Zhao, Y.; Zhang, Y.; Konarov, A.; Chen, P. Fabrication and Characterization of an Effective Polymer Nanocomposite Electrolyte Membrane for High Performance Lithium/Sulfur Batteries. *J. Electrochem. Soc.* **2013**, *160*, A1052–A1060. [[CrossRef](#)]
78. Shi, G.M.; Chen, H.; Jean, Y.C.; Chung, T.S. Sorption, swelling, and free volume of polybenzimidazole (PBI) and PBI/zeolitic imidazolate framework (ZIF-8) nano-composite membranes for pervaporation. *Polymer* **2013**, *54*, 774–783. [[CrossRef](#)]
79. Lin, W.; Zhu, T.; Li, Q.; Yi, S.; Li, Y. Study of pervaporation for dehydration of caprolactam through PVA/nano silica composite membranes. *Desalination* **2012**, *285*, 39–45. [[CrossRef](#)]
80. Karkhanechi, H.; Kazemian, H.; Nazockdast, H.; Mozdianfard, M.R.; Bidoki, S.M. Fabrication of Homogenous Polymer-Zeolite Nanocomposites as Mixed-Matrix Membranes for Gas Separation. *Chem. Eng. Technol.* **2012**, *35*, 885–892. [[CrossRef](#)]
81. Li, L.-H.; Deng, J.-C.; Deng, H.-R.; Liu, Z.-L.; Xin, L. Synthesis and characterization of chitosan/ZnO nanoparticle composite membranes. *Carbohydr. Res.* **2010**, *345*, 994–998. [[CrossRef](#)]
82. Maximous, N.; Nakhla, G.; Wan, W.; Wong, K. Preparation, characterization and performance of Al<sub>2</sub>O<sub>3</sub>/PES membrane for wastewater filtration. *J. Membr. Sci.* **2009**, *341*, 67–75. [[CrossRef](#)]
83. Amanipour, M.; Ganji Babakhani, E.; Safekordi, A.; Zamaniyan, A.; Heidari, M. Effect of CVD parameters on hydrogen permeation properties in a nano-composite SiO<sub>2</sub>-Al<sub>2</sub>O<sub>3</sub> membrane. *J. Membr. Sci.* **2012**, *423*, 530–535. [[CrossRef](#)]
84. Li, X.; Yu, Y.; Meng, Y. Novel Quaternized Poly(arylene ether sulfone)/Nano-ZrO<sub>2</sub> Composite Anion Exchange Membranes for Alkaline Fuel Cells. *ACS Appl. Mater. Interfaces* **2013**, *5*, 1414–1422. [[CrossRef](#)] [[PubMed](#)]
85. Van Gestel, T.; Sebold, D.; Meulenberg, W.A.; Bram, M.; Buchkremer, H.-P. Manufacturing of new nano-structured ceramic-metallic composite microporous membranes consisting of ZrO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub> and stainless steel. *Solid State Ion.* **2008**, *179*, 1360–1366. [[CrossRef](#)]
86. Shin, W.-K.; Lee, Y.-S.; Kim, D.-W. Hybrid Composite Membranes Based on Polyethylene Separator and Al<sub>2</sub>O<sub>3</sub> Nanoparticles for Lithium-Ion Batteries. *J. Nanosci. Nanotechnol.* **2013**, *13*, 3705–3710. [[CrossRef](#)]
87. Xu, J.; Bhattacharyya, D. Fe/Pd Nanoparticle Immobilization in Microfiltration Membrane Pores: Synthesis, Characterization, and Application in the Dechlorination of Polychlorinated Biphenyls. *Ind. Eng. Chem. Res.* **2007**, *46*, 2348–2359. [[CrossRef](#)]
88. Hong, J.; He, Y. Effects of nano sized zinc oxide on the performance of PVDF microfiltration membranes. *Desalination* **2012**, *302*, 71–79. [[CrossRef](#)]
89. Zhao, Q.; Zhao, D.L.; Chung, T.-S. Thin-film nanocomposite membranes incorporated with defective ZIF-8 nanoparticles for brackish water and seawater desalination. *J. Membr. Sci.* **2021**, *625*, 119158. [[CrossRef](#)]
90. Bose, J.; Dasgupta, J.; Adhikari, U.; Sikder, J. Tuning permeation characteristics of cellulose acetate membrane embedded with raw and amine-functionalized silicon carbide nanoparticle for oil-water separation. *J. Water Process Eng.* **2021**, *41*, 102019. [[CrossRef](#)]
91. Wen, M.; Chen, M.; Chen, K.; Li, P.-L.; Lv, C.; Zhang, X.; Yao, Y.; Yang, W.; Huang, G.; Ren, G.-K.; et al. Superhydrophobic composite graphene oxide membrane coated with fluorinated silica nanoparticles for hydrogen isotopic water separation in membrane distillation. *J. Membr. Sci.* **2021**, *626*, 119136. [[CrossRef](#)]
92. Kazemi, F.; Jafarzadeh, Y.; Masoumi, S.; Rostamizadeh, M. Oil-in-water emulsion separation by PVC membranes embedded with GO-ZnO nanoparticles. *J. Environ. Chem. Eng.* **2021**, *9*, 104992. [[CrossRef](#)]
93. De Guzman, M.R.; Andra, C.K.A.; Ang, M.B.M.Y.; Dizon, G.V.C.; Caparanga, A.R.; Huang, S.-H.; Lee, K.-R. Increased performance and antifouling of mixed-matrix membranes of cellulose acetate with hydrophilic nanoparticles of polydopamine-sulfobetaine methacrylate for oil-water separation. *J. Membr. Sci.* **2021**, *620*, 118881. [[CrossRef](#)]
94. Zhang, S.; Liu, Y.; Li, D.; Wang, Q.; Ran, F. Water-soluble MOF nanoparticles modified polyethersulfone membrane for improving flux and molecular retention. *Appl. Surf. Sci.* **2020**, *505*, 144553. [[CrossRef](#)]
95. Zhao, D.L.; Yeung, W.S.; Zhao, Q.; Chung, T.-S. Thin-film nanocomposite membranes incorporated with UiO-66-NH<sub>2</sub> nanoparticles for brackish water and seawater desalination. *J. Membr. Sci.* **2020**, *604*, 118039. [[CrossRef](#)]
96. Kotp, Y.H. High-flux TFN nanofiltration membranes incorporated with Camphor-Al<sub>2</sub>O<sub>3</sub> nanoparticles for brackish water desalination. *Chemosphere* **2021**, *265*, 128999. [[CrossRef](#)] [[PubMed](#)]
97. Matindi, C.N.; Hu, M.; Kadanyo, S.; Ly, Q.V.; Gumbi, N.N.; Dlamini, D.S.; Li, J.; Hu, Y.; Cui, Z.; Li, J. Tailoring the morphology of polyethersulfone/sulfonated polysulfone ultrafiltration membranes for highly efficient separation of oil-in-water emulsions using TiO<sub>2</sub> nanoparticles. *J. Membr. Sci.* **2021**, *620*, 118868. [[CrossRef](#)]
98. Barati, N.; Husein, M.M.; Azaiez, J. Modifying ceramic membranes with in situ grown iron oxide nanoparticles and their use for oily water treatment. *J. Membr. Sci.* **2021**, *617*, 118641. [[CrossRef](#)]
99. He, J.; Xiong, D.; Zhou, P.; Xiao, X.; Ni, F.; Deng, S.; Shen, F.; Tian, D.; Long, L.; Luo, L. A novel homogenous in-situ generated ferrihydrite nanoparticles/polyethersulfone composite membrane for removal of lead from water: Development, characterization, performance and mechanism. *Chem. Eng. J.* **2020**, *393*, 124696. [[CrossRef](#)]

100. Liu, R.; Raman, A.K.Y.; Shaik, I.; Aichele, C.; Kim, S.-J. Inorganic microfiltration membranes incorporated with hydrophilic silica nanoparticles for oil-in-water emulsion separation. *J. Water Process Eng.* **2018**, *26*, 124–130. [[CrossRef](#)]
101. Zhang, D.-S.; Abadikhah, H.; Wang, J.-W.; Hao, L.-Y.; Xu, X.; Agathopoulos, S.  $\beta$ -SiAlON ceramic membranes modified with SiO<sub>2</sub> nanoparticles with high rejection rate in oil-water emulsion separation. *Ceram. Int.* **2019**, *45*, 4237–4242. [[CrossRef](#)]
102. Rowley, J.; Abu-Zahra, N.H. Synthesis and characterization of polyethersulfone membranes impregnated with (3-aminopropyltriethoxysilane) APTES-Fe<sub>3</sub>O<sub>4</sub> nanoparticles for As(V) removal from water. *J. Environ. Chem. Eng.* **2019**, *7*, 102875. [[CrossRef](#)]
103. Hokkanen, S.; Repo, E.; Lou, S.; Sillanpää, M. Removal of arsenic(V) by magnetic nanoparticle activated microfibrillated cellulose. *Chem. Eng. J.* **2015**, *260*, 886–894. [[CrossRef](#)]
104. Islam, M.S.; McCutcheon, J.R.; Rahaman, M.S. A high flux polyvinyl acetate-coated electrospun nylon 6/SiO<sub>2</sub> composite microfiltration membrane for the separation of oil-in-water emulsion with improved antifouling performance. *J. Membr. Sci.* **2017**, *537*, 297–309. [[CrossRef](#)]
105. Sani, H.A.; Ahmad, M.B.; Hussein, M.Z.; Ibrahim, N.A.; Musa, A.; Saleh, T.A. Nanocomposite of ZnO with montmorillonite for removal of lead and copper ions from aqueous solutions. *Process Saf. Environ. Prot.* **2017**, *109*, 97–105. [[CrossRef](#)]
106. Wang, J.; Wu, Y.; Yang, Z.; Guo, H.; Cao, B.; Tang, C.Y. A novel gravity-driven nanofibrous membrane for point-of-use water disinfection: Polydopamine-induced in situ silver incorporation. *Sci. Rep.* **2017**, *7*, 2334. [[CrossRef](#)] [[PubMed](#)]
107. Dickson, D.; Liu, G.; Cai, Y. Adsorption kinetics and isotherms of arsenite and arsenate on hematite nanoparticles and aggregates. *J. Environ. Manag.* **2017**, *186*, 261–267. [[CrossRef](#)]
108. Fazlzadeh, M.; Rahmani, K.; Zarei, A.; Abdoallahzadeh, H.; Nasiri, F.; Khosravi, R. A novel green synthesis of zero valent iron nanoparticles (NZVI) using three plant extracts and their efficient application for removal of Cr (VI) from aqueous solutions. *Adv. Powder Technol.* **2017**, *28*, 122–130. [[CrossRef](#)]
109. Mousakhani, M.; Sarlak, N. Electrospun composite nanofibre adsorbents for effective removal of Cd<sup>2+</sup> from polluted water. *Mater. Chem. Phys.* **2020**, *256*, 123578. [[CrossRef](#)]
110. Fan, H.-L.; Zhou, S.-F.; Jiao, W.-Z.; Qi, G.-S.; Liu, Y.-Z. Removal of heavy metal ions by magnetic chitosan nanoparticles prepared continuously via high-gravity reactive precipitation method. *Carbohydr. Polym.* **2017**, *174*, 1192–1200. [[CrossRef](#)]
111. Xiong, C.; Wang, W.; Tan, F.; Luo, F.; Chen, J.; Qiao, X. Investigation on the efficiency and mechanism of Cd (II) and Pb (II) removal from aqueous solutions using MgO nanoparticles. *J. Hazard. Mater.* **2015**, *299*, 664–674. [[CrossRef](#)] [[PubMed](#)]
112. Li, J.; Chen, C.; Zhu, K.; Wang, X. Nanoscale zero-valent iron particles modified on reduced graphene oxides using a plasma technique for Cd (II) removal. *J. Taiwan Inst. Chem. Eng.* **2016**, *59*, 389–394. [[CrossRef](#)]
113. Du, L.; Quan, X.; Fan, X.; Wei, G.; Chen, S. Conductive CNT/nanofiber composite hollow fiber membranes with electrospun support layer for water purification. *J. Membr. Sci.* **2020**, *596*, 117613. [[CrossRef](#)]
114. Savasari, M.; Emadi, M.; Bahmanyar, M.A.; Biparva, P. Optimization of Cd (II) removal from aqueous solution by ascorbic acid-stabilized zero valent iron nanoparticles using response surface methodology. *J. Ind. Eng. Chem.* **2015**, *21*, 1403–1409. [[CrossRef](#)]
115. Gupta, V.K.; Chandra, R.; Tyagi, I.; Verma, M. Removal of hexavalent chromium ions using CuO nanoparticles for water purification applications. *J. Colloid Interface Sci.* **2016**, *478*, 54–62. [[CrossRef](#)] [[PubMed](#)]
116. Bhadra, J.; Parangusan, H.; Popelka, A.; Lehocky, M.; Humpolicek, P.; Al-Thani, N. Electrospun Polystyrene/PANI-Ag fibers for organic dye removal and antibacterial application. *J. Environ. Chem. Eng.* **2020**, *8*, 103746. [[CrossRef](#)]
117. Al Nafiey, A.; Addad, A.; Sieber, B.; Chastanet, G.; Barras, A.; Szunerits, S.; Boukherroub, R. Reduced graphene oxide decorated with Co<sub>3</sub>O<sub>4</sub> nanoparticles (rGO-Co<sub>3</sub>O<sub>4</sub>) nanocomposite: A reusable catalyst for highly efficient reduction of 4-nitrophenol, and Cr(VI) and dye removal from aqueous solutions. *Chem. Eng. J.* **2017**, *322*, 375–384. [[CrossRef](#)]
118. Tabesh, S.; Davar, F.; Loghman-Estarki, M.R. Preparation of  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> nanoparticles using modified sol-gel method and its use for the adsorption of lead and cadmium ions. *J. Alloy. Compd.* **2018**, *730*, 441–449. [[CrossRef](#)]
119. Martinez-Vargas, S.; Martínez, A.I.; Hernández-Beteta, E.E.; Mijangos-Ricardez, O.F.; Vázquez-Hipólito, V.; Patiño-Carachure, C.; Hernandez-Flores, H.; López-Luna, J. Arsenic adsorption on cobalt and manganese ferrite nanoparticles. *J. Mater. Sci.* **2017**, *52*, 6205–6215. [[CrossRef](#)]
120. Wang, Z.; Sahadevan, R.; Crandall, C.; Menkhous, T.J.; Fong, H. Hot-pressed PAN/PVDF hybrid electrospun nanofiber membranes for ultrafiltration. *J. Membr. Sci.* **2020**, *611*, 118327. [[CrossRef](#)]
121. Chen, K.; He, J.; Li, Y.; Cai, X.; Zhang, K.; Liu, T.; Hu, Y.; Lin, D.; Kong, L.; Liu, J. Removal of cadmium and lead ions from water by sulfonated magnetic nanoparticle adsorbents. *J. Colloid Interface Sci.* **2017**, *494*, 307–316. [[CrossRef](#)]
122. Agarwal, S.; Tyagi, I.; Gupta, V.K.; Dehghani, M.H.; Jaafari, J.; Balarak, D.; Asif, M. Rapid removal of noxious nickel (II) using novel  $\gamma$ -alumina nanoparticles and multiwalled carbon nanotubes: Kinetic and isotherm studies. *J. Mol. Liq.* **2016**, *224*, 618–623. [[CrossRef](#)]
123. Depault, F.; Cojocar, M.; Fortin, F.; Chakrabarti, S.; Lemieux, N. Genotoxic effects of chromium (VI) and cadmium (II) in human blood lymphocytes using the electron microscopy in situ end-labeling (EM-ISEL) assay. *Toxicol. Vitro.* **2006**, *20*, 513–518. [[CrossRef](#)] [[PubMed](#)]
124. Xu, Z.; Li, X.; Teng, K.; Zhou, B.; Ma, M.; Shan, M.; Jiao, K.; Qian, X.; Fan, J. High flux and rejection of hierarchical composite membranes based on carbon nanotube network and ultrathin electrospun nanofibrous layer for dye removal. *J. Membr. Sci.* **2017**, *535*, 94–102. [[CrossRef](#)]

125. Davarnejad, R.; Panahi, P. Cu (II) removal from aqueous wastewaters by adsorption on the modified Henna with Fe<sub>3</sub>O<sub>4</sub> nanoparticles using response surface methodology. *Sep. Purif. Technol.* **2016**, *158*, 286–292. [[CrossRef](#)]
126. Yang, Y.; Li, Y.; Cao, L.; Wang, Y.; Li, L.; Li, W. Electrospun PVDF-SiO<sub>2</sub> nanofibrous membranes with enhanced surface roughness for oil-water coalescence separation. *Sep. Purif. Technol.* **2021**, *269*, 118726. [[CrossRef](#)]
127. Fouladgar, M.; Beheshti, M.; Sabzyan, H. Single and binary adsorption of nickel and copper from aqueous solutions by  $\gamma$ -alumina nanoparticles: Equilibrium and kinetic modeling. *J. Mol. Liq.* **2015**, *211*, 1060–1073. [[CrossRef](#)]
128. Sundaran, S.P.; Reshmi, C.R.; Sagitha, P.; Manaf, O.; Sujith, A. Multifunctional graphene oxide loaded nanofibrous membrane for removal of dyes and coliform from water. *J. Environ. Manag.* **2019**, *240*, 494–503. [[CrossRef](#)]
129. Liu, W.; Zhang, P.; Borthwick, A.G.L.; Chen, H.; Ni, J. Adsorption mechanisms of thallium (I) and thallium (III) by titanate nanotubes: Ion-exchange and co-precipitation. *J. Colloid Interface Sci.* **2014**, *423*, 67–75. [[CrossRef](#)]
130. Zdraveva, E.; Fang, J.; Mijovic, B.; Lin, T. 11—Electrospun nanofibers. In *Structure and Properties of High-Performance Fibers*; Bhat, G., Ed.; Woodhead Publishing: Oxford, UK, 2017; pp. 267–300. [[CrossRef](#)]
131. Zhang, Q.G.; Deng, C.; Soyekwo, F.; Liu, Q.L.; Zhu, A.M. Sub-10 nm Wide Cellulose Nanofibers for Ultrathin Nanoporous Membranes with High Organic Permeation. *Adv. Funct. Mater.* **2016**, *26*, 792–800. [[CrossRef](#)]
132. Ling, S.; Jin, K.; Kaplan, D.L.; Buehler, M.J. Ultrathin Free-Standing *Bombyx mori* Silk Nanofibril Membranes. *Nano Lett.* **2016**, *16*, 3795–3800. [[CrossRef](#)]
133. Du, C.; Wang, Z.; Liu, G.; Wang, W.; Yu, D. One-step electrospinning PVDF/PVP-TiO<sub>2</sub> hydrophilic nanofiber membrane with strong oil-water separation and anti-fouling property. *Colloids Surf. A Physicochem. Eng. Asp.* **2021**, *624*, 126790. [[CrossRef](#)]
134. Liu, F.; Wang, L.; Li, D.; Liu, Q.; Deng, B. Preparation and characterization of novel thin film composite nanofiltration membrane with PVDF tree-like nanofiber membrane as composite scaffold. *Mater. Des.* **2020**, *196*, 109101. [[CrossRef](#)]
135. Lv, Y.; Xia, J.; Yang, Y.; Chen, Y.; Liu, T. Thin-film composite membranes with mineralized nanofiber supports for highly efficient nanofiltration. *Compos. Commun.* **2021**, *24*, 100695. [[CrossRef](#)]
136. Abd Halim, N.S.; Wirzal, M.D.H.; Hizam, S.M.; Bilad, M.R.; Nordin, N.A.H.M.; Sambudi, N.S.; Putra, Z.A.; Yusoff, A.R.M. Recent Development on Electrospun Nanofiber Membrane for Produced Water Treatment: A review. *J. Environ. Chem. Eng.* **2021**, *9*, 104613. [[CrossRef](#)]
137. Xu, H.; Liu, H.; Huang, Y.; Xiao, C. Three-dimensional structure design of tubular polyvinyl chloride hybrid nanofiber membranes for water-in-oil emulsion separation. *J. Membr. Sci.* **2021**, *620*, 118905. [[CrossRef](#)]
138. Su, Y.; Fan, T.; Bai, H.; Guan, H.; Ning, X.; Yu, M.; Long, Y. Bioinspired Superhydrophobic and Superlipophilic Nanofiber Membrane with Pine Needle-like Structure for Efficient Gravity-driven Oil/Water Separation. *Sep. Purif. Technol.* **2021**, *274*, 119098. [[CrossRef](#)]
139. Zhang, T.; Xiao, C.; Zhao, J.; Liu, X.; Ji, D.; Xu, H. One-step preparation of tubular nanofibers and micro/nanospheres covered membrane with 3D micro/nano structure for highly efficient emulsified oil/water separation. *J. Taiwan Inst. Chem. Eng.* **2021**, *122*, 210–221. [[CrossRef](#)]
140. Obaid, M.; Mohamed, H.O.; Alayande, A.B.; Kang, Y.; Ghaffour, N.; Kim, I.S. Facile fabrication of superhydrophilic and underwater superoleophobic nanofiber membranes for highly efficient separation of oil-in-water emulsion. *Sep. Purif. Technol.* **2021**, *272*, 118954. [[CrossRef](#)]
141. Yin, H.; Zhao, J.; Li, Y.; Liao, Y.; Huang, L.; Zhang, H.; Chen, L. Electrospun SiNPs/ZnNPs-SiO<sub>2</sub>/TiO<sub>2</sub> nanofiber membrane with asymmetric wetting: Ultra-efficient separation of oil-in-water and water-in-oil emulsions in multiple extreme environments. *Sep. Purif. Technol.* **2021**, *255*, 117687. [[CrossRef](#)]
142. Venkatesh, K.; Arthanareeswaran, G.; Chandra Bose, A.; Suresh Kumar, P.; Kweon, J. Diethylenetriaminepentaacetic acid-functionalized multi-walled carbon nanotubes/titanium oxide-PVDF nanofiber membrane for effective separation of oil/water emulsion. *Sep. Purif. Technol.* **2021**, *257*, 117926. [[CrossRef](#)]
143. Wang, W.; Lin, J.; Cheng, J.; Cui, Z.; Si, J.; Wang, Q.; Peng, X.; Turng, L.-S. Dual super-amphiphilic modified cellulose acetate nanofiber membranes with highly efficient oil/water separation and excellent antifouling properties. *J. Hazard. Mater.* **2020**, *385*, 121582. [[CrossRef](#)]
144. Li, N.; Wang, W.; Zhu, L.; Cui, W.; Chen, X.; Zhang, B.; Zhang, Z. A novel electro-cleanable PAN-ZnO nanofiber membrane with superior water flux and electrocatalytic properties for organic pollutant degradation. *Chem. Eng. J.* **2020**, *421*, 127857. [[CrossRef](#)]
145. Ozbey-Unal, B.; Gezmis-Yavuz, E.; Eryildiz, B.; Koseoglu-Imer, D.Y.; Keskinler, B.; Koyuncu, I. Boron removal from geothermal water by nanofiber-based membrane distillation membranes with significantly improved surface hydrophobicity. *J. Environ. Chem. Eng.* **2020**, *8*, 104113. [[CrossRef](#)]
146. Wang, X.; Xiao, C.; Liu, H.; Chen, M.; Xu, H.; Luo, W.; Zhang, F. Robust functionalization of underwater superoleophobic PVDF-HFP tubular nanofiber membranes and applications for continuous dye degradation and oil/water separation. *J. Membr. Sci.* **2020**, *596*, 117583. [[CrossRef](#)]
147. Moatmed, S.M.; Khedr, M.H.; El-dek, S.I.; Kim, H.-Y.; El-Deen, A.G. Highly efficient and reusable superhydrophobic/superoleophilic polystyrene@ Fe<sub>3</sub>O<sub>4</sub> nanofiber membrane for high-performance oil/water separation. *J. Environ. Chem. Eng.* **2019**, *7*, 103508. [[CrossRef](#)]
148. Choi, H.Y.; Bae, J.H.; Hasegawa, Y.; An, S.; Kim, I.S.; Lee, H.; Kim, M. Thiol-functionalized cellulose nanofiber membranes for the effective adsorption of heavy metal ions in water. *Carbohydr. Polym.* **2020**, *234*, 115881. [[CrossRef](#)]

149. Zhang, W.; Yang, P.; Li, X.; Zhu, Z.; Chen, M.; Zhou, X. Electrospun lignin-based composite nanofiber membrane as high-performance absorbent for water purification. *Int. J. Biol. Macromol.* **2019**, *141*, 747–755. [[CrossRef](#)]
150. Gao, J.; Li, B.; Wang, L.; Huang, X.; Xue, H. Flexible membranes with a hierarchical nanofiber/microsphere structure for oil adsorption and oil/water separation. *J. Ind. Eng. Chem.* **2018**, *68*, 416–424. [[CrossRef](#)]
151. Cao, J.; Cheng, Z.; Kang, L.; Chu, M.; Wu, D.; Li, M.; Xie, S.; Wen, R. Novel stellate poly(vinylidene fluoride)/polyethersulfone microsphere-nanofiber electrospun membrane with special wettability for oil/water separation. *Mater. Lett.* **2017**, *207*, 190–194. [[CrossRef](#)]
152. Zhang, Q.; Wang, H.; Fan, X.; Lv, F.; Chen, S.; Quan, X. Fabrication of TiO<sub>2</sub> nanofiber membranes by a simple dip-coating technique for water treatment. *Surf. Coat. Technol.* **2016**, *298*, 45–52. [[CrossRef](#)]
153. Wang, R.; Guan, S.; Sato, A.; Wang, X.; Wang, Z.; Yang, R.; Hsiao, B.S.; Chu, B. Nanofibrous microfiltration membranes capable of removing bacteria, viruses and heavy metal ions. *J. Membr. Sci.* **2013**, *446*, 376–382. [[CrossRef](#)]
154. Karim, Z.; Hakalahti, M.; Tammelin, T.; Mathew, A.P. In situ TEMPO surface functionalization of nanocellulose membranes for enhanced adsorption of metal ions from aqueous medium. *RSC Adv.* **2017**, *7*, 5232–5241. [[CrossRef](#)]
155. Zhu, Q.; Wang, Y.; Li, M.; Liu, K.; Hu, C.; Yan, K.; Sun, G.; Wang, D. Activable carboxylic acid functionalized crystalline nanocellulose/PVA-co-PE composite nanofibrous membrane with enhanced adsorption for heavy metal ions. *Sep. Purif. Technol.* **2017**, *186*, 70–77. [[CrossRef](#)]
156. Halim, A.; Xu, Y.; Lin, K.-H.; Kobayashi, M.; Kajiyama, M.; Enomae, T. Fabrication of cellulose nanofiber-deposited cellulose sponge as an oil-water separation membrane. *Sep. Purif. Technol.* **2019**, *224*, 322–331. [[CrossRef](#)]
157. Gopakumar, D.A.; Pasquini, D.; Henrique, M.A.; de Moraes, L.C.; Grohens, Y.; Thomas, S. Meldrum's Acid Modified Cellulose Nanofiber-Based Polyvinylidene Fluoride Microfiltration Membrane for Dye Water Treatment and Nanoparticle Removal. *ACS Sustain. Chem. Eng.* **2017**, *5*, 2026–2033. [[CrossRef](#)]
158. Zhan, H.; Peng, N.; Lei, X.; Huang, Y.; Li, D.; Tao, R.; Chang, C. UV-induced self-cleanable TiO<sub>2</sub>/nanocellulose membrane for selective separation of oil/water emulsion. *Carbohydr. Polym.* **2018**, *201*, 464–470. [[CrossRef](#)]
159. Cruz-Tato, P.; Ortiz-Quiles, E.O.; Vega-Figueroa, K.; Santiago-Martoral, L.; Flynn, M.; Díaz-Vázquez, L.M.; Nicolau, E. Metalized Nanocellulose Composites as a Feasible Material for Membrane Supports: Design and Applications for Water Treatment. *Environ. Sci. Technol.* **2017**, *51*, 4585–4595. [[CrossRef](#)]
160. Leitch, M.E.; Li, C.; Ikkala, O.; Mauter, M.S.; Lowry, G.V. Bacterial Nanocellulose Aerogel Membranes: Novel High-Porosity Materials for Membrane Distillation. *Environ. Sci. Technol. Lett.* **2016**, *3*, 85–91. [[CrossRef](#)]
161. Yang, R.; Aubrecht, K.B.; Ma, H.; Wang, R.; Grubbs, R.B.; Hsiao, B.S.; Chu, B. Thiol-modified cellulose nanofibrous composite membranes for chromium (VI) and lead (II) adsorption. *Polymer* **2014**, *55*, 1167–1176. [[CrossRef](#)]
162. Hou, Y.; Duan, C.; Zhu, G.; Luo, H.; Liang, S.; Jin, Y.; Zhao, N.; Xu, J. Functional bacterial cellulose membranes with 3D porous architectures: Conventional drying, tunable wettability and water/oil separation. *J. Membr. Sci.* **2019**, *591*, 117312. [[CrossRef](#)]
163. Zhang, W.; Wang, X.; Zhang, Y.; van Bochove, B.; Mäkilä, E.; Seppälä, J.; Xu, W.; Willför, S.; Xu, C. Robust shape-retaining nanocellulose-based aerogels decorated with silver nanoparticles for fast continuous catalytic discoloration of organic dyes. *Sep. Purif. Technol.* **2020**, *242*, 116523. [[CrossRef](#)]
164. Cheng, R.; Kang, M.; Zhuang, S.; Shi, L.; Zheng, X.; Wang, J. Adsorption of Sr (II) from water by mercerized bacterial cellulose membrane modified with EDTA. *J. Hazard. Mater.* **2019**, *364*, 645–653. [[CrossRef](#)]
165. Amiralian, N.; Mustapic, M.; Hossain, M.S.A.; Wang, C.; Konarova, M.; Tang, J.; Na, J.; Khan, A.; Rowan, A. Magnetic nanocellulose: A potential material for removal of dye from water. *J. Hazard. Mater.* **2020**, *394*, 122571. [[CrossRef](#)]
166. Min, L.-L.; Zhong, L.-B.; Zheng, Y.-M.; Liu, Q.; Yuan, Z.-H.; Yang, L.-M. Functionalized chitosan electrospun nanofiber for effective removal of trace arsenate from water. *Sci. Rep.* **2016**, *6*, 32480. [[CrossRef](#)]
167. Deng, S.; Liu, X.; Liao, J.; Lin, H.; Liu, F. PEI modified multiwalled carbon nanotube as a novel additive in PAN nanofiber membrane for enhanced removal of heavy metal ions. *Chem. Eng. J.* **2019**, *375*, 122086. [[CrossRef](#)]
168. Cai, Z.J.; Yang, H.Z.; Xu, Y.; Wang, C.K. Preparation of Polyindole Nanofibers and Their Cadmium Ion Adsorption Performance. *Acta Polym. Sin.* **2015**, *5*, 581–588.
169. Wu, S.; Li, F.; Wang, H.; Fu, L.; Zhang, B.; Li, G. Effects of poly (vinyl alcohol) (PVA) content on preparation of novel thiol-functionalized mesoporous PVA/SiO<sub>2</sub> composite nanofiber membranes and their application for adsorption of heavy metal ions from aqueous solution. *Polymer* **2010**, *51*, 6203–6211. [[CrossRef](#)]
170. Zhou, W.T.; He, J.X.; Cui, S.Z.; Gao, W.D. Nanofibrous Membrane of Silk Fibroin/Cellulose Acetate Blend for Heavy Metal Ion Adsorption. *Adv. Mater. Res.* **2011**, *148–149*, 1431–1435. [[CrossRef](#)]
171. Alipour, D.; Keshtkar, A.R.; Moosavian, M.A. Adsorption of thorium(IV) from simulated radioactive solutions using a novel electrospun PVA/TiO<sub>2</sub>/ZnO nanofiber adsorbent functionalized with mercapto groups: Study in single and multi-component systems. *Appl. Surf. Sci.* **2016**, *366*, 19–29. [[CrossRef](#)]
172. Min, L.-L.; Yuan, Z.-H.; Zhong, L.-B.; Liu, Q.; Wu, R.-X.; Zheng, Y.-M. Preparation of chitosan based electrospun nanofiber membrane and its adsorptive removal of arsenate from aqueous solution. *Chem. Eng. J.* **2015**, *267*, 132–141. [[CrossRef](#)]
173. Haddad, M.Y.; Alharbi, H.F.; Karim, M.R.; Aijaz, M.O.; Alharthi, N.H. Preparation of TiO<sub>2</sub> incorporated polyacrylonitrile electrospun nanofibers for adsorption of heavy metal ions. *J. Polym. Res.* **2018**, *25*, 218. [[CrossRef](#)]



174. Aquino, R.R.; Tolentino, M.S.; Amen, S.C.S.; Arceo, M.A.V.; Dolojan, M.E.S.; Basilia, B.A. Preparation of cellulose acetate blended with chitosan nanostructured membrane via electrospinning for Cd<sup>2+</sup> adsorption in artificial wastewater. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *191*, 012137. [[CrossRef](#)]
175. Keshtkar, A.R.; Tabatabaefar, A.; Vaneghi, A.S.; Moosavian, M.A. Electrospun polyvinylpyrrolidone/silica/3-aminopropyltriethoxysilane composite nanofiber adsorbent: Preparation, characterization and its application for heavy metal ions removal from aqueous solution. *J. Environ. Chem. Eng.* **2016**, *4*, 1248–1258. [[CrossRef](#)]
176. Li, L.; Zhang, J.; Li, Y.; Yang, C. Removal of Cr (VI) with a spiral wound chitosan nanofiber membrane module via dead-end filtration. *J. Membr. Sci.* **2017**, *544*, 333–341. [[CrossRef](#)]
177. Bassyouni, D.; Mohamed, M.; El-Ashtouky, E.-S.; El-Latif, M.A.; Zaatout, A.; Hamad, H. Fabrication and characterization of electrospun Fe<sub>3</sub>O<sub>4</sub>/o-MWCNTs/polyamide 6 hybrid nanofibrous membrane composite as an efficient and recoverable adsorbent for removal of Pb (II). *Microchem. J.* **2019**, *149*, 103998. [[CrossRef](#)]
178. Ki, C.S.; Gang, E.; Um, I.; Park, Y.W. Nanofibrous membrane of wool keratose/silk fibroin blend for heavy metal ion adsorption. *J. Membr. Sci.* **2007**, *302*, 20–26. [[CrossRef](#)]
179. Taha, A.A.; Qiao, J.; Li, F.; Zhang, B. Preparation and application of amino functionalized mesoporous nanofiber membrane via electrospinning for adsorption of Cr<sup>3+</sup> from aqueous solution. *J. Environ. Sci.* **2012**, *24*, 610–616. [[CrossRef](#)]
180. Zia, Q.; Tabassum, M.; Lu, Z.; Khawar, M.T.; Song, J.; Gong, H.; Meng, J.; Li, Z.; Li, J. Porous poly(L-lactic acid)/chitosan nanofibres for copper ion adsorption. *Carbohydr. Polym.* **2020**, *227*, 115343. [[CrossRef](#)]
181. Abbasizadeh, S.; Keshtkar, A.R.; Mousavian, M.A. Preparation of a novel electrospun polyvinyl alcohol/titanium oxide nanofiber adsorbent modified with mercapto groups for uranium (VI) and thorium (IV) removal from aqueous solution. *Chem. Eng. J.* **2013**, *220*, 161–171. [[CrossRef](#)]
182. Bornillo, K.A.S.; Kim, S.; Choi, H. Cu (II) removal using electrospun dual-responsive polyethersulfone-poly (dimethyl amino) ethyl methacrylate (PES-PDMAEMA) blend nanofibers. *Chemosphere* **2020**, *242*, 125287. [[CrossRef](#)] [[PubMed](#)]
183. Wu, R.-X.; Zheng, G.-F.; Li, W.-W.; Zhong, L.-B.; Zheng, Y.-M. Electrospun Chitosan Nanofiber Membrane for Adsorption of Cu (II) from Aqueous Solution: Fabrication, Characterization and Performance. *J. Nanosci. Nanotechnol.* **2018**, *18*, 5624–5635. [[CrossRef](#)] [[PubMed](#)]
184. Peter, K.T.; Myung, N.V.; Cwiertny, D.M. Surfactant-assisted fabrication of porous polymeric nanofibers with surface-enriched iron oxide nanoparticles: Composite filtration materials for removal of metal cations. *Environ. Sci. Nano* **2018**, *5*, 669–681. [[CrossRef](#)]
185. Wang, P.; Wang, L.; Dong, S.; Zhang, G.; Shi, X.; Xiang, C.; Li, L. Adsorption of hexavalent chromium by novel chitosan/poly(ethylene oxide)/permutit electrospun nanofibers. *New J. Chem.* **2018**, *42*, 17740–17749. [[CrossRef](#)]
186. Sun, B.; Li, X.; Zhao, R.; Yin, M.; Wang, Z.; Jiang, Z.; Wang, C. Hierarchical aminated PAN/γ-AIOOH electrospun composite nanofibers and their heavy metal ion adsorption performance. *J. Taiwan Inst. Chem. Eng.* **2016**, *62*, 219–227. [[CrossRef](#)]
187. Zhang, S.; Shi, Q.; Korfiatis, G.; Christodoulatos, C.; Wang, H.; Meng, X. Chromate removal by electrospun PVA/PEI nanofibers: Adsorption, reduction, and effects of co-existing ions. *Chem. Eng. J.* **2020**, *387*, 124179. [[CrossRef](#)]
188. Xiao, S.; Ma, H.; Shen, M.; Wang, S.; Huang, Q.; Shi, X. Excellent copper (II) removal using zero-valent iron nanoparticle-immobilized hybrid electrospun polymer nanofibrous mats. *Colloids Surf. A Physicochem. Eng. Asp.* **2011**, *381*, 48–54. [[CrossRef](#)]
189. Hadi Najafabadi, H.; Irani, M.; Roshanfekar Rad, L.; Heydari Haratameh, A.; Haririan, I. Removal of Cu<sup>2+</sup>, Pb<sup>2+</sup> and Cr<sup>6+</sup> from aqueous solutions using a chitosan/graphene oxide composite nanofibrous adsorbent. *RSC Adv.* **2015**, *5*, 16532–16539. [[CrossRef](#)]
190. Wu, C.; Wang, H.; Wei, Z.; Li, C.; Luo, Z. Polydopamine-mediated surface functionalization of electrospun nanofibrous membranes: Preparation, characterization and their adsorption properties towards heavy metal ions. *Appl. Surf. Sci.* **2015**, *346*, 207–215. [[CrossRef](#)]
191. Zhao, R.; Li, X.; Li, Y.; Li, Y.; Sun, B.; Zhang, N.; Chao, S.; Wang, C. Functionalized magnetic iron oxide/polyacrylonitrile composite electrospun fibers as effective chromium (VI) adsorbents for water purification. *J. Colloid Interface Sci.* **2017**, *505*, 1018–1030. [[CrossRef](#)]
192. Jiang, M.; Han, T.; Wang, J.; Shao, L.; Qi, C.; Zhang, X.M.; Liu, C.; Liu, X. Removal of heavy metal chromium using cross-linked chitosan composite nanofiber mats. *Int. J. Biol. Macromol.* **2018**, *120*, 213–221. [[CrossRef](#)]
193. Bozorgi, M.; Abbasizadeh, S.; Samani, F.; Mousavi, S.E. Performance of synthesized cast and electrospun PVA/chitosan/ZnO-NH<sub>2</sub> nano-adsorbents in single and simultaneous adsorption of cadmium and nickel ions from wastewater. *Environ. Sci. Pollut. Res.* **2018**, *25*, 17457–17472. [[CrossRef](#)]
194. Cai, Z.; Song, X.; Zhang, Q.; Zhai, T. Electrospun polyindole nanofibers as a nano-adsorbent for heavy metal ions adsorption for wastewater treatment. *Fibers Polym.* **2017**, *18*, 502–513. [[CrossRef](#)]
195. Ma, F.-f.; Zhang, N.; Wei, X.; Yang, J.-h.; Wang, Y.; Zhou, Z.-w. Blend-electrospun poly(vinylidene fluoride)/polydopamine membranes: Self-polymerization of dopamine and the excellent adsorption/separation abilities. *J. Mater. Chem. A* **2017**, *5*, 14430–14443. [[CrossRef](#)]
196. Aluigi, A.; Tonetti, C.; Vineis, C.; Tonin, C.; Mazzuchetti, G. Adsorption of copper (II) ions by keratin/PA6 blend nanofibres. *Eur. Polym. J.* **2011**, *47*, 1756–1764. [[CrossRef](#)]
197. Hou, X.; Zhou, H.; Zhang, J.; Cai, Y.; Huang, F.; Wei, Q. High Adsorption Pearl-Necklace-Like Composite Membrane Based on Metal-Organic Framework for Heavy Metal Ion Removal. *Part. Part. Syst. Charact.* **2018**, *35*, 1700438. [[CrossRef](#)]

198. Lakhdhar, I.; Belosinschi, D.; Mangin, P.; Chabot, B. Development of a bio-based sorbent media for the removal of nickel ions from aqueous solutions. *J. Environ. Chem. Eng.* **2016**, *4*, 3159–3169. [[CrossRef](#)]
199. Rad, L.R.; Momeni, A.; Ghazani, B.F.; Irani, M.; Mahmoudi, M.; Noghreh, B. Removal of Ni<sup>2+</sup> and Cd<sup>2+</sup> ions from aqueous solutions using electrospun PVA/zeolite nanofibrous adsorbent. *Chem. Eng. J.* **2014**, *256*, 119–127. [[CrossRef](#)]
200. Zhang, S.; Shi, Q.; Christodoulatos, C.; Korfiatis, G.; Meng, X. Adsorptive filtration of lead by electrospun PVA/PAA nanofiber membranes in a fixed-bed column. *Chem. Eng. J.* **2019**, *370*, 1262–1273. [[CrossRef](#)]
201. Shooto, N.D.; Dikio, C.W.; Wankasi, D.; Sikhwivhilu, L.M.; Mtunzi, F.M.; Dikio, E.D. Novel PVA/MOF Nanofibres: Fabrication, Evaluation and Adsorption of Lead Ions from Aqueous Solution. *Nanoscale Res. Lett.* **2016**, *11*, 414. [[CrossRef](#)]
202. Wang, J.; Pan, K.; He, Q.; Cao, B. Polyacrylonitrile/polypyrrole core/shell nanofiber mat for the removal of hexavalent chromium from aqueous solution. *J. Hazard. Mater.* **2013**, *244–245*, 121–129. [[CrossRef](#)]
203. Zang, L.; Lin, R.; Dou, T.; Lu, W.; Ma, J.; Sun, L. Electrospun superhydrophilic membranes for effective removal of Pb (II) from water. *Nanoscale Adv.* **2019**, *1*, 389–394. [[CrossRef](#)]
204. Wang, M.; Li, X.; Zhang, T.; Deng, L.; Li, P.; Wang, X.; Hsiao, B.S. Eco-friendly poly(acrylic acid)-sodium alginate nanofibrous hydrogel: A multifunctional platform for superior removal of Cu(II) and sustainable catalytic applications. *Colloids Surf. A Physicochem. Eng. Asp.* **2018**, *558*, 228–241. [[CrossRef](#)]
205. Wanjale, S.; Birajdar, M.; Jog, J.; Neppalli, R.; Causin, V.; Karger-Kocsis, J.; Lee, J.; Panzade, P. Surface tailored PS/TiO<sub>2</sub> composite nanofiber membrane for copper removal from water. *J. Colloid Interface Sci.* **2016**, *469*, 31–37. [[CrossRef](#)]
206. Razzaz, A.; Ghorban, S.; Hosayni, L.; Irani, M.; Aliabadi, M. Chitosan nanofibers functionalized by TiO<sub>2</sub> nanoparticles for the removal of heavy metal ions. *J. Taiwan Inst. Chem. Eng.* **2016**, *58*, 333–343. [[CrossRef](#)]
207. Haddad, M.Y.; Alharbi, H.F. Enhancement of heavy metal ion adsorption using electrospun polyacrylonitrile nanofibers loaded with ZnO nanoparticles. *J. Appl. Polym. Sci.* **2019**, *136*, 47209. [[CrossRef](#)]
208. Lin, Y.; Cai, W.; He, H.; Wang, X.; Wang, G. Three-dimensional hierarchically structured PAN@ $\gamma$ -AIOOH fiber films based on a fiber templated hydrothermal route and their recyclable strong Cr(vi)-removal performance. *RSC Adv.* **2012**, *2*, 1769–1773. [[CrossRef](#)]
209. Pouya, E.S.; Fatoorehchi, H.; Foroughi-Dahr, M. Batch removal of Pb (II) ions from aqueous medium using gamma-AIO nanoparticles/ethyl cellulose adsorbent fabricated via electrospinning method: An equilibrium isotherm and characterization study. *Pol. J. Chem. Technol.* **2018**, *20*, 32–39. [[CrossRef](#)]
210. Pi, H.; Wang, R.; Ren, B.; Zhang, X.; Wu, J. Facile Fabrication of Multi-Structured SiO<sub>2</sub>@PVDF-HFP Nanofibrous Membranes for Enhanced Copper Ions Adsorption. *Polymers* **2018**, *10*, 1385. [[CrossRef](#)] [[PubMed](#)]
211. Makaremi, M.; Lim, C.X.; Pasbakhsh, P.; Lee, S.M.; Goh, K.L.; Chang, H.; Chan, E.S. Electrospun functionalized polyacrylonitrile-chitosan Bi-layer membranes for water filtration applications. *RSC Adv.* **2016**, *6*, 53882–53893. [[CrossRef](#)]
212. Chen, H.; Lin, J.; Zhang, N.; Chen, L.; Zhong, S.; Wang, Y.; Zhang, W.; Ling, Q. Preparation of MgAl-EDTA-LDH based electrospun nanofiber membrane and its adsorption properties of copper (II) from wastewater. *J. Hazard. Mater.* **2018**, *345*, 1–9. [[CrossRef](#)]
213. Islam, M.S.; Rahaman, M.S.; Yeum, J.H. Phosphine-functionalized electrospun poly(vinyl alcohol)/silica nanofibers as highly effective adsorbent for removal of aqueous manganese and nickel ions. *Colloids Surf. A Physicochem. Eng. Asp.* **2015**, *484*, 9–18. [[CrossRef](#)]
214. Teng, M.; Wang, H.; Li, F.; Zhang, B. Thioether-functionalized mesoporous fiber membranes: Sol-gel combined electrospun fabrication and their applications for Hg<sup>2+</sup> removal. *J. Colloid Interface Sci.* **2011**, *355*, 23–28. [[CrossRef](#)] [[PubMed](#)]
215. Shariful, M.I.; Sepehr, T.; Mehrali, M.; Ang, B.C.; Amalina, M.A. Adsorption capability of heavy metals by chitosan/poly(ethylene oxide)/activated carbon electrospun nanofibrous membrane. *J. Appl. Polym. Sci.* **2018**, *135*, 45851. [[CrossRef](#)]
216. Tan, P.; Wen, J.; Hu, Y.; Tan, X. Adsorption of Cu<sup>2+</sup> and Cd<sup>2+</sup> from aqueous solution by novel electrospun poly(vinyl alcohol)/graphene oxide nanofibers. *RSC Adv.* **2016**, *6*, 79641–79650. [[CrossRef](#)]
217. Bhalara, P.D.; Balasubramanian, K.; Banerjee, B.S. Spider-Web Textured Electrospun Composite of Graphene for Sorption of Hg (II) Ions. *Mater. Focus* **2015**, *4*, 154–163. [[CrossRef](#)]
218. Efome, J.E.; Rana, D.; Matsuura, T.; Lan, C.Q. Metal-organic frameworks supported on nanofibers to remove heavy metals. *J. Mater. Chem. A* **2018**, *6*, 4550–4555. [[CrossRef](#)]
219. Efome, J.E.; Rana, D.; Matsuura, T.; Lan, C.Q. Insight Studies on Metal-Organic Framework Nanofibrous Membrane Adsorption and Activation for Heavy Metal Ions Removal from Aqueous Solution. *ACS Appl. Mater. Interfaces* **2018**, *10*, 18619–18629. [[CrossRef](#)] [[PubMed](#)]
220. Habiba, U.; Siddique, T.A.; Joo, T.C.; Salleh, A.; Ang, B.C.; Afifi, A.M. Synthesis of chitosan/polyvinyl alcohol/zeolite composite for removal of methyl orange, Congo red and chromium(VI) by flocculation/adsorption. *Carbohydr. Polym.* **2017**, *157*, 1568–1576. [[CrossRef](#)]
221. Min, L.-L.; Yang, L.-M.; Wu, R.-X.; Zhong, L.-B.; Yuan, Z.-H.; Zheng, Y.-M. Enhanced adsorption of arsenite from aqueous solution by an iron-doped electrospun chitosan nanofiber mat: Preparation, characterization and performance. *J. Colloid Interface Sci.* **2019**, *535*, 255–264. [[CrossRef](#)]
222. Beheshti, H.; Irani, M.; Hosseini, L.; Rahimi, A.; Aliabadi, M. Removal of Cr (VI) from aqueous solutions using chitosan/MWCNT/Fe<sub>3</sub>O<sub>4</sub> composite nanofibers-batch and column studies. *Chem. Eng. J.* **2016**, *284*, 557–564. [[CrossRef](#)]
223. Gerstner, E. Nobel Prize 2010: Andre Geim & Konstantin Novoselov. *Nat. Phys.* **2010**, *6*, 836. [[CrossRef](#)]

224. Whitby, R.L.D. Chemical Control of Graphene Architecture: Tailoring Shape and Properties. *ACS Nano* **2014**, *8*, 9733–9754. [[CrossRef](#)]
225. Safaei, S.; Tavakoli, R. On the design of graphene oxide nanosheets membranes for water desalination. *Desalination* **2017**, *422*, 83–90. [[CrossRef](#)]
226. Chen, X.; Zhu, Y.-B.; Yu, H.; Liu, J.Z.; Easton, C.D.; Wang, Z.; Hu, Y.; Xie, Z.; Wu, H.-A.; Zhang, X.; et al. Ultrafast water evaporation through graphene membranes with subnanometer pores for desalination. *J. Membr. Sci.* **2021**, *621*, 118934. [[CrossRef](#)]
227. Modi, A.; Bellare, J. Zeolitic imidazolate framework-67/carboxylated graphene oxide nanosheets incorporated polyethersulfone hollow fiber membranes for removal of toxic heavy metals from contaminated water. *Sep. Purif. Technol.* **2020**, *249*, 117160. [[CrossRef](#)]
228. Amid, M.; Nabian, N.; Delavar, M. Fabrication of polycarbonate ultrafiltration mixed matrix membranes including modified halloysite nanotubes and graphene oxide nanosheets for olive oil/water emulsion separation. *Sep. Purif. Technol.* **2020**, *251*, 117332. [[CrossRef](#)]
229. Li, W.; Zhang, L.; Zhang, X.; Zhang, M.; Liu, T.; Chen, S. Atomic insight into water and ion transport in 2D interlayer nanochannels of graphene oxide membranes: Implication for desalination. *J. Membr. Sci.* **2020**, *596*, 117744. [[CrossRef](#)]
230. Zeng, G.; Wei, K.; Zhang, H.; Zhang, J.; Lin, Q.; Cheng, X.; Sengupta, A.; Chiao, Y.-H. Ultra-high oil-water separation membrane based on two-dimensional MXene(Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>) by co-incorporation of halloysite nanotubes and polydopamine. *Appl. Clay Sci.* **2021**, *211*, 106177. [[CrossRef](#)]
231. Feng, X.; Yu, Z.; Long, R.; Sun, Y.; Wang, M.; Li, X.; Zeng, G. Polydopamine intimate contacted two-dimensional/two-dimensional ultrathin nylon basement membrane supported RGO/PDA/MXene composite material for oil-water separation and dye removal. *Sep. Purif. Technol.* **2020**, *247*, 116945. [[CrossRef](#)]
232. Zhao, H.; Chen, S.; Quan, X.; Yu, H.; Zhao, H. Integration of microfiltration and visible-light-driven photocatalysis on g-C<sub>3</sub>N<sub>4</sub> nanosheet/reduced graphene oxide membrane for enhanced water treatment. *Appl. Catal. B Environ.* **2016**, *194*, 134–140. [[CrossRef](#)]
233. Yang, J.; Shen, Z.; He, J.; Li, Y. Efficient separation of small organic contaminants in water using functionalized nanoporous graphene membranes: Insights from molecular dynamics simulations. *J. Membr. Sci.* **2021**, *630*, 119331. [[CrossRef](#)]
234. Zhang, X.; Zhang, Z.; Zeng, Z.; Du, S.; Liu, E. Superoleophobic graphene oxide/halloysite nanotube composite membranes for oil-water separation. *Mater. Chem. Phys.* **2021**, *263*, 124347. [[CrossRef](#)]
235. Pytlakowska, K.; Kocot, K.; Hachula, B.; Pilch, M.; Wrzalik, R.; Zubko, M. Determination of heavy metal ions by energy dispersive X-ray fluorescence spectrometry using reduced graphene oxide decorated with molybdenum disulfide as solid adsorbent. *Spectrochim. Acta Part B At. Spectrosc.* **2020**, *167*, 105846. [[CrossRef](#)]
236. Sirajudheen, P.; Karthikeyan, P.; Ramkumar, K.; Meenakshi, S. Effective removal of organic pollutants by adsorption onto chitosan supported graphene oxide-hydroxyapatite composite: A novel reusable adsorbent. *J. Mol. Liq.* **2020**, *318*, 114200. [[CrossRef](#)]
237. Liu, J.; Liu, G.; Liu, W. Preparation of water-soluble  $\beta$ -cyclodextrin/poly(acrylic acid)/graphene oxide nanocomposites as new adsorbents to remove cationic dyes from aqueous solutions. *Chem. Eng. J.* **2014**, *257*, 299–308. [[CrossRef](#)]
238. Zeng, T.; Yu, Y.; Li, Z.; Zuo, J.; Kuai, Z.; Jin, Y.; Wang, Y.; Wu, A.; Peng, C. 3D MnO<sub>2</sub> nanotubes@ reduced graphene oxide hydrogel as reusable adsorbent for the removal of heavy metal ions. *Mater. Chem. Phys.* **2019**, *231*, 105–108. [[CrossRef](#)]
239. Arshad, F.; Selvaraj, M.; Zain, J.; Banat, F.; Haija, M.A. Polyethylenimine modified graphene oxide hydrogel composite as an efficient adsorbent for heavy metal ions. *Sep. Purif. Technol.* **2019**, *209*, 870–880. [[CrossRef](#)]
240. Mahmoudi, E.; Azizkhani, S.; Mohammad, A.W.; Ng, L.Y.; Benamor, A.; Ang, W.L.; Ba-Abbad, M. Simultaneous removal of Congo red and cadmium (II) from aqueous solutions using graphene oxide–silica composite as a multifunctional adsorbent. *J. Environ. Sci.* **2020**, *98*, 151–160. [[CrossRef](#)] [[PubMed](#)]
241. Bu, J.; Yuan, L.; Zhang, N.; Liu, D.; Meng, Y.; Peng, X. High-efficiency adsorption of methylene blue dye from wastewater by a thiosemicarbazide functionalized graphene oxide composite. *Diam. Relat. Mater.* **2020**, *101*, 107604. [[CrossRef](#)]
242. Bao, S.; Yang, W.; Wang, Y.; Yu, Y.; Sun, Y. One-pot synthesis of magnetic graphene oxide composites as an efficient and recoverable adsorbent for Cd (II) and Pb (II) removal from aqueous solution. *J. Hazard. Mater.* **2020**, *381*, 120914. [[CrossRef](#)]
243. Wang, W.; Cai, K.; Wu, X.; Shao, X.; Yang, X. A novel poly(m-phenylenediamine)/reduced graphene oxide/nickel ferrite magnetic adsorbent with excellent removal ability of dyes and Cr (VI). *J. Alloy. Compd.* **2017**, *722*, 532–543. [[CrossRef](#)]
244. Abd-Elhamid, A.I.; Kamoun, E.A.; El-Shanshory, A.A.; Soliman, H.M.A.; Aly, H.F. Evaluation of graphene oxide-activated carbon as effective composite adsorbent toward the removal of cationic dyes: Composite preparation, characterization and adsorption parameters. *J. Mol. Liq.* **2019**, *279*, 530–539. [[CrossRef](#)]
245. Chen, H.; Meng, Y.; Jia, S.; Hua, W.; Cheng, Y.; Lu, J.; Wang, H. Graphene oxide modified waste newspaper for removal of heavy metal ions and its application in industrial wastewater. *Mater. Chem. Phys.* **2020**, *244*, 122692. [[CrossRef](#)]
246. Gupta, K.; Khatri, O.P. Reduced graphene oxide as an effective adsorbent for removal of malachite green dye: Plausible adsorption pathways. *J. Colloid Interface Sci.* **2017**, *501*, 11–21. [[CrossRef](#)]
247. Hassan, A.M.; Wan Ibrahim, W.A.; Bakar, M.B.; Sanagi, M.M.; Sutirman, Z.A.; Nodeh, H.R.; Mokhter, M.A. New effective 3-aminopropyltrimethoxysilane functionalized magnetic sporopollenin-based silica coated graphene oxide adsorbent for removal of Pb (II) from aqueous environment. *J. Environ. Manag.* **2020**, *253*, 109658. [[CrossRef](#)] [[PubMed](#)]

248. Alrobei, H.; Prashanth, M.K.; Manjunatha, C.R.; Kumar, C.B.P.; Chitrabanu, C.P.; Shivaramu, P.D.; Kumar, K.Y.; Raghu, M.S. Adsorption of anionic dye on eco-friendly synthesised reduced graphene oxide anchored with lanthanum aluminate: Isotherms, kinetics and statistical error analysis. *Ceram. Int.* **2020**, *47*, 10322–10331. [[CrossRef](#)]
249. Wei, M.-P.; Chai, H.; Cao, Y.-L.; Jia, D.-Z. Sulfonated graphene oxide as an adsorbent for removal of Pb<sup>2+</sup> and methylene blue. *J. Colloid Interface Sci.* **2018**, *524*, 297–305. [[CrossRef](#)] [[PubMed](#)]
250. Adel, M.; Ahmed, M.A.; Mohamed, A.A. Effective removal of cationic dyes from aqueous solutions using reduced graphene oxide functionalized with manganese ferrite nanoparticles. *Compos. Commun.* **2020**, *22*, 100450. [[CrossRef](#)]
251. Anush, S.M.; Chandan, H.R.; Gayathri, B.H.; Asma; Manju, N.; Vishalakshi, B.; Kalluraya, B. Graphene oxide functionalized chitosan-magnetite nanocomposite for removal of Cu (II) and Cr (VI) from waste water. *Int. J. Biol. Macromol.* **2020**, *164*, 4391–4402. [[CrossRef](#)]
252. Wang, X.; Lu, J.; Cao, B.; Liu, X.; Lin, Z.; Yang, C.; Wu, R.; Su, X.; Wang, X. Facile synthesis of recycling Fe<sub>3</sub>O<sub>4</sub>/graphene adsorbents with potassium humate for Cr (VI) removal. *Colloids Surf. A Physicochem. Eng. Asp.* **2019**, *560*, 384–392. [[CrossRef](#)]
253. Chang, S.; Zhang, Q.; Lu, Y.; Wu, S.; Wang, W. High-efficiency and selective adsorption of organic pollutants by magnetic CoFe<sub>2</sub>O<sub>4</sub>/graphene oxide adsorbents: Experimental and molecular dynamics simulation study. *Sep. Purif. Technol.* **2020**, *238*, 116400. [[CrossRef](#)]
254. Jun, B.-M.; Kim, S.; Kim, Y.; Her, N.; Heo, J.; Han, J.; Jang, M.; Park, C.M.; Yoon, Y. Comprehensive evaluation on removal of lead by graphene oxide and metal organic framework. *Chemosphere* **2019**, *231*, 82–92. [[CrossRef](#)] [[PubMed](#)]
255. Das, T.R.; Sharma, P.K. Bimetal oxide decorated graphene oxide (Gd<sub>2</sub>O<sub>3</sub>/Bi<sub>2</sub>O<sub>3</sub>@GO) nanocomposite as an excellent adsorbent in the removal of methyl orange dye. *Mater. Sci. Semicond. Process.* **2020**, *105*, 104721. [[CrossRef](#)]
256. Sitko, R.; Musielak, M.; Serda, M.; Talik, E.; Zawisza, B.; Gagor, A.; Malecka, M. Thiosemicarbazide-grafted graphene oxide as superior adsorbent for highly efficient and selective removal of mercury ions from water. *Sep. Purif. Technol.* **2021**, *254*, 117606. [[CrossRef](#)]
257. Labiadh, L.; Kamali, A.R. 3D graphene nanoedges as efficient dye adsorbents with ultra-high thermal regeneration performance. *Appl. Surf. Sci.* **2019**, *490*, 383–394. [[CrossRef](#)]
258. Barik, B.; Kumar, A.; Nayak, P.S.; Achary, L.S.K.; Rout, L.; Dash, P. Ionic liquid assisted mesoporous silica-graphene oxide nanocomposite synthesis and its application for removal of heavy metal ions from water. *Mater. Chem. Phys.* **2020**, *239*, 122028. [[CrossRef](#)]
259. Gupta, A.; Viltres, H.; Gupta, N.K. Sono-adsorption of organic dyes onto CoFe<sub>2</sub>O<sub>4</sub>/Graphene oxide nanocomposite. *Surf. Interfaces* **2020**, *20*, 100563. [[CrossRef](#)]
260. Yusuf, M.; Song, K. Removal of Co (II) and Cr (III) from aqueous solution by graphene nanosheet/ $\delta$ -MnO<sub>2</sub>: Batch and column studies. *Chem. Eng. Res. Des.* **2020**, *159*, 477–490. [[CrossRef](#)]
261. Kumar Sahoo, S.; Kumar Sahoo, J.; Kumar Panigrahi, G.; Kumar Pattanayak, D.; Sundar Rout, A.; Lenka, A. Preparation of graphene oxide from Bio-soot wastes: As an efficient adsorbent for highly noxious Congo red dye. *FlatChem* **2020**, *24*, 100198. [[CrossRef](#)]
262. Dai, K.; Liu, G.; Xu, W.; Deng, Z.; Wu, Y.; Zhao, C.; Zhang, Z. Judicious fabrication of bifunctionalized graphene oxide/MnFe<sub>2</sub>O<sub>4</sub> magnetic nanohybrids for enhanced removal of Pb (II) from water. *J. Colloid Interface Sci.* **2020**, *579*, 815–822. [[CrossRef](#)] [[PubMed](#)]