Environmental Chemistry Letters (2021) 19:1457–1475
https://doi.org/10.1007/s10311-020-01112-8

REVIEW

Carbon-based membrane materials and applications in water and wastewater treatment: a review

Chen Li[1] · Jie Yang[1] · Luying Zhang[1] · Shibo Li[1] · Yin Yuan[1] · Xin Xiao[1] · Xinfei Fan[1] · Chengwen Song[1]

Received: 2 September 2020 / Accepted: 5 October 2020 / Published online: 20 October 2020
© Springer Nature Switzerland AG 2020

Abstract

Water contamination and freshwater shortage are calling for advanced technologies of water recycling. High performance of membrane separation has been recently obtained using carbon-based membrane materials such as carbon, carbon nanotubes, carbon fiber membranes, activated carbon and graphene. Properties of carbon materials improve fouling mitigation, hydrophilicity and permeate quality. Here, we review the fabrication of carbon-based membrane materials and applications in water treatment. The major points are: 1) carbon membranes derived from coal and phenolic resins have been widely used in water treatment. Coal-based carbon membranes used as both electrode and membrane filter display high potential owing to their electrical conductivity. 2) Four types of carbon nanotube membranes are presented, with focus on carbon nanotubes that show high separation performance. 3) Carbon fiber membranes show high permeability due to abundant functional groups on the surface. 4) Activated carbon membranes are promising for organic matter removal owing to their high surface area, micro- and macroscopic structure, and various chemical functional groups. (5) Graphene-based membranes with unique laminar pores are very promising.

Keywords Membrane · Carbon materials · Wastewater treatment · Water purification · Separation

Introduction

The industrial development and population growth have led to serious and sustainable challenge toward the water resources in the twenty-first century (Ma et al. 2017; Menachem and William 2011; Crini and Lichtfouse 2018; Salgot and Folch 2018). The World Health Organization estimates that more than 1.2 billion people worldwide have gotten sick or died through drinking contaminated water, and the number is expected to significantly grow in the coming years (Maggie 2007; Montgomery and Elimelech 2007; Wilson et al. 2018). Hence, in order to reduce the hazards from water pollution to humankind, various technologies and industrial processes for water treatment or purification have been developed and applied rapidly in recent years (Hayat et al. 2017; Jiao et al. 2017; Pintor et al. 2016; Zheng et al. 2015; Bouabidi et al. 2018; Bello and Raman 2018).

Among them, membrane separation has been accepted as a promising and pervasive technology arising from its numerous advantages of no chemical additives requirement, low energy demand, easy operation, high separation selectivity and good stability (Chowdhury et al. 2018; Gin and Noble 2011; Lau et al. 2018; Li et al. 2016a, b, c, d; Madhura et al. 2017; Rezakazemi et al. 2017; Thakur and Voicu 2016). As one of the dominated factors to determine membrane performance, membrane materials should be primarily concerned for exploring high-performance membranes. Recently, carbon-based materials including coal, phenolic resin, carbon nanotube, carbon fiber, activated carbon, graphene, etc. have been used to develop membranes with optimal structure and performance due to their excellent physicochemical properties (Anand et al. 2018; Goh et al. 2016; Thines et al. 2017; Madima et al. 2020; Wei et al. 2018). This review aims to provide an overview on recent developments on carbon-based membrane materials for water treatment. A brief discussion of the existing challenges and their prospects were also considered. This article is an abridged version of the chapter by Li et al. (2020b).

✉ Xinfei Fan
fxf0909@dlmu.edu.cn

✉ Chengwen Song
chengwensong@dlmu.edu.cn

[1] College of Environmental Science and Engineering, Dalian Maritime University, Dalian 116026, China

Carbon membranes

Carbon membranes, as novel porous inorganic membranes, are usually prepared by pyrolysis of carbonaceous materials. Due to their huge advantages including good resistance to high temperature and chemical solvent erosion, developed micron or nanometer porosity, high mechanical strength, easy preparation and high degree of cleanliness, they have shown attractive prospects on gas and liquid separations. The research on carbon membranes originated in the 1960s, which firstly focused on the adsorption and surface diffusion process of gas through carbon membranes. Since then, Ash et al. (1973) have made great contribution in this field and a great deal of subsequent researches have been done (Ismail and David 2001; Li et al. 2016a, b, c, d; Qin et al. 2017; Wei et al. 2007). Recently, with the development of membrane fabrication technology, microporous carbon membranes have been explored and successfully applied for water and wastewater treatments (Bauer et al. 1992; Li et al. 2016a, b, c, d; Sun et al. 2018; Tahri et al. 2013). Among them, the carbon membranes prepared with coal or phenolic resin were the mostly studied, thus introduced in the following part.

Coal-based carbon membranes

Coal, as a kind of natural mixture composed of macromolecular cross-linked polymers and inorganic minerals, is a great material for preparing carbon membranes. In the past 2 decades, a series of systematic investigations on the controlled preparation of carbon membranes derived from coal were carried out by our research group. The pore structure, mechanical strength, physical and chemical properties and electrical conductivity of coal-based carbon membranes were further optimized. As expected, the coal-based carbon membranes showed excellent water treatment performance (Song et al. 2006). In addition, some other researchers also use coal as a precursor to prepare carbon membranes and use them in water treatment. Low-cost carbon membranes prepared from fly-ash of burning coal have been used for the clarification of centrifuged kiwifruit juice (Qin et al. 2015b). Tubular carbon microfiltration membrane was prepared by mixing coal powder with phenolic resin solution and organic additives and was successfully applied to the retention of dye wastewater (Tahri et al. 2013). However, during treatment process, the retention and accumulation of pollutants on the membrane surface and inside the membrane pores would give rise to serious membrane fouling. In order to tackle this problem, our group utilized the electrical conductivity of coal-based carbon membranes and designed a coupling system which employed coal-based carbon membranes both as the filter and anode. Thus significant improvement on removal efficiency and antifouling ability were obtained due to the electrochemical oxidation synthetic effect (Fig. 1). This system not only displayed excellent removal efficiency for organic pollutants (such as oil droplets) larger than the membrane pores (Li et al. 2016a, b, c, d), but also demonstrated great potential on those pollutants with a smaller molecule size than the membrane pore size including dyes, bisphenol A, phenol and antibiotics (Sun et al. 2018; Tao et al. 2017a; Yin et al. 2016). Moreover, microorganisms such as microalgae and Vibrio cholerae were also effectively removed (Tao et al. 2017b). Compared with other membrane processes such as ultrafiltration, nanofiltration and reverse osmosis, this technology possessed obvious advantages on processing capacity and energy consumption.

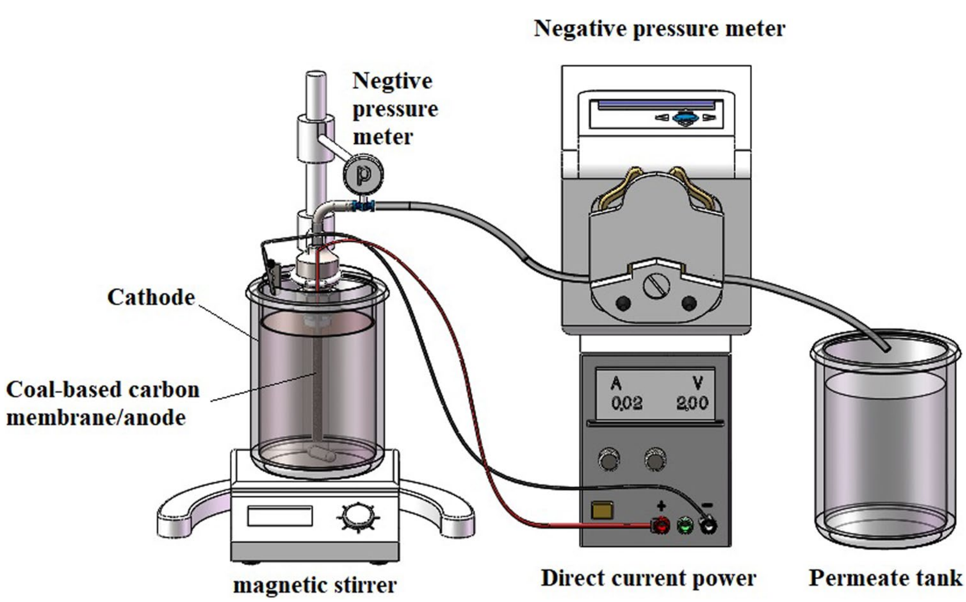

Fig. 1 Coal-based carbon membrane coupling with electrochemical oxidation technology. In this system, the coal-based carbon membrane with abundant pores, thermal stability and great conductivity was used in this system both as a microfiltration membrane and an anode. The permeability and removal efficiency of the system was significantly enhanced when coupled with the electrochemical synergistic effect

Although the coupling system has been proved to be effective for organic wastewater treatment, further potential for improvement in the removal efficiency and life span of the coupling system is often limited by the relatively low electrochemical activity of membrane electrode materials. Therefore, improving electrochemical activity of the membrane electrode material is a key to make a significant breakthrough in this field. Yang et al. (2011) presented the design of a novel electrocatalytic membrane reactor by loading TiO_2 electrocatalyst on carbon membrane surface by a sol–gel approach to enhance electron transfer and membrane permeability. In this operation process, once the membrane anode was electrified, it not only electrochemically decomposed H_2O into gas and liquid microflows to avoid membrane fouling, but also generated reactive intermediates which could indirectly decompose the organic foulants into CO_2 and H_2O or biodegradable products to realize the self-cleaning function of the electrocatalytic membrane. Further, this TiO_2/carbon membrane showed great performance on tetracycline removal with 100% tetracycline and 87.8% chemical oxygen demand (COD) removal rate achieved (Liu et al. 2016). Similarly, Sn–SnO_2 was coated on carbon membrane to enhance its treatment performance, The tetracycline removal rate of Sb–SnO_2/carbon membrane could achieve 96.5% after 6 h operation compared to 72.8% for carbon membrane (Liu et al. 2017a, b). Besides, the Bi–SnO_2/carbon electrocatalytic membrane was fabricated via a simple electrochemical reduction and hydrothermal method by Wang et al. (2018). The Bi–SnO_2/carbon membrane could continuously remove and inactivate *E. coli* in water through flow-through mode. As a result, the sterilization efficiency reached more than 99.99% under the conditions of cell voltage of 4 V, flow rate of 1.4 mL/min and *E. coli* initial concentration of 1.0×10^4 CFU/mL, owing to the synergistic effect of the membrane separation and electrocatalytic oxidation. In order to further enhance the electrocatalytic activity of the membrane, a facile dynamic electrodeposition method was developed by Li et al. (2020a), by which CuO nanoparticles were uniformly deposited on both the surface and pore walls of a coal-based carbon membrane. The prepared dynamic electrodeposited CuO/carbon membrane exhibited superior removal ability with Rhodamine B, COD and total organic carbon (TOC) removal efficiency of 99.96%, 71.82% and 64.29%, respectively, which were 18.7–20.1 and 1.5–1.8 times higher than that of the original carbon membrane and the conventional electrodeposited CuO/carbon membrane.

In addition, a novel integration system coupled coal-based carbon membrane with sulfate radicals-based advanced oxidation processes was proved to have great wastewater treatment potential. Under the optimal condition, the integrated system achieved 100% phenol removal efficiency which attributed to the co-existence of radical and nonradical mechanisms (Fan et al. 2019).

Phenolic resin-based carbon membranes

Phenolic resins are applied as another precursors of carbon membranes due to their low cost, thermosetting property and high carbon yield (Muylaert et al. 2012). Several scholars have successfully prepared phenolic resins-based carbon membrane for water and wastewater treatment. A method for preparing symmetric carbon membrane was presented by Wei et al. (2012). The carbon membrane was synthesized via sol–gel synthesis followed by super-critical drying with CO_2 at 50 °C and 10 MPa. Due to its mesoporous property, the pure water flux could achieve at 13.4 L m^{-2} h^{-1} and the molecular weight cutoff was about 2000. Tubular carbon membranes on an ultrafiltration substrate were prepared by thermosetting phenolic resin and carbon black (Tahri et al. 2016) and were applied efficiently to the treatment of industrial dyeing effluent. On the other hand, the fabrication and application of asymmetric tubular carbon membranes were studied. A simple approach for preparing carbon membranes was presented by Qin et al. (2015a) with macroporous ceramic membrane as substrate and carbon layer loaded via sol–gel polymerization of resorcinol and formaldehyde. Owing to its uniform pores and high mesopore volume, the pure water flux of the obtained carbon membrane was as high as 167 L m^{-2} h^{-1} bar^{-1}. Song et al. (2017) developed carbon alumina mixed matrix membranes by impregnating phenolic resin in porous alumina matrix via a vacuum-assisted method. The results showed that membranes with high water fluxes and salt rejections could be easily tailored. Based on this, the effects of different substrates and coating conditions on the formation of carbon/ceramic substrate for desalination were studied (Song et al. 2018). Besides, the preparation and separation performance assessment of carbon membranes derived from phenolic resin by a vacuum-assisted method and carbonization in an inert atmosphere were shown (Abd et al. 2017). The study of phenolic resin-based carbon membrane for phenol and phosphoric acid removal by Zhao et al. (2018) showed that the maximum removal rates could reach 81.9% for phenol and 55.3% for phosphoric acid. Due to the excellent electrical conductivity of carbon membranes, studies on coal-based carbon membranes above have proved that coupling electrocatalysis and membrane separation technology was one of the feasible ways to enhance the treatment performance. Similarly, phenolic resin-based carbon membrane was also used as electrocatalytic electrode for water and wastewater treatment. Study result showed that TiO_2 phenolic resin/activated carbon carbon-based membranes had the superb electrochemical activity and catalytic degradation efficiency with the COD and phenol removal rates of 86.5% and 94.6% (Hui et al. 2020).

Carbon nanotube membranes

Carbon nanotubes, as an important kind of carbon materials, with remarkable electrical, thermal, mechanical and optical properties, carbon nanotubes have been widely used in sensor, super-capacitor, lithium-ion battery, etc. (Apul and Karanfil 2015; Gupta et al. 2013; Patino et al. 2015; Ren et al. 2011; Yu et al. 2014). Carbon nanotubes were firstly discovered by Ijima (1991). Soon after, researchers observed ultrahigh water flow rates in carbon nanotubes and this discovery produced great expectation that carbon nanotubes could be used as an ideal material for water treatment (Ahn et al. 2012; Lee et al. 2011; Whitby and Quirk 2007). The concept of carbon nanotube membrane was introduced by Li and Richard (2000) when they studied the mass transfer phenomenon in single-walled carbon nanotubes. Recently, carbon nanotubes membranes are getting more and more attention in water treatment field. Carbon nanotubes membranes are usually classified into vertically aligned carbon nanotubes membranes, horizontally aligned carbon nanotubes membranes, mixed matrix carbon nanotubes membranes and electrochemical carbon nanotubes membranes (as shown in Fig. 2).

Vertically-aligned carbon nanotubes membranes

The vertically aligned carbon nanotube membrane was firstly constructed by Bruce et al. (2004) with a high water flux. After that, the membranes prepared by Baek et al. (2014) and Holt et al. (2004) demonstrated that the water flux was most three times higher than a typical ultrafiltration membrane. This was mainly owing to the effect of the compact nanotube forest and short nanochannel length. In addition, vertically aligned carbon nanotube membranes also exhibited certain antimicrobial and antifouling capacities (Ihsanullah et al. 2016; Lee et al. 2015; Mainak et al. 2005; Matsumoto et al. 2017; Park et al. 2014; Vijwani et al. 2018; Zhao et al. 2013a, b). Excellent oil removal efficiency was proved by using prepared membranes for oil–water mixture treatment (Hsieh et al. 2016; Lee and Baik 2010). A key

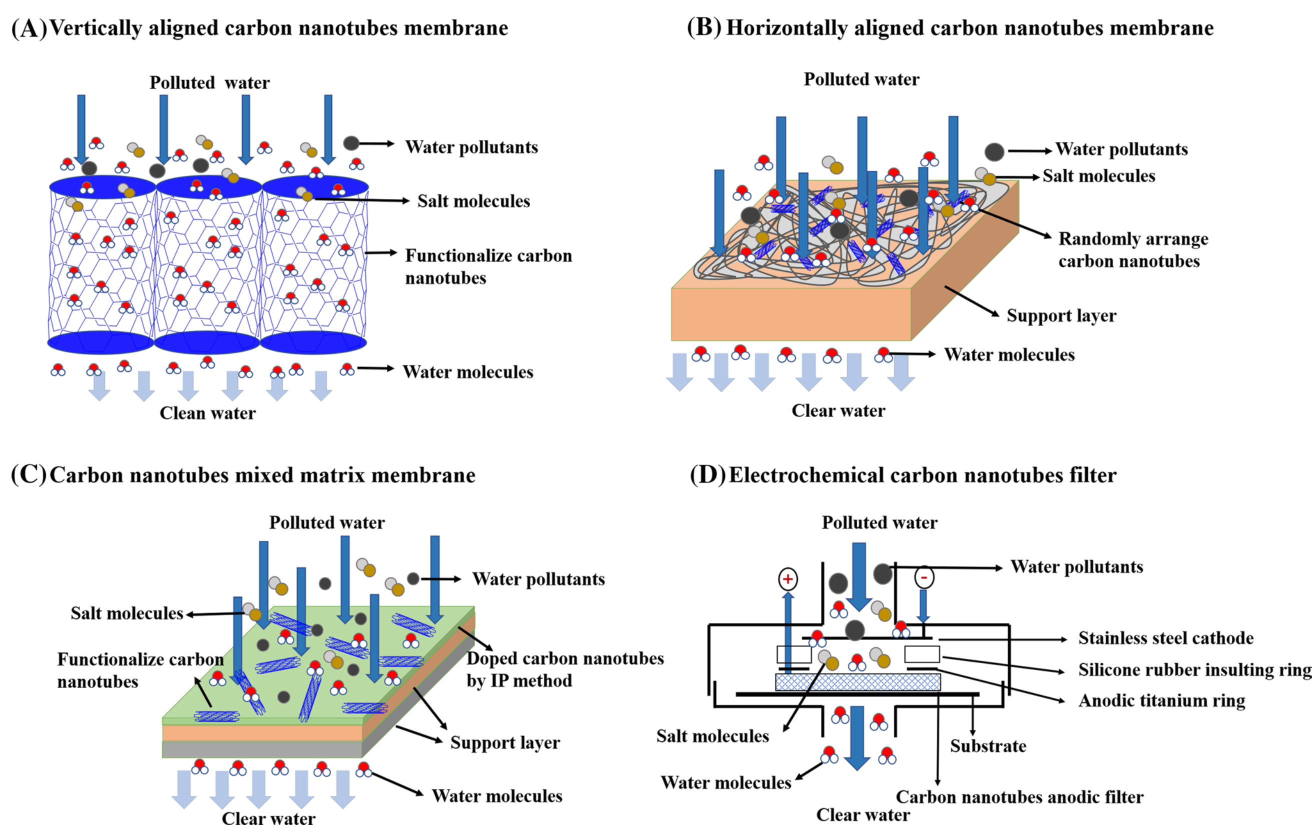

Fig. 2 Mechanism of water passing through the four types of carbon nanotubes membranes: **a** vertically aligned carbon nanotubes membrane, **b** horizontally aligned carbon nanotubes membrane which are randomly arranged horizontally on a porous support layer, **c** mixed matrix carbon nanotubes membrane which are directly doped into the polymer membranes by interfacial polymerization or phase inversion, **d** electrochemical carbon nanotubes membrane

challenge on preparing these kinds of membranes was to align the carbon nanotubes over a sufficiently large area for comprehensive water treatment (Ali et al. 2019). Instead of conventional preparation methods, Wu et al. (2014) utilized an electric field to obtain vertically aligned carbon nanotubes membranes. Electro-casting allowed multi-walled carbon nanotubes to grow vertically and disperse more evenly. However, complex manufacturing techniques were still major obstacle to make these membranes suitable for large-scale applications (Ihsanullah 2019).

Horizontally-aligned carbon nanotubes membranes

In addition to vertically aligned pattern, carbon nanotubes can aggregate with each other by Van der Waals interactions to form horizontally aligned carbon nanotubes membranes (Ihsanullah 2019). Due to the disordered arrangement of functionalized carbon nanotubes, the horizontally aligned carbon nanotubes membranes can provide rich porous structure and large specific surface area (Sears et al. 2010), which makes them possess high water flux, high adsorption capacity to natural organic matter (Yang et al. 2013) and strong antimicrobial actions (Ihsanullah et al. 2015; Kang et al. 2007). Li et al. (2015) found that a "slanted carbon nanotubes membrane" exhibited higher water flux than a typical vertically aligned carbon nanotubes membrane, as this kind of art structure could obviously lower the energy barrier for filling water into the carbon nanotubes. Brady et al. (2008) reported that the horizontally aligned single-walled carbon nanotubes membrane displayed high removal rate for the virus MS_2 bacteriophage. Horizontally aligned carbon nanotubes membranes were also applied to direct contact membrane distillation, showing high water flux and good desalination ability (Dumée et al. 2010). Subsequently, the membrane was modified by two chemical ways; the resultant membrane had a larger contact angle (140° compared with 125°) that further improved its treatment performance (Dumée et al. 2011).

However, carbon nanotubes usually tend to aggregate when they dispersed in a polymer matrix or solvent. Therefore, it was difficult to prepare a uniform dispersion. For this reason, several surfactants such as Triton-X100 and sodium lauryl sulfate were adopted to improve the dispersion of carbon nanotubes in aqueous solution (Wu et al. 2010a, b, c). Besides, chemical functionalization was regarded as another effective way to increase the hydrophilicity and stability of carbon nanotubes suspensions (Yang et al. 2013). Some researchers covalently grafted functional groups including amines, fluorine and sulfhydryl groups onto carbon nanotubes to help them disperse in horizontally aligned carbon nanotubes membranes (Ansón-Casaos et al. 2010; Darryl et al. 2010).

Mixed matrix-carbon nanotubes membranes

Compared with the above two types of membranes, mixed matrix membranes are easier to be commercialized for their simple preparation procedures. For preparing mixed matrix-carbon nanotubes membranes, functional carbon nanotubes are generally added into polymeric membranes by several synthesis techniques (Ali et al. 2019; Ihsanullah 2019) including phase inversion (Brunet et al. 2008; Choi et al. 2006; Majeed et al. 2012), interfacial polymerization (Kim et al. 2014; Shen et al. 2013), solution mixing (Ahmed et al. 2013), spray-assisted layer-by-layer (Liu et al. 2013), polymer grafting (Shawky et al. 2011), polymerization (Zarrabi et al. 2016; Zhao et al. 2014) and colloidal precipitation (Ho et al. 2017). The prepared membranes exhibit excellent properties for ultrafiltration (Choi et al. 2006; Majeed et al. 2012), nanofiltration (Shen et al. 2013; Wu et al. 2010a), microfiltration (Madaeni et al. 2013; Medina-Gonzalez and Remigy 2011), reverse osmosis (Kim et al. 2014) and forward osmosis (Amini et al. 2013) applications. Researches about the membrane performance of mixed matrix nanotubes membranes are listed in Table 1.

Electrochemical carbon nanotubes membranes

Electrochemical carbon nanotubes membrane for wastewater treatment is a novel technique, in which the membranes are used both as a filter for separation and electrodes for electrochemical degradation (Ahmed et al. 2016; de Lannoy et al. 2012; Ho et al. 2018; Lalia et al. 2015; Yi et al. 2018). Thus, they exhibit great potential on wastewater treatment due to high degradation efficiency, low energy consumption and simple operation process (Bakr and Rahaman 2016, 2017; Liu et al. 2017a, b; Motoc et al. 2013). Besides, by transferring electrons directly through the surface of the membrane electrode, the solute transfer restriction of the conventional batch electrochemical process is overcome. A novel carbon nanotubes-based membrane with a sandwich-like structure was prepared by Wei et al. (2017). Low concentration of microcystin-LR (0.5 mg/L) was removed economically and efficiently (> 99.8%). Besides, the selectivity of iron ions (> 98%) was obtained by applying an electric field to the membranes (Duan et al. 2017; Gao et al. 2017) and metoprolol degradation rate of 97% was reached by using a nanoparticulate zero-valent iron modified multi-walled carbon nanotubes membrane under the applied voltage of 1 V (Yanez et al. 2017).

Graphene-based membranes

Graphene, materials, consisting of a compact accumulation of sp2 hybrid carbon atoms, were reported for the first time by Novoselov et al. (2004). Since then, graphene and

Table 1 Membrane performance of mixed matrix-carbon nanotubes membranes

Material	Application	Preparation method	Carbon nanotubes amount (wt%)	Flux	Target remove objects	Removal/rejection efficiency (%)	References
Carbon nanotubes/polysulfone	Ultrafiltration	Phase inversion	1.5	21 m^3/m^2 day (4 bar)	Polyethylene oxide	99	Choi et al. (2006)
Carbon nanotubes/polyacrylonitrile	Ultrafiltration	Phase inversion	0.5–2	53 L/m^2 h (2 bar)	–	–	Majeed et al. (2012)
Carbon nanotubes/polysulfone	Ultrafiltration	Phase inversion	0–1	–	Cr(VI), Cr(III)	94.2, 78.2	Shah and Murthy (2013)
Carbon nanotubes/polysulfone	Ultrafiltration	Phase inversion	0.1	70.7 ± 1.8 L/m^2 h	–	–	Yin et al. (2013)
Carbon nanotubes/polyphenylene sulfone	Ultrafiltration	Phase inversion	0.5	56.91 L/m^2 h (345 kPa)	Pepsin, trypsin	90, 84	Lawrence et al. (2012)
Carbon nanotubes/brominated polyphenylene oxide/triethanolamine	Ultrafiltration	Phase inversion	5	487 L/m^2 h (0.2 MPa)	Egg albumin	94	Wu et al. (2010b)
Carbon nanotubes/polyethersulfone	Ultrafiltration	Phase inversion	0–2	184 L/m^2 h (3 bar)	Bovine serum albumin	88	Rahimpour et al. (2012)
Carbon nanotubes/polyaniline/polyethersulfone	Ultrafiltration	In situ polymerization and phase inversion	0–2	1400 L/m^2 h (1 bar)	Natural organic matter	80	Lee et al. (2016)
Carbon nanotubes/TiO_2/polysulfone	Ultrafiltration	Phase inversion	0–1	210 L/m^2 h	Humic acid	56	Esfahani et al. (2015)
Carbon nanotubes/poly(vinyl alcohol)	Ultrafiltration	Pressure filtering deposition	0–20	1440 L/m^2 h	Polyethylene oxide	> 90	de Lannoy et al. (2012)
Carbon nanotubes/polyvinylidene fluoride	Ultrafiltration	Phase inversion	0–2	225 L/m^2 h	Bovine serum albumin	86.0	Ma et al. (2013)
Poly(vinyl alcohol)/carbon nanotubes/polyacrylonitrile	Ultrafiltration	Electrospinning	10	270.1 L/m^2 h (0.1 MPa)	Oil	99.5	You et al. (2013)
Carbon nanotubes/polyvinylidene fluoride	Ultrafiltration	Phase inversion	1	620 L/m^2 h	Bovine serum albumin	31.8	Zhao et al. (2013a, b)
Carbon nanotubes/polyethersulfone	Ultrafiltration	Phase inversion	0–2	21.2 kg/m^2 h	Chemical oxygen demand, total phenol	72.6, 89.5	Zirehpour et al. (2014)
Carbon nanotubes/polyvinylpyrrolidone/polyethersulfone	Ultrafiltration	Phase inversion	0–0.5	–	Bovine serum albumin, pepsin, trypsin	93.4, 74.7, 59.4	Masoomaa et al. (2015)
Carbon nanotubes/polyacrylonitrile/polyvinylpyrrolidone	Ultrafiltration	Phase inversion	0.2	121 L/m^2 h	Oil	100	Santosh et al. (2018)

Table 1 (continued)

Material	Application	Preparation method	Carbon nanotubes amount (wt%)	Flux	Target remove objects	Removal/rejection efficiency (%)	References
Carbon nanotubes/polyvinylidene fluoride/polyurethane	Ultrafiltration	sequential electrospinning	0–1	–	Oil	> 94	Gu et al. (2018)
Carbon nanotubes/polyamide	Reverse osmosis	Interfacial polymerization	2	44 L/m^2 h (15.5 bar)	NaCl	95	Kim et al. (2014)
Carbon nanotubes/m-phenylene diamine	Reverse osmosis	Interfacial polymerization	0.1	13.6 L/m^2 h	Salt	93.4	Park et al. (2012)
Carbon nanotubes/polyamide	Reverse osmosis	Interfacial polymerization	0–0.01	28.9 L/m^2 h	NaCl	> 96	Farahbakhsh et al. (2017)
Carbon nanotubes/poly(piperazine amide)	Nanofiltration/ultrafiltration	Interfacial polymerization	0–0.02	13.2 L/m^2 h (1 bar)	Na_2SO_4	96.8	Zheng et al. (2017)
Carbon nanotubes/polyester	Nanofiltration	Interfacial polymerization	0.05	4.7 L/m^2 h	Salt	Improved	Wu et al. (2010a)
Carbon nanotubes/poly(methyl methacrylate)	Nanofiltration	Interfacial polymerization	0.67	~ 1.94×10^{-3} cm^3/cm^2 s	Na_2SO_4	99	Shen et al. (2013)
Carbon nanotubes/polyamide	Nanofiltration	Interfacial polymerization	0–0.01	61.7 L/m^2 h (Na_2SO_4), 60.8 L/m^2 h (NaCl)	Na_2SO_4, NaCl	36.71, 95.72	Zarrabi et al. (2016)
Carbon nanotubes/polyethersulfone	Nanofiltration	Phase inversion	0–0.06	23.7 L/m^2 h	Na_2SO_4, $MgSO_4$, NaCl	65, 45, 20	Vatanpour et al. (2014)
Carbon nanotubes/polyethersulfone	Nanofiltration	Phase inversion	0–0.1	40 kg/m^2 h (0.4 MPa)	Salt	100	Daraei et al. (2013)
Carbon nanotubes/polyethersulfone/ZnO	Nanofiltration	Non-solvent induced phase inversion	0–1	16.7 kg/m^2 h	Direct Red 16	> 90	Zinadini et al. (2017)
Carbon nanotubes/polyethersulfone	Nanofiltration	Phase inversion	0.4	–	Rhodamine B, Crystal violet, Indigo carmine, Orange G	99.23, 98.43, 87.12, 82.13	Mohammad et al. (2018)
Carbon nanotubes/polysulfone/Pebax	Nanofiltration	Solution casting and solvent evaporation	0–2	–	Oil	99.79	Saadati and Pakizeh (2017)
Carbon nanotubes/polyethersulfone	Nanofiltration	Phase inversion	0.01–1	38.91 L/m^2 h	Na_2SO_4	87.25	Wang et al. (2015)
Carbon nanotubes/polyethersulfone	Nanofiltration	Phase inversion	0–0.1	< 0.1wt%	Acid orange 7	99	Ghaemi et al. (2015)
Carbon nanotubes/polysulfone	Microfiltration	Phase inversion	1–20	1200 L/m^2 h (1 bar)	Brilliant blue	~ 96	Medina-Gonzalez and Remigy (2011)
Carbon nanotubes/polyvinylidene fluoride/polydimethylsiloxane	Microfiltration	Deposition and coating	0.05	~ 38 kg/m^2 h (4 bar)	Na_2SO_4	~ 80	Madaeni et al. (2013)

Table 1 (continued)

Material	Application	Preparation method	Carbon nanotubes amount (wt%)	Flux	Target remove objects	Removal/rejection efficiency (%)	References
Carbon nanotubes/polyacrylonitrile/polypropylene	–	Electrostatic spraying	1	3891.85 L/m^2 h (0.1 MPa)	Indigo	98.7	Xu et al. (2017)
Carbon nanotubes/polyethersulfone	–	Solution casting	3	61 L/m^2 h	Cd (II)	27	Mansourpanah et al. (2011)
Carbon nanotubes/chitosan/poly(vinyl alcohol)	–	Casting and evaporation	0–2	–	Cu (II)	Doubled	Salehi et al. (2012)
Carbon nanotubes/polyvinylidene fluoride/Fe_2O_3	–	In situ polymerization	0.2	–	Cyclohexanoic acid	48	Alpatova et al. (2015)
Carbon nanotubes/polyhydroxybutyrate–calcium alginate	–	Electrospinning	–	32.95 L/m^2 h	Brilliant blue	98.20	Guo et al. (2016)
Carbon nanotubes/polyethersulfone	–	Phase inversion	0–0.5	–	Bisphenol A, nonylphenol	56, 76	Kaminska et al. (2015)

graphene oxide have been extensively applied to construct novel membranes with laminar pores. These materials have been also used as blender to improve the hydrophilicity, surface charges and antifouling ability of the polymeric membranes (Hebbar et al. 2017; Jilani et al. 2018).

Support-free graphene membranes

According to the theoretical calculation, the single-layered graphene membrane can completely desalinate brine water and seawater, showing great potential for water treatment (Cohen-Tanugi and Grossman 2012). Previous research suggested that highly permeable single-layered graphene membranes could achieve by controlling the pore size and functional groups (Cohen-Tanugi and Grossman 2012). O'Hern et al. (2014) reported their works on the controlled high-density subnanometer pores in graphene membranes which allowed the transport of salt but rejected larger organic molecule. The effects of pressure and wall interaction on the water transport through graphene membranes were carried out by molecular dynamic simulation (Shahbabaei et al. 2017). It showed that the water flux was much high owing to strong hydrogen bonds. Besides, due to excellent selectivity, membranes exhibit great potential in selective ions transportation and separation. Kabiri et al. (2016) synthesized a thiol-functionalized graphene membrane with a unique three-dimensional porous structure to remove mercury ions (Hg^{2+}) from water. The results indicated that the removal efficiency reached almost 100% for removing low (4 mg/L) and high (120 mg/L) concentration of Hg^{2+}.

Graphene oxide membranes

Graphene oxide is a reforming form of graphene in which oxygen and hydrogen atoms are bonded with carbon atoms (Hu and Mi 2013). It is usually obtained by oxidizing graphite with a strong acid or oxidant. Due to the presence of oxygen and hydrogen-based functional groups, graphene oxide can be well dispersed in water and other organic solvents, which favors the preparation of graphene oxide-based membranes (Stankovich et al. 2007). Several researches of graphene oxide membranes preparation and its application have been made in recent decades. Graphene oxide nanosheets were coated on a highly porous nanofibrous mat directly using vacuum suction method by Wang et al. (2016). The obtained graphene oxide layer exhibits "ideal" pathways (hydrophobic nanochannels) for water molecule (Fig. 3). As a result, water flux under an extremely low external pressure (0.1 bar) significantly increased and high removal performance of 100% rejection of Congo red and 56.7% rejection of Na_2SO_4 obtained. Besides, Nair et al. (2012) studied the water mobility in nanochannels between graphene oxide tablets under different conditions. It showed that the layer

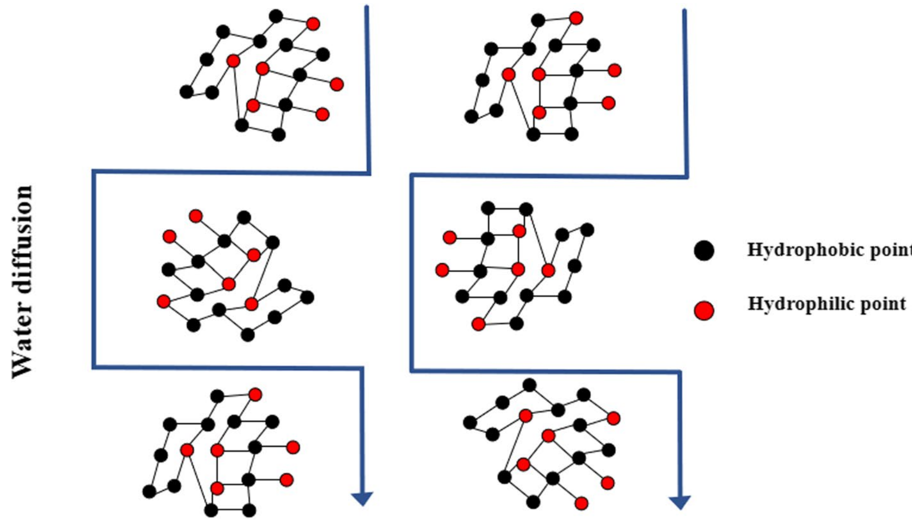

Fig. 3 Graphene oxide membrane for water transport. In the treatment process, water molecules firstly arrived at the hydrophilic "gate" (space between the two adjacent graphene oxide nanosheets or defects of graphene oxide nanosheets) and aggregated at this place. After passing through the "gate," water molecules slipped through the hydrophobic nanochannel at a high speed with low or no friction

spacing between the original graphene oxide membrane and the stacked graphene oxide membrane was about 0.6 nm in the dry condition. Because of the diffusion of water molecules to graphene oxide layer, the increased interlayer spacing between graphene oxide membranes resulted in water molecules obtained high mobility. However, when the graphene oxide membrane was immersed in an ionic solution, the increased gap by the hydration of the sheet cannot repel K^+ and Na^+ ions and make the membrane inappropriate for desalination applications (Joshi et al. 2014). Addressing to this issue, graphene oxide (graphene oxide–COOH) was functionalized with glycine and carboxylation for preparing membrane to achieve high salt rejection efficiency (Yuan et al. 2017). In addition to the layer spacing, it was found that the morphological characteristics of graphene oxide membranes, such as corrugation, could improve the separation performance (Qiu et al. 2011). Similar to the study of graphene oxide membrane in ions transport, Chang et al. (2017) reported that carboxylation could increase the hydrophilicity of graphene oxide membrane by which improved the efficiency of dye removal. Such improvement was potentially attributed to surface charge density. Nowadays, graphene oxide membranes were also applied for oil removal from wastewater. Zhao et al. (2016) intercalated palygorskite nanorods into adjacent graphene oxide nanosheets before assembling into laminate structures, the prepared graphene oxide membranes showed excellent anti-oil performance in the separation process of water-containing oil emulsion.

Graphene oxide composite membranes

Although graphene oxide membranes with a good capability can be prepared by simple methods, these membranes would be trapped in the use of pressure-driven systems. Liu et al. (2015) found that the composite membrane prepared by adding graphene oxide to polysulfone displayed superior pressure-resisted ability, mechanical strength and water permeability. Similarly, research conducted by Lai et al. (2016) demonstrated that water flux and salt removal were improved by integrating graphene oxide in polyamide membrane. Kochameshki et al. (2017) synthesized a polysulfone nanocomposite membrane modified with graphene grafted with diallyldimethylammonium chloride. The results showed that the water flux increased to about 450 L/m^2 h and the heavy metal ion rejection rate increased to 86.68% (Cu^{2+}) and 88.68% (Cd^{2+}). Besides, Choi et al. (2013) fabricated a dual-action barrier coating layer of graphene oxide on the surface of polyamide reverse osmosis membrane. The antifouling tests indicated that the graphene oxide coating layer could increase the surface hydrophilicity and decrease the surface roughness, which promoted the antifouling performance against a protein foulant. There were some researchers reporting the improvement in the chlorine resistance of the polyamide membranes incorporated with graphene oxide (Safarpour et al. 2015). In their opinion, the chemically stable graphene oxide plate embedded in the polyamide layer and acted a barrier layer, protecting the polyamide from chlorine erosion (Choi et al. 2013). The researchers also identified that the separation performance of graphene oxide mixed membrane used for dyes removal were all higher than that of their counterparts (Qiu et al. 2011). Due to superior separation characteristic, graphene oxide-doped polymer membranes were also applied on oil–water separation (Zhang et al. 2017) and intricate wastewater treatment (Sun et al. 2015). Compared to modify graphene oxide with active substances, graphene oxide hybrid membranes by adding graphene oxide into polymer membranes achieves more significant advantages on improved water flux, mechanical stability and fouling resistance. There is no doubt that graphene oxide hybrid membranes will provide us the new insight into the optimization graphene-based membranes.

Carbon fiber membranes

Support-free carbon fiber membranes

Since Shimpei et al. (1986) accidentally found that carbon fibers facilitated microbial attachment and possessed excellent adsorption capacity for pollutants, the research works focused on carbon fibers for water treatment were widely carried out (Manawi et al. 2018; Ahmed et al. 2015; Xu and Luo 2012). The support-free carbon fiber membranes are generally obtained by forming carbon fiber precursors into membrane shape, and then stabilized and carbonized via thermal treatment. Rika et al. (2017) prepared carbon nanofiber membranes by electrospinning followed by carbonization. Results showed that the adsorption capacity, permeability and adsorption kinetics of the carbon nanofiber membranes were about 10 times, 6 times and 2 times higher than that of the traditional activated carbon membrane, respectively. However, such carbon fiber membranes usually suffered from serious membrane fouling, limiting their application.

Carbon fiber hybrid membranes

In order to expand the application of carbon fiber membrane in water treatment, researchers have developed a variety of carbon fiber hybrid membranes, which combined the advantages of carbon fiber and membrane technology. Yang and Tsai (2008, 2009) prepared carbon fibers/carbon/alumina tubular composite membrane and applied it in a crossflow electrocoagulation/electrofiltration module for Cu-chemical mechanical polishing wastewater treatment. Under the optimal experimental conditions, the turbidity of the permeate was less than 1 NTU, and the removal rates of total solid content, copper, total organic carbon and silicon were 72%, 92%, 81% and 87%, respectively. Li et al. (2013a, b) reported their works on domestic sewage treatment using biological carbon fiber membrane for effectively intercept sludge and most organic matter. Yue et al. (2018) fabricated layered porous dynamic separation membranes containing primary and secondary nanostructures by in situ growth of ZnO nanowires on carbon fibers. The membrane could switch wettability between super-hydrophilicity and high hydrophobicity by simply annealing alternatively in air and vacuum environment (Fig. 4), and indicated more than 98% separation efficiency in dewater and deoiling modes.

The composite membranes using carbon fiber cloth as the substrate

Taking advantage of the good mechanical properties of carbon fiber cloth, various functional materials have been loaded on it to fabricate the composite membranes for wastewater treatment. Li et al. (2016a, b, c, d) successfully prepared a catalytic cathode membrane by loading Pd-reduced graphene oxide–$CoFe_2O_4$ catalyst on carbon fiber cloth and used it in microbial fuel cell/membrane bioreactor coupling system for wastewater treatment. Xiao et al. (2017) obtained carbon fiber/C_3N_4 cloth by a dip-coating and thermal condensation method, the composite membrane possessed excellent flexibility and strong visible-light absorption for the degradation of flowing wastewater. To further improve the treatment efficiency, Shen et al. (2018) inserted TiO_2 between C_3N_4 and carbon fiber, the modified membrane showed enhanced photocatalytic activity for degrading various organic pollutants in comparison with carbon fiber/C_3N_4 cloth.

Activated carbon membranes

Activated carbon, as a unique multifunctional material with high surface area, micro–meso- and macroscopic structure and various chemical functional groups, is recognized worldwide as one of the most popular adsorbents in water treatment (Amit et al. 2013; Gopinath and Kadirvelu 2018; Danish and Ahmad 2018). Adham et al. (2016) successfully applied it into hollow fiber ultrafiltration system to investigate the influence of carbon particle size on organic matter adsorption and wastewater treatment performance. Then, Jacangelo et al. (1995) found that activated carbon could adsorb organics to prevent the formation of membrane fouling in membrane separation processes. Several studies also demonstrated that membrane bioreactor achieved high removal efficiency for trace organic pollutants in synthetic and real wastewater by the use of granular activated carbon (Amaral et al. 2014; Jia et al. 2014).

Activated carbon-coated membranes

Activated carbon can be coated on membranes by coating method and dipping method et al. to enhance membrane separation performance while removing contaminants from wastewater. Thiruvenkatachari et al. (2006) prepared activated carbon pre-coated microfiltration membrane with wood-based, coal-based and coconut shell-based activated carbon for wastewater treatment. After 8 h operation, 63% of organic pollutants were removed by wood-based activated carbon-coated membrane, 57% by coal-based activated carbon-coated membrane and 56% by

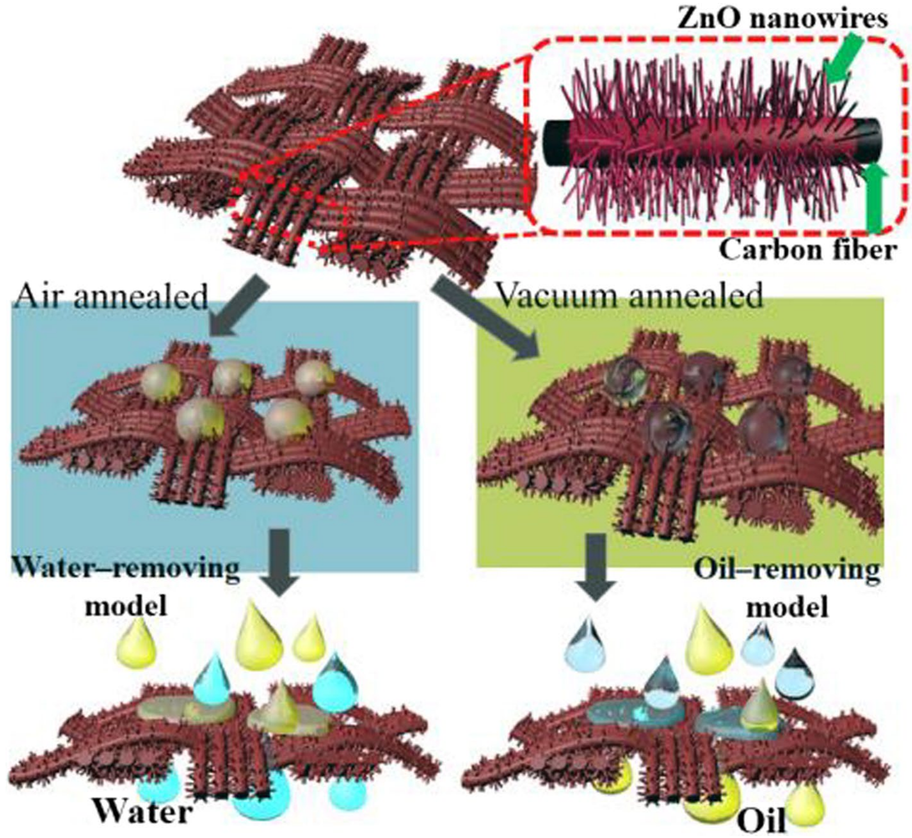

Fig. 4 ZnO–carbon fiber dynamic membrane for oil/water mixtures treatment. The as-fabricated membrane is capable of switching into water-removing model with super-hydrophilicity via simply annealing under air environment and switching into oil-removing model with high hydrophobicity via simply annealing under vacuum environment

coconut shell-based activated carbon-coated membrane, which were all higher than that of non-pre-coated membrane. Simultaneously, the decrease in membrane flux was prevented effectively (less than 20% of initial flux). But in the absence of long-term experiments, this work was too early to elucidate the underlying mechanisms of the effects observed in it. Meanwhile, the optimal amount of particle activated carbon had not been determined, so the stability of the membrane remained to be investigated. Amaral et al. (2016) developed microfiltration membranes coated by superfine powdered activated carbon for drinking water treatment. The coated membranes achieved excellent removal efficiency because superfine powdered activated carbon was more favorable for the adsorption of pollutants due to its smaller particle size compared with conventional activated carbon. However, comparing with the original membrane, the membrane coated by superfine powdered activated carbon caused flux loss, and the flux reduction caused by small particles were larger than the large particles. Bae et al. (2007) designed activated carbon membrane with carbon whiskers for wastewater and drinking water treatments. The carbon whiskers on the activated carbon membrane could significantly prevent the deposition and accumulation of particles, extending membrane lifetime (Fig. 5). The adsorption capacity of activated carbon membrane with carbon whiskers for phenol was comparable to that of industrial activated carbon and it had better stability.

Support-free activated carbon membranes

Support-free activated carbon membrane is a novel carbon-based membrane, which not only has excellent thermal stability and chemical stability of inorganic membrane

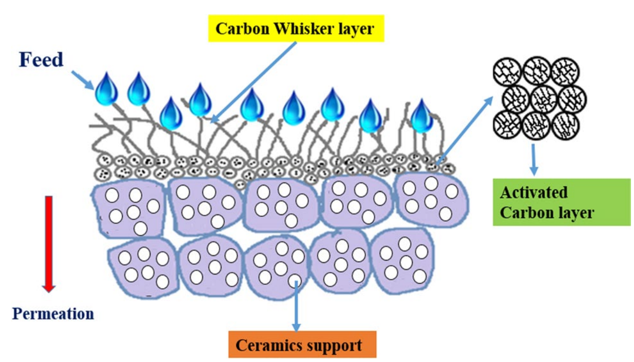

Fig. 5 Structure of an activated carbon membrane with carbon whiskers. Carbon whiskers on membrane surface were used for preventing the deposition and accumulation of particles. Activated carbon layer below carbon whiskers was assembled for the adsorption of dissolved organics

materials, but also owns excellent electrical conductivity and rich pore structure of carbon materials. Li et al. (2017) designed and prepared a support-free activated carbon membrane by mixing activated carbon, binder, pore former and conductive agent followed by compression modeling and carbonization. It could adjust its multilevel channel structure, regulate its adsorption and membrane separation performance, and simultaneously support the catalyst on the carbon membrane substrate coupling with electrochemical technology. When the triple-functional carbon membrane material was used for deep purification of the source water and advanced treatment of the wastewater, the developed pore structure could effectively adsorb pollutants such as organic molecules, microorganisms and heavy metals. The membrane surfaces and pores were enriched. At the same time, combining with the function of membrane separation and electrocatalytic oxidation, the pollutants were separated and degraded to achieve the effect of deep purification. This greatly simplified the advanced treatment process of water, and had broad the application prospects.

Activated carbon hybrid membranes

In order to further improve membrane performance, activated carbon was also adopted as function material to be mixed in membrane matrix (Aghili et al. 2017). Ahmad et al. (2018) fabricated high-performance hybrid ceramic/activated carbon symmetric membrane to purify oily wastewater (Fig. 6). The hybrid membrane possessed complex micro-nano-channel networks, which achieved two times higher porosity in comparison with Al_2O_3 membrane. As expected, the oil removal efficiency of the hybrid membrane could reach 99.02%. On the whole, the development of a cost-effective membrane by doping a cheap material, such as activated carbon, could create a complementary structure, producing strong competitiveness in wastewater treatment.

Conclusion

Carbon-based membrane materials including carbon membranes, carbon nanotube membranes, carbon fiber membranes, activated carbon membranes, graphene-based membranes, etc. are explored for highly efficient water and wastewater treatment. Various methods including surface modification, operation parameter optimization and technologies combination are adopted to optimize membrane performance. All these attempts have been proved with fruitful results and make great progress in this field. Although these carbon-based membrane materials have exhibited promising potential in the field of water treatment, further studies are still required to achieve the commercial application level. The concerned challenges are listed below:

1. More advanced membrane preparation technology should be developed to fabricate high-performance carbon-based membrane materials.
2. The electric assistance might speed up the corrosion of carbon-based membrane materials, shortening the lifetime and cause secondary pollution. Therefore, developing the modification technology of existing carbon materials, exploring novel carbon materials with great potential are important to pursue higher separation efficiency and better antifouling performance.
3. The vast majority of carbon-based membrane materials are carried out in laboratory scale, while much efforts should be paid before the pilot- and industrial-scale applications. In this process, the stability of carbon-

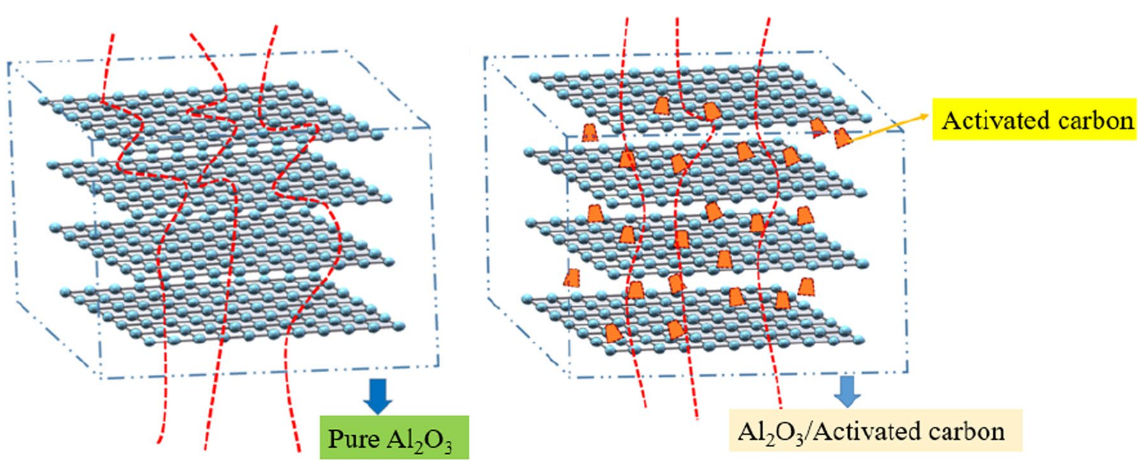

Fig. 6 Al_2O_3 and Al_2O_3/activated carbon hybrid membranes. Incorporating AC in the alumina matrix could pose porous structure of the membrane matrix, resulting in extra micro-channels for water to pass through the membrane. Both the filtration and adsorption efficiencies were increased

based membrane materials needs to be further investigated during long-term operation.

Although it would take a long time and quite great effort to resolve the remaining challenges, it is worth affirming that carbon-based membrane materials have promising potential in dealing with a large variety of water and wastewater application in the future.

Acknowledgements This work was supported by the National Natural Science Foundation of China (51708085, 21476034) and Program for Liaoning Innovative Talents in University.

References

Abd J, Wang D, Yacou C, Motuzas J, Smart S, Diniz da Costa CJ (2017) Vacuum-assisted tailoring of pore structures of phenolic resin derived carbon membranes. J Membr Sci 525:240–248. https://doi.org/10.1016/j.memsci.2016.11.002

Adham SS, Snoeyink VL, Clark MM, Bersillon J-L (2016) Predicting and verifying organics removal by PAC in an ultrafiltration system. J Am Water Works Assoc 83:81–91

Aghili F, Ghoreyshi A, Rahimpour A, Rahimnejad M (2017) Coating of mixed-matrix membranes with powdered activated carbon for fouling control and treatment of dairy effluent. Process Saf Environ 107:528–539. https://doi.org/10.1016/j.psep.2017.03.013

Ahmad K, Anita B, Marijke J, Gordon M, Muataz A (2018) Novel hybrid ceramic/carbon membrane for oil removal. J Membr Sci 559:42–53. https://doi.org/10.1016/j.memsci.2018.05.003

Ahmed F, Santos C, Mangadlao J, Advincula R, Rodrigues D (2013) Antimicrobial PVK: SWNT nanocomposite coated membrane for water purification: performance and toxicity testing. Water Res 47:3966–3975. https://doi.org/10.1016/j.watres.2012.10.055

Ahmed Y, Al-Mamun A, Al Khatib M, Jameel A, AlSaadi M (2015) Efficient lead sorption from wastewater by carbon nanofibers. Environ Chem Lett 13:341–346. https://doi.org/10.1007/s10311-015-0509-3

Ahmed F, Lalia B, Kochkodan V, Hilal N, Hashaikeh R (2016) Electrically conductive polymeric membranes for fouling prevention and detection: a review. Desalination 391:1–15. https://doi.org/10.1016/j.desal.2016.01.030

Ahn C, Baek Y, Lee C, Kim S, Kim S, Lee S, Kim S, Bae S, Park J, Yoon J (2012) Carbon nanotube-based membranes: fabrication and application to desalination. J Ind Eng Chem 18:1551–1559. https://doi.org/10.1016/j.jiec.2012.04.005

Ali S, Rehman S, Luan H, Farid M, Huang H (2019) Challenges and opportunities in functional carbon nanotubes for membrane-based water treatment and desalination. Sci Total Environ 646:1126–1139. https://doi.org/10.1016/j.scitotenv.2018.07.348

Alpatova A, Meshref M, McPhedran K, Gamal El-Din M (2015) Composite polyvinylidene fluoride (PVDF) membrane impregnated with Fe_2O_3 nanoparticles and multiwalled carbon nanotubes for catalytic degradation of organic contaminants. J Membr Sci 490:227–235. https://doi.org/10.1016/j.memsci.2015.05.001

Amaral M, Lange L, Borges C (2014) Evaluation of the use of powdered activated carbon in membrane bioreactor for the treatment of bleach pulp mill effluent. Water Environ Res 86:788–799. https://doi.org/10.2175/106143014x13975035526383

Amaral P, Partlan E, Li M, Lapolli F, Mefford O, Karanfil T, Ladner D (2016) Superfine powdered activated carbon (S-PAC) coatings on microfiltration membranes: effects of milling time on contaminant removal and flux. Water Res 100:429–438. https://doi.org/10.1016/j.watres.2016.05.034

Amini M, Jahanshahi M, Rahimpour A (2013) Synthesis of novel thin film nanocomposite (TFN) forward osmosis membranes using functionalized multi-walled carbon nanotubes. J Membr Sci 435:233–241. https://doi.org/10.1016/j.memsci.2013.01.041

Amit B, William H, Marcia M, Mika S (2013) An overview of the modification methods of activated carbon for its water treatment applications. Chem Eng J 219:499–511. https://doi.org/10.1016/j.cej.2012.12.038

Anand A, Unnikrishnan B, Mao J, Lin H, Huang C (2018) Graphene-based nanofiltration membranes for improving salt rejection, water flux and antifouling—a review. Desalination 429:119–133. https://doi.org/10.1016/j.desal.2017.12.012

Ansón-Casaos A, González-Domínguez J, Terrado E, Martínez M (2010) Surfactant-free assembling of functionalized single-walled carbon nanotube buckypapers. Carbon 48:1480–1488. https://doi.org/10.1016/j.carbon.2009.12.043

Apul O, Karanfil T (2015) Adsorption of synthetic organic contaminants by carbon nanotubes: a critical review. Water Res 68:34–55. https://doi.org/10.1016/j.watres.2014.09.032

Ash R, Barrer RM, Lowson RT (1973) Transport of single gases and of binary gas mixtures in a microporous carbon membrane. J Chem Soc 69:2166–2178

Bae S, Lee C, Kang L, Sakoda A (2007) Preparation, characterization, and application of activated carbon membrane with carbon whiskers. Desalination 202:247–252. https://doi.org/10.1016/j.desal.2005.12.061

Baek Y, Kim C, Seo D, Kim T, Lee J, Kim Y, Ahn K, Bae S, Lee S, Lim J, Lee K, Yoon J (2014) High performance and antifouling vertically aligned carbon nanotube membrane for water purification. J Membr Sci 460:171–177. https://doi.org/10.1016/j.memsci.2014.02.042

Bakr A, Rahaman M (2016) Electrochemical efficacy of a carboxylated multiwalled carbon nanotube filter for the removal of ibuprofen from aqueous solutions under acidic conditions. Chemosphere 153:508–520. https://doi.org/10.1016/j.chemosphere.2016.03.078

Bakr A, Rahaman M (2017) Removal of bisphenol a by electrochemical carbon-nanotube filter: influential factors and degradation pathway. Chemosphere 185:879–887. https://doi.org/10.1016/j.chemosphere.2017.07.082

Bauer J, Elyassini J, Moncorge G, Nodari T, Totino E (1992) New developments and applications of carbon membranes. Key Eng Mater 61–62:207–212. https://doi.org/10.4028/www.scientific.net/KEM.61-62.207

Bello M, Raman A (2018) Synergy of adsorption and advanced oxidation processes in recalcitrant wastewater treatment. Environ Chem Lett 17:1125–1142. https://doi.org/10.1007/s10311-018-00842-0

Bouabidi Z, El-Naas M, Zhang Z (2018) Immobilization of microbial cells for the biotreatment of wastewater: a review. Environ Chem Lett 17:241–257. https://doi.org/10.1007/s10311-018-0795-7

Brady Estevez A, Kang S, Elimelech M (2008) A single-walled-carbon-nanotube filter for removal of viral and bacterial pathogens. Small 4:481–484. https://doi.org/10.1002/smll.200700863

Bruce J, Hinds N, Chopra T, Rantell R, Andrews V, Leonidas G (2004) Aligned multiwalled carbon nanotube membranes. Science 303:62–65. https://doi.org/10.1126/science.1092048

Brunet L, Lyon D, Zodrow K, Rouch J, Caussat B, Serp P, Remigy J, Wiesner M, Alvarez P (2008) Properties of membranes containing semi-dispersed carbon nanotubes. Environ Eng Sci 25:565–576. https://doi.org/10.1089/ees.2007.0076

Chang Y, Shen Y, Kong D, Ning J, Xiao Z, Liang J, Zhi L (2017) Fabrication of the reduced preoxidized graphene-based nanofiltration membranes with tunable porosity and good performance. RSC Adv 7:2544–2549. https://doi.org/10.1039/c6ra24746f

Choi J, Jegal J, Kim W (2006) Fabrication and characterization of multi-walled carbon nanotubes/polymer blend membranes. J Membr Sci 284:406–415. https://doi.org/10.1016/j.memsci.2006.08.013

Choi W, Choi J, Bang J, Lee J (2013) Layer-by-layer assembly of graphene oxide nanosheets on polyamide membranes for durable reverse-osmosis applications. ACS Appl Mater Interfaces 5:12510–12519. https://doi.org/10.1021/am403790s

Chowdhury Z, Sagadevan S, Johan R, Shah S, Adebesi A, Md S, Rafique R (2018) A review on electrochemically modified carbon nanotubes (CNTs) membrane for desalination and purification of water. Mater Res Express 5:102001. https://doi.org/10.1088/2053-1591/aada65

Cohen-Tanugi D, Grossman J (2012) Water desalination across nanoporous graphene. Nano Lett 12:3602–3608. https://doi.org/10.1021/nl3012853

Crini G, Lichtfouse E (2018) Advantages and disadvantages of techniques used for wastewater treatment. Environ Chem Lett 17:145–155. https://doi.org/10.1007/s10311-018-0785-9

Danish M, Ahmad T (2018) A review on utilization of wood biomass as a sustainable precursor for activated carbon production and application. Renew Sustain Energy Rev 87:1–21. https://doi.org/10.1016/j.rser.2018.02.003

Daraei P, Madaeni S, Ghaemi N, Ahmadi Monfared H, Khadivi M (2013) Fabrication of PES nanofiltration membrane by simultaneous use of multi-walled carbon nanotube and surface graft polymerization method: comparison of MWCNT and PAA modified MWCNT. Sep Purif Technol 104:32–44. https://doi.org/10.1016/j.seppur.2012.11.004

Darryl N, Rebecca A, Kan-Sheng C, Haifa H, Kimberly A, Thomas J, Chol S, Geoffrey F, Harold W, Steve F (2010) Assembly of cross-linked multi-walled carbon nanotube mats. Carbon 48:987–994. https://doi.org/10.1016/j.carbon.2009.11.016

de Lannoy C, Jassby D, Davis D, Wiesner M (2012) A highly electrically conductive polymer–multiwalled carbon nanotube nanocomposite membrane. J Membr Sci 415–416:718–724. https://doi.org/10.1016/j.memsci.2012.05.061

Duan W, Chen G, Chen C, Sanghvi R, Iddya A, Walker S, Liu H, Ronen A, Jassby D (2017) Electrochemical removal of hexavalent chromium using electrically conducting carbon nanotube/polymer composite ultrafiltration membranes. J Membr Sci 531:160–171. https://doi.org/10.1016/j.memsci.2017.02.050

Dumée L, Sears K, Schütz J, Finn N, Huynh C, Hawkins S, Duke M, Gray S (2010) Characterization and evaluation of carbon nanotube bucky-paper membranes for direct contact membrane distillation. J Membr Sci 351:36–43. https://doi.org/10.1016/j.memsci.2010.01.025

Dumée L, Germain V, Sears K, Schütz J, Finn N, Duke M, Cerneaux S, Cornu D, Gray S (2011) Enhanced durability and hydrophobicity of carbon nanotube bucky paper membranes in membrane distillation. J Membr Sci 376:241–246. https://doi.org/10.1016/j.memsci.2011.04.024

Esfahani M, Jameson T, Holly S, Martha W (2015) Effects of a dual nanofiller, nano-TiO_2 and MWCNT, for polysulfone-based nanocomposite membranes for water purification. Desalination 372:47–56. https://doi.org/10.1016/j.desal.2015.06.014

Fan X, Li S, Sun M, Song C, Xiao J, Du J, Tao P, Sun T, Shao M, Wang T (2019) Degradation of phenol by coal-based carbon membrane integrating sulfate radicals-based advanced oxidation processes. Ecotoxicol Environ Saf 185:109662. https://doi.org/10.1016/j.ecoenv.2019.109662

Farahbakhsh J, Delnavaz M, Vatanpour V (2017) Investigation of raw and oxidized multiwalled carbon nanotubes in fabrication of reverse osmosis polyamide membranes for improvement in desalination and antifouling properties. Desalination 410:1–9. https://doi.org/10.1016/j.desal.2017.01.031

Gao F, Du X, Hao X, Li S, Zheng J, Yang Y, Han N, Guan G (2017) Electrical double layer ion transport with cell voltage-pulse potential coupling circuit for separating dilute lead ions from wastewater. J Membr Sci 535:20–27. https://doi.org/10.1016/j.memsci.2017.04.009

Ghaemi N, Madaeni S, Daraei P, Rajabi H, Shojaeimehr T, Rahimpour F, Shirvani B (2015) PES mixed matrix nanofiltration membrane embedded with polymer wrapped MWCNT: fabrication and performance optimization in dye removal by RSM. J Hazard Mater 298:111–121. https://doi.org/10.1016/j.jhazmat.2015.05.018

Gin D, Noble R (2011) Designing the next generation of chemical separation membranes. Science 332:674–676

Goh K, Karahan H, Wei L, Bae T, Fane A, Wang R, Chen Y (2016) Carbon nanomaterials for advancing separation membranes: a strategic perspective. Carbon 109:694–710. https://doi.org/10.1016/j.carbon.2016.08.077

Gopinath A, Kadirvelu K (2018) Strategies to design modified activated carbon fibers for the decontamination of water and air. Environ Chem Lett 16:1137–1168. https://doi.org/10.1007/s10311-018-0740-9

Gu J, Gu H, Zhang Q, Zhao Y, Li N, Xiong J (2018) Sandwich-structured composite fibrous membranes with tunable porous structure for waterproof, breathable, and oil–water separation applications. J Colloid Interface Sci 514:386–395. https://doi.org/10.1016/j.jcis.2017.12.032

Guo J, Zhang Q, Cai Z, Zhao K (2016) Preparation and dye filtration property of electrospun polyhydroxybutyrate–calcium alginate/carbon nanotubes composite nanofibrous filtration membrane. Sep Purif Technol 161:69–79. https://doi.org/10.1016/j.seppur.2016.01.036

Gupta V, Kumar R, Nayak A, Saleh T, Barakat M (2013) Adsorptive removal of dyes from aqueous solution onto carbon nanotubes: a review. Adv Colloid Interface Sci 193–194:24–34. https://doi.org/10.1016/j.cis.2013.03.003

Hayat K, Menhas S, Bundschuh J, Chaudhary H (2017) Microbial biotechnology as an emerging industrial wastewater treatment process for arsenic mitigation: a critical review. J Clean Prod 151:427–438. https://doi.org/10.1016/j.jclepro.2017.03.084

Hebbar RS, Isloor AM, Inamuddin AA (2017) Carbon nanotube- and graphene-based advanced membrane materials for desalination. Environ Chem Lett 15:643–671. https://doi.org/10.1007/s10311-017-0653-z

Ho K, Teow Y, Ang W, Mohammad A (2017) Novel GO/OMWCNTs mixed-matrix membrane with enhanced antifouling property for palm oil mill effluent treatment. Sep Purif Technol 177:337–349. https://doi.org/10.1016/j.seppur.2017.01.014

Ho K, Teow Y, Mohammad A, Ang W, Lee P (2018) Development of graphene oxide (GO)/multi-walled carbon nanotubes (MWCNTs) nanocomposite conductive membranes for electrically enhanced fouling mitigation. J Membr Sci 552:189–201. https://doi.org/10.1016/j.memsci.2018.02.001

Holt J, Noy A, Huser T, Eaglesham D, Bakajin O (2004) Fabrication of a carbon nanotube-embedded silicon nitride membrane for studies of nanometer-scale mass transport. J Am Chem Soc 4:2245–2250

Hsieh C, Hsu J, Hsu H, Lin W, Juang R (2016) Hierarchical oil–water separation membrane using carbon fabrics decorated with carbon nanotubes. Surf Coat Technol 286:148–154. https://doi.org/10.1016/j.surfcoat.2015.12.035

Hu M, Mi B (2013) Enabling graphene oxide nanosheets as water separation membranes. Environ Sci Technol 47:3715–3723. https://doi.org/10.1021/es400571g

Hui H, Chen Z, Wang S, Xiong G, Wang H, Wang T, Li J (2020) Fabrication and structure control of phenolic resin/activated carbon-based carbon membrane. Membr Sci Technol 40:132–138

Ihsanullah (2019) Carbon nanotube membranes for water purification: developments, challenges, and prospects for the future. Sep Purif Technol 209:307–337. https://doi.org/10.1016/j.seppur.2018.07.043

Ihsanullah, Laoui T, Al-Amer A, Khalil A, Abbas A, Khraisheh M, Atieh M (2015) Novel anti-microbial membrane for desalination pretreatment: a silver nanoparticle-doped carbon nanotube membrane. Desalination 376:82–93. https://doi.org/10.1016/j.desal.2015.08.017

Ihsanullah, Al Amer A, Laoui T, Abbas A, Al-Aqeeli N, Patel F, Khraisheh M, Atieh M, Hilal N (2016) Fabrication and antifouling behaviour of a carbon nanotube membrane. Mater Des 89:549–558. https://doi.org/10.1016/j.matdes.2015.10.018

Iijima S (1991) Helical microtubules of graphitic carbon. Nature 354:56–58. https://doi.org/10.1038/354056a0

Ismail AF, David LIB (2001) A review on the latest development of carbon membranes for gas separation. J Membr Sci 193:1–18. https://doi.org/10.1016/s03767388(01)00510-5

Jacangelo J, Laîné J, Cummings E, Adham S (1995) UF with pretreatment for removing DBP precursors. J Am Water Works Ass 87:100–112

Jia S, Han H, Hou H, Zhuang H, Fang F, Zhao Q (2014) Treatment of coal gasification wastewater by membrane bioreactor hybrid powdered activated carbon (MBR-PAC) system. Chemosphere 117:753–759. https://doi.org/10.1016/j.chemosphere.2014.09.085

Jiao W, Luo S, He Z, Liu Y (2017) Applications of high gravity technologies for wastewater treatment: a review. Chem Eng J 313:912–927. https://doi.org/10.1016/j.cej.2016.10.125

Jilani A, Othman M, Ansari M, Hussain S, Ismail A, Khan IU (2018) Graphene and its derivatives: synthesis, modifications, and applications in wastewater treatment. Environ Chem Lett 16:1301–1323. https://doi.org/10.1007/s10311-018-0755-2

Joshi R, Carbone P, Wang F, Kravets V, Su Y, Grigorieva I, Wu H, Geim A, Nair R (2014) Precise and ultrafast molecular sieving through graphene oxide membranes. Science 343:752–754. https://doi.org/10.1126/science.1245711

Kabiri S, Tran D, Cole M, Losic D (2016) Functionalized three-dimensional (3D) graphene composite for high efficiency removal of mercury. Environ Sci–Water Res 2:390–402. https://doi.org/10.1039/c5ew00254k

Kaminska G, Bohdziewicz J, Calvo J, Prádanos P, Palacio L, Hernández A (2015) Fabrication and characterization of polyethersulfone nanocomposite membranes for the removal of endocrine disrupting micropollutants from wastewater. Mechanisms and performance. J Membr Sci 493:66–79. https://doi.org/10.1016/j.memsci.2015.05.047

Kang S, Pinault M, Pfefferle L, Elimelech M (2007) Single-walled carbon nanotubes exhibit strong antimicrobial activity. Langmuir 23:8670–8673. https://doi.org/10.1021/la701067r

Kim H, Choi K, Baek Y, Kim DG, Shim J, Yoon J, Lee J (2014) High-performance reverse osmosis CNT/polyamide nanocomposite membrane by controlled interfacial interactions. ACS Appl Mater Inter 6:2819–2829. https://doi.org/10.1021/am405398f

Kochameshki M, Marjani A, Mahmoudian M, Farhadi K (2017) Grafting of diallyldimethylammonium chloride on graphene oxide by raft polymerization for modification of nanocomposite polysulfone membranes using in water treatment. Chem Eng J 309:206–221. https://doi.org/10.1016/j.cej.2016.10.008

Lai G, Lau W, Goh P, Ismail A, Yusof N, Tan Y (2016) Graphene oxide incorporated thin film nanocomposite nanofiltration membrane for enhanced salt removal performance. Desalination 387:14–24. https://doi.org/10.1016/j.desal.2016.03.007

Lalia B, Ahmed F, Shah T, Hilal N, Hashaikeh R (2015) Electrically conductive membranes based on carbon nanostructures for self-cleaning of biofouling. Desalination 360:8–12. https://doi.org/10.1016/j.desal.2015.01.006

Lau W, Emadzadeh D, Shahrin S, Goh P, Ismail A (2018) Ultrafiltration membranes incorporated with carbon-based nanomaterials for antifouling improvement and heavy metal removal. In: Carbon-based polymer nanocomposites for environmental and energy applications, pp 217–232. https://doi.org/10.1016/b978-0-12-813574-7.00009-5

Lawrence A, Alam J, Alhoshan M (2012) Carbon nanotubes-blended poly(phenylene sulfone) membranes for ultrafiltration applications. Appl Water Sci 3:93–103. https://doi.org/10.1007/s13201-012-0063-0

Lee C, Baik S (2010) Vertically-aligned carbon nano-tube membrane filters with superhydrophobicity and superoleophilicity. Carbon 48:2192–2197. https://doi.org/10.1016/j.carbon.2010.02.020

Lee K, Arnot T, Mattia D (2011) A review of reverse osmosis membrane materials for desalination—development to date and future potential. J Membr Sci 370:1–22. https://doi.org/10.1016/j.memsci.2010.12.036

Lee B, Baek Y, Lee M, Jeong D, Lee H, Yoon J, Kim Y (2015) A carbon nanotube wall membrane for water treatment. Nat Commun 6:7109. https://doi.org/10.1038/ncomms8109

Lee J, Ye Y, Ward A, Zhou C, Chen V, Minett A, Lee S, Liu Z, Chae S, Shi J (2016) High flux and high selectivity carbon nanotube composite membranes for natural organic matter removal. Sep Purif Technol 163:109–119. https://doi.org/10.1016/j.seppur.2016.02.032

Li S, Richard M (2000) Single carbon nanotube membranes: a well-defined model for studying mass transport through nanoporous materials. J Am Chem Soc 122:12340–12345. https://doi.org/10.1021/ja002429w

Li M, Hai R, Yang L, Wang X, Li Y (2013a) Comparative study on biological carbon fiber membrane and common membrane treating sewage. Environ Sci Technol 36:126–130 **(in Chinese)**

Li M, Hai R, Yang L, Wang X, Li Y (2013b) Performance parameter optimization of biological carbon fiber membrane treating domestic wastewater. Environ Sci Technol 36:54–60 **(in Chinese)**

Li J, Kong X, Lu D, Liu Z (2015) Italicized carbon nanotube facilitating water transport: a molecular dynamics simulation. Sci Bull 60:1580–1586. https://doi.org/10.1007/s11434-015-0888-7

Li C, Song C, Tao P, Sun M, Pan Z, Wang T, Shao M (2016a) Enhanced separation performance of coal-based carbon membranes coupled with an electric field for oily wastewater treatment. Sep Purif Technol 168:47–56. https://doi.org/10.1016/j.seppur.2016.05.020

Li J, Wei W, Lin Q, Zhang J (2016b) Effects of pyrolysis temperature on the properties of phenol–formaldehyde resin based carbon molecular sieve membrane. Mater Sci Forum 848:738–742. https://doi.org/10.4028/www.scientific.net/MSF.848.738

Li L, Chen M, Dong Y, Dong X, Cerneaux S, Hampshire S, Cao J, Zhu L, Zhu Z, Liu J (2016c) A low-cost alumina-mullite composite hollow fiber ceramic membrane fabricated via phase-inversion and sintering method. J Eur Ceram Soc 36:2057–2066. https://doi.org/10.1016/j.jeurceramsoc.2016.02.020

Li Y, Liu L, Yang F (2016d) High flux carbon fiber cloth membrane with thin catalyst coating integrates bio-electricity generation in wastewater treatment. J Membr Sci 505:130–137. https://doi.org/10.1016/j.memsci.2016.01.038

Li L, Pan Z, Yang J, Tao P, Song C, Wang C, Wang T (2017) Carbon membranes with triple functions of adsorption/electrocatalysis/membrane separation and their preparation methods, China, pp 1–10

Li C, Feng G, Pan Z, Song C, Fan X, Tao P, Wang T, Shao M, Zhao S (2020a) High-performance electrocatalytic microfiltration CuO/carbon membrane by facile dynamic electrodeposition for small-sized organic pollutants removal. J Membr Sci 601:117913. https://doi.org/10.1016/j.memsci.2020.117913

Li C, Yang J, Zhang L, Li S, Yuan Y, Xiao X, Fan X, Song C (2020b) Developments of carbon-based membrane materials for water treatment. Membr Environ Appl 42:121–175. https://doi.org/10.1007/978-3-030-33978-4_4

Liu L, Son M, Chakraborty S, Bhattacharjee C, Choi H (2013) Fabrication of ultra-thin polyelectrolyte/carbon nanotube membrane by spray-assisted layer-by-layer technique: characterization and its anti-protein fouling properties for water treatment. Desalin Water Treat 51:6194–6200. https://doi.org/10.1080/19443994.2013.780767

Liu X, Duan J, Yang J, Huang T, Zhang N, Wang Y, Zhou Z (2015) Hydrophilicity, morphology and excellent adsorption ability of poly(vinylidene fluoride) membranes induced by graphene oxide and polyvinylpyrrolidone. Colloid Surface A 486:172–184. https://doi.org/10.1016/j.colsurfa.2015.09.036

Liu Z, Zhu M, Wang Z, Wang H, Deng C, Li K (2016) Effective degradation of aqueous tetracycline using a nano-TiO_2/carbon electrocatalytic membrane. Materials (Basel) 9:364. https://doi.org/10.3390/ma9050364

Liu Z, Xu M, Yang Z, Wang Y, Wang S, Wang H (2017a) Efficient removal of organic dyes from water by β-cyclodextrin functionalized graphite carbon nitride composite. ChemistrySelect 2:1753–1758. https://doi.org/10.1002/slct.201602032

Liu Z, Zhu M, Zhao L, Deng C, Ma J, Wang Z, Liu H, Wang H (2017b) Aqueous tetracycline degradation by coal-based carbon electrocatalytic filtration membrane: effect of nano antimony-doped tin dioxide coating. Chem Eng J 314:59–68. https://doi.org/10.1016/j.cej.2016.12.093

Ma J, Zhao Y, Xu Z, Min C, Zhou B, Li Y, Li B, Niu J (2013) Role of oxygen-containing groups on MWCNTs in enhanced separation and permeability performance for PVDF hybrid ultrafiltration membranes. Desalination 320:1–9. https://doi.org/10.1016/j.desal.2013.04.012

Ma L, Dong X, Chen M, Zhu L, Wang C, Yang F, Dong Y (2017) Fabrication and water treatment application of carbon nanotubes (CNTs)-based composite membranes: a review. Membranes (Basel) 7:16. https://doi.org/10.3390/membranes7010016

Madaeni S, Zinadini S, Vatanpour V (2013) Preparation of superhydrophobic nanofiltration membrane by embedding multiwalled carbon nanotube and polydimethylsiloxane in pores of microfiltration membrane. Sep Purif Technol 111:98–107. https://doi.org/10.1016/j.seppur.2013.03.033

Madhura L, Kanchi S, Sabela MI, Singh S, Bisetty K (2017) Membrane technology for water purification. Environ Chem Lett 16:343–365. https://doi.org/10.1007/s10311-017-0699-y

Madima N, Mishra S, Inamuddin I, Mishra A (2020) Carbon-based nanomaterials for remediation of organic and inorganic pollutants from wastewater. A review. Environ Chem Lett. https://doi.org/10.1007/s10311-020-01001-0

Maggie A (2007) Water and sanitation in developing countries: including health in the equation. Environ Sci Technol 41:14–27. https://doi.org/10.1021/es072435t

Mainak M, Nitin C, Bruce J (2005) Effect of tip functionalization on transport through vertically oriented carbon nanotube membranes. J Am Chem Soc 127:9062–9070. https://doi.org/10.1021/ja043013b

Majeed S, Fierro D, Buhr K, Wind J, Du B, Boschetti-de-Fierro A, Abetz V (2012) Multi-walled carbon nanotubes (MWCNTs) mixed polyacrylonitrile (PAN) ultrafiltration membranes. J Membr Sci 403–404:101–109. https://doi.org/10.1016/j.memsci.2012.02.029

Manawi Y, Ihsanullah, Samara A, Al-Ansari T, Atieh M (2018) A review of carbon nanomaterials' synthesis via the chemical vapor deposition (CVD) method. Materials (Basel) 11:882. https://doi.org/10.3390/ma11050822

Mansourpanah Y, Madaeni S, Rahimpour A, Adeli M, Hashemi M, Moradian M (2011) Fabrication new PES-based mixed matrix nanocomposite membranes using polycaprolactone modified carbon nanotubes as the additive: property changes and morphological studies. Desalination 277:171–177. https://doi.org/10.1016/j.desal.2011.04.022

Masoomaa HB, Irfanc M, Woei-Jye L (2015) Acid functionalized MWCNT/PVP nanocomposite as new additive for fabrication of ultrafiltration membrane with improved anti-fouling resistance. RSC Adv 5:1–17. https://doi.org/10.1039/C5RA11344J

Matsumoto H, Tsuruoka S, Hayashi Y, Abe K, Hata K, Zhang S, Saito Y, Aiba M, Tokunaga T, Iijima T, Hayashi T, Inoue H, Amaratunga G (2017) Water transport phenomena through membranes consisting of vertically-aligned double-walled carbon nanotube array. Carbon 120:358–365. https://doi.org/10.1016/j.carbon.2017.05.034

Medina-Gonzalez Y, Remigy J (2011) Sonication-assisted preparation of pristine MWCNT–polysulfone conductive microporous membranes. Mater Lett 65:229–232. https://doi.org/10.1016/j.matlet.2010.10.016

Menachem E, William A (2011) The future of seawater desalination: energy, technology, and the environment. Science 333:712–713. https://doi.org/10.1126/science.1200488

Mohammad P, Toraj M, Omid B (2018) Effective treatment of dye wastewater via positively charged TETA-MWCNT/PES hybrid nanofiltration membranes. Sep Purif Technol 194:488–502. https://doi.org/10.1016/j.seppur.2017.11.070

Montgomery M, Elimelech M (2007) Water and sanitation in developing countries: including health in the equation. Environ Sci Technol 41:17–24. https://doi.org/10.1021/es072435t

Motoc S, Remes A, Pop A, Manea F, Schoonman J (2013) Electrochemical detection and degradation of ibuprofen from water on multi-walled carbon nanotubes-epoxy composite electrode. J Environ Sci 25:838–847. https://doi.org/10.1016/s1001-0742(12)60068-0

Muylaert I, Verberckmoes A, De Decker J, Van Der Voort P (2012) Ordered mesoporous phenolic resins: highly versatile and ultra stable support materials. Adv Colloid Interface 175:39–51. https://doi.org/10.1016/j.cis.2012.03.007

Nair R, Wu H, Jayaram P, Grigorieva I, Geim A (2012) Unimpeded permeation of water through helium-leak-tight graphene-based membranes. Science 335:442–444. https://doi.org/10.1126/science.1211694

Novoselov K, Geim A, Morozov S, Jiang D, Zhang Y, Dubonos S, Grigorieva I, Firsov A (2004) Electric field effect in atomically thin carbon films. Science 306:666–669. https://doi.org/10.1126/science.1102896

O'Hern S, Boutilier M, Idrobo J, Song Y, Kong J, Laoui T, Atieh M, Karnik R (2014) Selective ionic transport through tunable subnanometer pores in single-layer graphene membranes. Nano Lett 14:1234–1241. https://doi.org/10.1021/nl404118f

Park J, Choi W, Kim S, Chun B, Bang J, Lee K (2012) Enhancement of chlorine resistance in carbon nanotube based nanocomposite reverse osmosis membranes. Desalin Water Treat 15:198–204. https://doi.org/10.5004/dwt.2010.1686

Park S, Jung J, Lee S, Baek Y, Yoon J, Seo D, Kim Y (2014) Fouling and rejection behavior of carbon nanotube membranes. Desalination 343:180–186. https://doi.org/10.1016/j.desal.2013.10.005

Patino Y, Diaz E, Ordonez S, Gallegos-Suarez E, Guerrero-Ruiz A, Rodriguez-Ramos I (2015) Adsorption of emerging pollutants on functionalized multiwall carbon nanotubes.

Chemosphere 136:174–180. https://doi.org/10.1016/j.chemosphere.2015.04.089

Pintor A, Vilar V, Botelho C, Boaventura R (2016) Oil and grease removal from wastewaters: sorption treatment as an alternative to state-of-the-art technologies. A critical review. Chem Eng J 297:229–255. https://doi.org/10.1016/j.cej.2016.03.121

Qin G, He J, Wei W (2015a) Ultrafiltration carbon membranes from organic sol–gel process. Chem Eng Commun 203:381–388. https://doi.org/10.1080/00986445.2014.1001890

Qin G, Lü X, Wei W, Li J, Cui R, Hu S (2015b) Microfiltration of kiwifruit juice and fouling mechanism using fly-ash-based ceramic membranes. Food Bioprod Process 96:278–284. https://doi.org/10.1016/j.fbp.2015.09.006

Qin G, Zhang Y, Wei W (2017) Facile synthesis of a nitrogen-doped carbon membrane for CO_2 capture. Mater Lett 209:75–77. https://doi.org/10.1016/j.matlet.2017.07.100

Qiu L, Zhang X, Yang W, Wang Y, Simon G, Li D (2011) Controllable corrugation of chemically converted graphene sheets in water and potential application for nanofiltration. Chem Commun (Camb) 47:5810–5812. https://doi.org/10.1039/c1cc10720h

Rahimpour A, Jahanshahi M, Khalili S, Mollahosseini A, Zirepour A, Rajaeian B (2012) Novel functionalized carbon nanotubes for improving the surface properties and performance of polyethersulfone (PES) membrane. Desalination 286:99–107. https://doi.org/10.1016/j.desal.2011.10.039

Ren X, Chen C, Nagatsu M, Wang X (2011) Carbon nanotubes as adsorbents in environmental pollution management: a review. Chem Eng J 170:395–410. https://doi.org/10.1016/j.cej.2010.08.045

Rezakazemi M, Khajeh A, Mesbah M (2017) Membrane filtration of wastewater from gas and oil production. Environ Chem Lett 16:367–388. https://doi.org/10.1007/s10311-017-0693-4

Rika J, Yong Z, Hao F, Todd J (2017) Electrospun lignin carbon nanofiber membranes with large pores for highly efficient adsorptive water treatment applications. J Water Process Eng 16:240–248. https://doi.org/10.1016/j.jwpe.2017.02.002

Saadati J, Pakizeh M (2017) Separation of oil/water emulsion using a new PSf/pebax/F-MWCNT nanocomposite membrane. J Taiwan Inst Chem E 71:265–276. https://doi.org/10.1016/j.jtice.2016.12.024

Safarpour M, Khataee A, Vatanpour V (2015) Thin film nanocomposite reverse osmosis membrane modified by reduced graphene oxide/TiO_2 with improved desalination performance. J Membr Sci 489:43–54. https://doi.org/10.1016/j.memsci.2015.04.010

Salehi E, Madaeni S, Rajabi L, Vatanpour V, Derakhshan A, Zinadini S, Ghorabi S, Ahmadi Monfared H (2012) Novel chitosan/poly(vinyl) alcohol thin adsorptive membranes modified with amino functionalized multi-walled carbon nanotubes for Cu(II) removal from water: preparation, characterization, adsorption kinetics and thermodynamics. Sep Purif Technol 89:309–319. https://doi.org/10.1016/j.seppur.2012.02.002

Salgot M, Folch M (2018) Wastewater treatment and water reuse. Curr Opin Environ Sci Health 2:64–74. https://doi.org/10.1016/j.coesh.2018.03.005

Santosh V, Gopinath J, Babu P, Sainath A, Reddy A (2018) Acetyl-d-glucopyranoside functionalized carbon nanotubes for the development of high performance ultrafiltration membranes. Sep Purif Technol 191:134–143. https://doi.org/10.1016/j.seppur.2017.09.018

Sears K, Dumée L, Schütz J, She M, Huynh C, Hawkins S, Duke M, Gray S (2010) Recent developments in carbon nanotube membranes for water purification and gas separation. Materials 3:127–149. https://doi.org/10.3390/ma3010127

Shah P, Murthy C (2013) Studies on the porosity control of MWCNT/polysulfone composite membrane and its effect on metal removal. J Membr Sci 437:90–98. https://doi.org/10.1016/j.memsci.2013.02.042

Shahbabaei M, Tang D, Kim D (2017) Simulation insight into water transport mechanisms through multilayer graphene-based membrane. Comput Mater Sci 128:87–97. https://doi.org/10.1016/j.commatsci.2016.10.044

Shawky H, Chae S, Lin S, Wiesner M (2011) Synthesis and characterization of a carbon nanotube/polymer nanocomposite membrane for water treatment. Desalination 272:46–50. https://doi.org/10.1016/j.desal.2010.12.051

Shen J, Yu C, Ruan H, Gao C, Van der Bruggen B (2013) Preparation and characterization of thin-film nanocomposite membranes embedded with poly(methyl methacrylate) hydrophobic modified multiwalled carbon nanotubes by interfacial polymerization. J Membr Sci 442:18–26. https://doi.org/10.1016/j.memsci.2013.04.018

Shen X, Song L, Luo L, Zhang Y, Zhu B, Liu J, Chen Z, Zhang L (2018) Preparation of TiO_2/C_3N_4 heterojunctions on carbon-fiber cloth as efficient filter-membrane-shaped photocatalyst for removing various pollutants from the flowing wastewater. J Colloid Interface Sci 532:798–807. https://doi.org/10.1016/j.jcis.2018.08.028

Shimpei G, Tomio A, Fumio M, Kunio M, Sugio O (1986) Process for the preparation of carbon fibers, vol 4554148. http://doi.org/10.1016/0008-6223(86)90196-x

Song C, Wang T, Pan Y, Qiu J (2006) Preparation of coal-based microfiltration carbon membrane and application in oily wastewater treatment. Sep Purif Technol 51:80–84. https://doi.org/10.1016/j.seppur.2005.12.026

Song Y, Wang D, Birkett G, Smart S, Diniz da Costa J (2017) Vacuum film etching effect of carbon alumina mixed matrix membranes. J Membr Sci 541:53–61. https://doi.org/10.1016/j.memsci.2017.06.082

Song Y, Motuzas J, Wang D, Birkett G, Smart S, Diniz da Costa J (2018) Substrate effect on carbon/ceramic mixed matrix membrane prepared by a vacuum-assisted method for desalination. Processes 6:47. https://doi.org/10.3390/pr6050047

Stankovich S, Dikin D, Piner R, Kohlhaas K, Kleinhammes A, Jia Y, Wu Y, Nguyen S, Ruoff R (2007) Synthesis of graphene-based nanosheets via chemical reduction of exfoliated graphite oxide. Carbon 45:1558–1565. https://doi.org/10.1016/j.carbon.2007.02.034

Sun X, Qin J, Xia P, Guo B, Yang C, Song C, Wang S (2015) Graphene oxide–silver nanoparticle membrane for biofouling control and water purification. Chem Eng J 281:53–59. https://doi.org/10.1016/j.cej.2015.06.059

Sun M, Feng G, Zhang M, Song C, Tao P, Wang T, Shao M (2018) Enhanced removal ability of phenol from aqueous solution using coal-based carbon membrane coupled with electrochemical oxidation process. Colloid Surf A 540:186–193. https://doi.org/10.1016/j.colsurfa.2018.01.006

Tahri N, Jedidi I, Cerneaux S, Cretin M, Ben Amar R (2013) Development of an asymmetric carbon microfiltration membrane: application to the treatment of industrial textile wastewater. Sep Purif Technol 118:179–187. https://doi.org/10.1016/j.seppur.2013.06.042

Tahri N, Jedidi I, Ayadi S, Cerneaux S, Cretin M, Ben Amar R (2016) Preparation of an asymmetric microporous carbon membrane for ultrafiltration separation: application to the treatment of industrial dyeing effluent. Desalin Water Treat 57:23473–23488. https://doi.org/10.1080/19443994.2015.1135826

Tao P, Xu Y, Song C, Yin Y, Yang Z, Wen S, Wang S, Liu H, Li S, Li C, Wang T, Shao M (2017a) A novel strategy for the removal of rhodamine B (RhB) dye from wastewater by coal-based carbon membranes coupled with the electric field. Sep Purif Technol 179:175–183. https://doi.org/10.1016/j.seppur.2017.02.014

Tao P, Xu Y, Zhou Y, Song C, Shao M, Wang T (2017b) Coal-based carbon membrane coupled with electrochemical oxidation process for the enhanced microalgae removal from simulated ballast water. Water Air Soil Pollut. https://doi.org/10.1007/s11270-017-3608-x

Thakur V, Voicu S (2016) Recent advances in cellulose and chitosan based membranes for water purification: a concise review. Carbohydr Polym 146:148–165. https://doi.org/10.1016/j.carbpol.2016.03.030

Thines R, Mubarak N, Nizamuddin S, Sahu J, Abdullah E, Ganesan P (2017) Application potential of carbon nanomaterials in water and wastewater treatment: a review. J Taiwan Inst Chem E 72:116–133. https://doi.org/10.1016/j.jtice.2017.01.018

Thiruvenkatachari R, Shim W, Lee J, Aim R, Moon H (2006) A novel method of powdered activated carbon (PAC) pre-coated microfiltration (MF) hollow fiber hybrid membrane for domestic wastewater treatment. Colloid Surface A 274:24–33. https://doi.org/10.1016/j.colsurfa.2005.08.026

Vatanpour V, Esmaeili M, Farahani M (2014) Fouling reduction and retention increment of polyethersulfone nanofiltration membranes embedded by amine-functionalized multi-walled carbon nanotubes. J Membr Sci 466:70–81. https://doi.org/10.1016/j.memsci.2014.04.031

Vijwani H, Nadagouda M, Mukhopadhyay S (2018) Robust nanocatalyst membranes for degradation of atrazine in water. J Water Process Eng 25:15–21. https://doi.org/10.1016/j.jwpe.2018.05.016

Wang L, Song X, Wang T, Wang S, Wang Z, Gao C (2015) Fabrication and characterization of polyethersulfone/carbon nanotubes (PES/CNTs) based mixed matrix membranes (MMMs) for nanofiltration application. Appl Surf Sci 330:118–125. https://doi.org/10.1016/j.apsusc.2014.12.183

Wang J, Zhang P, Liang B, Liu Y, Xu T, Wang L, Cao B, Pan K (2016) Graphene oxide as an effective barrier on a porous nanofibrous membrane for water treatment. ACS Appl Mater Interface 8:6211–6218. https://doi.org/10.1021/acsami.5b12723

Wang P, Deng Y, Hao L, Zhao L, Zhang X, Deng C, Liu H, Zhu M (2018) Continuous efficient removal and inactivation mechanism of *E. Coli* by bismuth doped SnO_2/C electrocatalytic membrane. Environ Sci Pollut Res 26:11399–11409. https://doi.org/10.1007/s11356-019-04576-6

Wei W, Qin G, Hu H, You L, Chen G (2007) Preparation of supported carbon molecular sieve membrane from novolac phenol–formaldehyde resin. J Membr Sci 303:80–85. https://doi.org/10.1016/j.memsci.2007.06.055

Wei W, Li N, Qin G (2012) Preparation of mesoporous carbon membranes for ultrafiltration with properties of environmental materials. Adv Mater Res 600:104–107. https://doi.org/10.4028/www.scientific.net/amr.600.104

Wei G, Quan X, Fan X, Chen S, Zhang Y (2017) Carbon-nanotube-based sandwich-like hollow fiber membranes for expanded microcystin-LR removal applications. Chem Eng J 319:212–218. https://doi.org/10.1016/j.cej.2017.02.125

Wei Y, Zhang Y, Gao X, Ma Z, Wang X, Gao C (2018) Multilayered graphene oxide membrane for water treatment: a review. Carbon 139:964–981. https://doi.org/10.1016/j.carbon.2018.07.040

Whitby M, Quirk N (2007) Fluid flow in carbon nanotubes and nanopipes. Nat Nanotechnol 2:87–94. https://doi.org/10.1038/nnano.2006.175

Wilson R, George G, Jose A (2018) Polymer membranes reinforced with carbon-based nanomaterials for water purification. In: New polymer nanocomposites for environmental remediation, pp 457–468

Wu H, Tang B, Wu P (2010a) MWNTs/polyester thin film nanocomposite membrane: an approach to overcome the trade-off effect between permeability and selectivity. J Am Chem Soc 114:16395–16400

Wu H, Tang B, Wu P (2010b) Novel ultrafiltration membranes prepared from a multi-walled carbon nanotubes/polymer composite. J Membr Sci 362:374–383. https://doi.org/10.1016/j.memsci.2010.06.064

Wu Q, Zhu W, Zhang C, Liang Z, Wang B (2010c) Study of fire retardant behavior of carbon nanotube membranes and carbon nanofiber paper in carbon fiber reinforced epoxy composites. Carbon 48:1799–1806. https://doi.org/10.1016/j.carbon.2010.01.023

Wu B, Li X, An D, Zhao S, Wang Y (2014) Electro-casting aligned MWCNTs/polystyrene composite membranes for enhanced gas separation performance. J Membr Sci 462:62–68. https://doi.org/10.1016/j.memsci.2014.03.015

Xiao F, Tian Y, Peng F, Li S, Jian S, Zhi G (2017) Growth of C_3N_4 nanosheets on carbon-fiber cloth as flexible and macroscale filter-membrane-shaped photocatalyst for degrading the flowing wastewater. Appl Catal B-Environ 219:425–431. https://doi.org/10.1016/j.apcatb.2017.07.059

Xu D, Luo Y (2012) The application of carbon fiber in harness of water environment—new task in 21th century. Hi-Tech Fiber Appl 37:49–56 **(in Chinese)**

Xu Z, Li X, Teng K, Zhou B, Ma M, Shan M, Jiao K, Qian X, Fan J (2017) High flux and rejection of hierarchical composite membranes based on carbon nanotube network and ultrathin electrospun nanofibrous layer for dye removal. J Membr Sci 535:94–102. https://doi.org/10.1016/j.memsci.2017.04.029

Yanez H, Wang Z, Lege S, Obst M, Roehler S, Burkhardt C, Zwiener C (2017) Application and characterization of electroactive membranes based on carbon nanotubes and zerovalent iron nanoparticles. Water Res 108:78–85. https://doi.org/10.1016/j.watres.2016.10.055

Yang G, Tsai C (2008) Preparation of carbon fibers/carbon/alumina tubular composite membranes and their applications in treating Cu-CMP wastewater by a novel electrochemical process. J Membr Sci. https://doi.org/10.1016/j.memsci.2008.04.060

Yang G, Tsai C (2009) Preparation of carbon fibers/carbon/alumina tubular composite membranes and their applications in treating Cu-CMP wastewater by a novel electrochemical process: part 2. J Membr Sci 331:100–108. https://doi.org/10.1016/j.memsci.2009.01.021

Yang Y, Li J, Wang H, Song X, Wang T, He B, Liang X, Ngo H (2011) An electrocatalytic membrane reactor with self-cleaning function for industrial wastewater treatment. Angew Chem Int Edit 50:2148–2150. https://doi.org/10.1002/anie.201005941

Yang X, Lee J, Yuan L, Chae S, Peterson V, Minett A, Yin Y, Harris A (2013) Removal of natural organic matter in water using functionalised carbon nanotube buckypaper. Carbon 59:160–166. https://doi.org/10.1016/j.carbon.2013.03.005

Yi G, Chen S, Quan X, Wei G, Fan X, Yu H (2018) Enhanced separation performance of carbon nanotube–polyvinyl alcohol composite membranes for emulsified oily wastewater treatment under electrical assistance. Sep Purif Technol 197:107–115. https://doi.org/10.1016/j.seppur.2017.12.058

Yin J, Zhu G, Deng B (2013) Multi-walled carbon nanotubes (MWNTs)/polysulfone (PSU) mixed matrix hollow fiber membranes for enhanced water treatment. J Membr Sci 437:237–248. https://doi.org/10.1016/j.memsci.2013.03.021

Yin Y, Li C, Song C, Tao P, Sun M, Pan Z, Wang T, Shao M (2016) The design of coal-based carbon membrane coupled with the electric field and its application on the treatment of malachite green (MG) aqueous solution. Colloid Surf A 506:629–636. https://doi.org/10.1016/j.colsurfa.2016.07.038

You H, Li X, Yang Y, Wang B, Li Z, Wang X, Zhu M, Hsiao B (2013) High flux low pressure thin film nanocomposite ultrafiltration membranes based on nanofibrous substrates. Sep Purif Technol 108:143–151. https://doi.org/10.1016/j.seppur.2013.02.014

Yu J, Zhao X, Yang H, Chen X, Yang Q, Yu L, Jiang J, Chen X (2014) Aqueous adsorption and removal of organic contaminants by carbon nanotubes. Sci Total Environ 482–483:241–251. https://doi.org/10.1016/j.scitotenv.2014.02.129

Yuan Y, Gao X, Wei Y, Wang X, Wang J, Zhang Y, Gao C (2017) Enhanced desalination performance of carboxyl functionalized graphene oxide nanofiltration membranes. Desalination 405:29–39. https://doi.org/10.1016/j.desal.2016.11.024

Yue X, Yang D, Qiu F, Zhu Y, Fang J (2018) In situ fabrication dynamic carbon fabrics membrane with tunable wettability for selective oil–water separation. J Ind Eng Chem 61:188–196. https://doi.org/10.1016/j.jiec.2017.12.016

Zarrabi H, Yekavalangi M, Vatanpour V, Shockravi A, Safarpour M (2016) Improvement in desalination performance of thin film nanocomposite nanofiltration membrane using amine-functionalized multiwalled carbon nanotube. Desalination 394:83–90. https://doi.org/10.1016/j.desal.2016.05.002

Zhang J, Xue Q, Pan X, Lu W, Ding D, Guo Q (2017) Graphene oxide/polyacrylonitrile fiber hierarchical-structured membrane for ultra-fast microfiltration of oil–water emulsion. Chem Eng J 307:643–649. https://doi.org/10.1016/j.cej.2016.08.124

Zhao H, Yu H, Chang H, Quan X, Chen S (2013a) CNTs–TiO_2/Al_2O_3 composite membrane with a photocatalytic function: fabrication and energetic performance in water treatment. Sep Purif Technol 116:360–365. https://doi.org/10.1016/j.seppur.2013.06.007

Zhao Y, Xu Z, Shan M, Min C, Zhou B, Li Y, Li B, Liu L, Qian X (2013b) Effect of graphite oxide and multi-walled carbon nanotubes on the microstructure and performance of PVDF membranes. Sep Purif Technol 103:78–83. https://doi.org/10.1016/j.seppur.2012.10.012

Zhao H, Qiu S, Wu L, Zhang L, Chen H, Gao C (2014) Improving the performance of polyamide reverse osmosis membrane by incorporation of modified multi-walled carbon nanotubes. J Membr Sci 450:249–256. https://doi.org/10.1016/j.memsci.2013.09.014

Zhao X, Su Y, Liu Y, Li Y, Jiang Z (2016) Free-standing graphene oxide–palygorskite nanohybrid membrane for oil/water separation. ACS Appl Mater Interfaces 8:8247–8256. https://doi.org/10.1021/acsami.5b12876

Zhao W, Liang Y, Wu Y, Wang D, Zhang B (2018) Removal of phenol and phosphoric acid from wastewater by microfiltration carbon membranes. Chem Eng Commun 205:1432–1441. https://doi.org/10.1080/00986445.2018.1457027

Zheng X, Zhang Z, Yu D, Chen X, Cheng R, Min S, Wang J, Xiao Q, Wang J (2015) Overview of membrane technology applications for industrial wastewater treatment in China to increase water supply. Resour Conserv Recycling 105:1–10. https://doi.org/10.1016/j.resconrec.2015.09.012

Zheng J, Li M, Yu K, Hu J, Zhang X, Wang L (2017) Sulfonated multiwall carbon nanotubes assisted thin-film nanocomposite membrane with enhanced water flux and anti-fouling property. J Membr Sci 524:344–353. https://doi.org/10.1016/j.memsci.2016.11.032

Zinadini S, Rostami S, Vatanpour V, Jalilian E (2017) Preparation of antibiofouling polyethersulfone mixed matrix NF membrane using photocatalytic activity of ZnO/MWCNTs nanocomposite. J Membr Sci 529:133–141. https://doi.org/10.1016/j.memsci.2017.01.047

Zirehpour A, Rahimpour A, Jahanshahi M, Peyravi M (2014) Mixed matrix membrane application for olive oil wastewater treatment: process optimization based on Taguchi design method. J Environ Manag 132:113–120. https://doi.org/10.1016/j.jenvman.2013.10.028

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.