Structural design of the electrospun nanofibrous membrane for membrane distillation application: a review

Kuk Chol Kim1,2 · Xiaoqiu Lin1 · Congju Li1

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Abstract
Although membrane distillation (MD) is a promising technology for water desalination and industrial wastewater treatment, the MD process is not widely applied in the global water industry due to the lack of a suitable membrane for the MD process. The design and appropriate manufacture are the most important factors for MD membrane optimization. The well-designed porous structure, superhydrophobic surface, and pore-wetting prevention of the membrane are vital properties of the MD membrane. Nowadays, electrospinning that is capable of manufacturing membranes with superhydrophobic or omniphobic properties is considered a promising technology. Electrospun nanofibrous membranes (ENMs) possess the characteristics of cylindrical morphology, re-entrant structure, and easy-shaping for a specific purpose, benefiting the membrane design and modification. Based on that, this review investigates the current state and future progress of the superhydrophobic, multi-layer, and omniphobic ENMs manufactured with various structural designs for seawater desalination and wastewater purification. We expect that this paper will provide some recommendations and guidance for further fabrication research and the configuration design of ENMs in the MD process for seawater desalination and wastewater purification.

Keywords Structural design · Electrospun nanofibrous membranes · Membrane distillation · Omniphobic · Superhydrophobic

Introduction
It is anticipated that about 1.8 billion people will experience a lack of water in 2025 (Connor 2012), (WWAP (United Nations World Water Assessment Programme) 2015). Seawater occupied 70% of the water on the earth, while only 2.5% could be used by humans (Nthunya et al. 2019). Hence, freshwater production from seawater is crucial for the sustainable existence of the Earth. Many desalination technologies, such as multiple stages flash distillation (Yan et al. 2007), multiple effect distillation (Mistry et al. 2013), ion exchange (Dow et al. 2016), and membrane distillation (MD), have been developed to solve water scarcity.

Membrane technology has displayed great potential in the elimination of heavy metal ions, antibacterial applications, and selective ion removal for all types of separation, such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) because of attractive advantages such as simpleness of operating conditions, no phase change, less energy consumption, compact design, and eco-friendly. This technology is facing a significant challenge of membrane fouling. Many studies have been conducted to develop a nanocomposite membrane with improved ion removal performance and antibacterial activity as an eco-friendly membrane-based water treatment technology. By combining the inherent properties of nanomaterials (for example, graphene oxide, carboxylated-graphene oxide, silver-doped multi-walled carbon nanotube (MWCNT)) with a polymer matrix (for example, polyphenylsulfone), nanocomposite membranes improved membrane flux, antifouling, antibacterial, and solute removal performance (Mohammad Jawaid et al. 2021; Shukla et al. 2018; Shukla et al. 2017; Shukla et al. 2019).
Membrane distillation (MD) is an emerging technology that is environmentally friendly and easy to operate (Deshmukh et al. 2018). Researchers have affirmed that the MD process treats high concentrations of wastewater and brine and has the possibility of utterly using solar heat and low-grade heat energy such as industrial waste heat (Efome et al. 2016), (Joachim Koschikowski 2003), (El-Bourawi et al. 2006). Also, MD can be applied for small-scale desalination in remote areas (Lin et al. 2014). The membrane of the MD process has superhydrophobic and superoleophobic properties, so it can separate oil from wastewater solution containing oil. It has the merits of mild operating temperature, a lower operating pressure, a low cost, no requirement for extensive pre-treatment, and less energy consumption compared to traditional separation processes (Alklaibi and Lior 2004), (Su et al. 2012), (Khalifa and Alawad 2018), (Criscuoli et al. 2008), (Tun et al. 2016), (Zarebska et al. 2014), (Liu and Wang 2013), (Tomaszewska and Morawski 1995), (Feng et al. 2008). Hence, MD has been considered a next-generation promising technique for water desalination (Lalia et al. 2013), (Tijing et al. 2014a).

Figure 1 exhibits the research situation on the MD from 2011 to 2021. The rapid increasing of the number of the published paper demonstrated that the research on the MD has attracted great attention and been extensively performed in recent years.

However, this technology has some main demerits, such as low flux and the membrane pores wetting and fouling or scaling. It is vital to elucidate the limiting effects of MD to improve the desalination efficiency of MD. There are many factors such as hydrophobic membrane, feed side temperature, cool side temperature, MD configuration, LEP (liquid entry pressure), and feed pre-treatment operations. The hydrophobic membrane offers a liquid–gas interface for mass and heat transfer while it does not participate in the separation, so it plays a vital role and key component in applying the MD process. Although the MD was invented in 1963 (Prince et al. 2014), the fact that MD has not yet been introduced into the water industry due to a lack of suitable membranes demonstrated that designing and manufacturing suitable membranes are of great importance.

An ideal membrane to ensure high performance in the MD process should possess good mechanical properties, low thermal conductivity, high thermal stability, hydrophobicity to prevent pore wetting, and a well-designed pore structure (high porosity, straight pore, narrow pore size distribution, appropriate pore size) to improve water flux (An et al. 2017; Bonyadi and Chung 2007; Ma et al. 2009; Shirazi et al. 2014; Woo et al. 2017). However, pore wetting is unavoidable in the MD process using these hydrophobic membranes, particularly in desalinating other wastewaters containing high levels of surfactants or low surface tension substances. The ideal membrane in the MD process should possess high LEP and low-fouling properties. Although the membrane material is hydrophobic, the membrane may be wetted because of the deposition of inorganic and organic foulants overtime on the membrane surface and internal pores (Zhou et al. 2021). It was reported that the most crucial reason for membrane wetting is because of the higher transmembrane pressure than the LEP value of hydrophobic membrane in the feed channel is applied for MD because of the membrane’s organic fouling and inorganic scaling (Guo et al. 2019).

In order to develop new MD membranes that repulse wetting by both water and other low surface tension contaminants and alleviate the membrane fouling, many MD membrane designs have been proposed and developed by mimicking the hierarchical structure of ramee and louts leaves: composite hydrophilic – hydrophobic membranes, superhydrophobic and omniphobic membranes. The lotus leaf does not display omniphobic property because the surface does not exhibit a re-entrant morphology (Zheng et al. 2018). However, the long-term MD operation will cause the air and/or vapor captured under the water-membrane interface to be lost and finally result in surface wetting, even though it displays a superhydrophobic and omniphobic property. Thus, further comparisons for membrane design manufactured in various structures (lotus, pillar, acicular multi-level re-entrant, pine-needle-like hierarchical structure, and so on) must be performed for better membrane performance.

Most of the commercially applicable hydrophobic membranes usually were fabricated by thermally induced phase separation (TIPS), non-solvent induced phase separation (NIPS), phase inversion sintering, and stretching methods for microfiltration (MF) purposes, and they possess some disadvantages such as inner disconnected microporous structures and poor porosity (Deng et al. 2018; Zhao et al. 2018). Those MF membranes are usually not precisely appropriate...
for MD operation and tend to experience low permeability and wetting problems making them unsatisfactory in the MD process. Electrospinning (ES) technology has been recognized as a promising and indispensable technique for manufacturing highly porous and durable nanofiber membranes due to the broad selectivity of polymer materials. The advantages of the electrospinning method over conventional membrane manufacturing methods are the same as the following: firstly, it can realize the mass production of nanofibers; secondly, it has unique structural characteristics: narrow pore size distribution, large surface area per unit volume or mass, interconnectivity, low tortuosity, excellent structural stability, steerable scaffold thickness (Ahmed et al. 2015; Li et al. 2015; Tijing et al. 2014a; Wang et al. 2013), and high porosity of about 80% (conventional membranes possess a porosity of 5–35% (Tlili and Alkanhal 2019)); thirdly, significantly, the electrospinning allows the fibrous membrane to construct an omniphobic surface because the ENMs are composed of a high number of nanofibers possessing cylindrical morphology, which can feature a re-entrant geometry (Hou et al. 2019).

Many researchers reviewed the fabrication procedures and the modification strategies of the various hydrophobic and hydrophilic membranes by using electrospinning and other methods used for water treatment: MD, pressure-driven membrane process, osmotically driven membrane process, membrane bioreactor, water–oil separation, heavy metal ion adsorption, and antibacterial nanofibrous membrane (Suja et al. 2017; Saikat et al. 2016; Shengjie Peng et al. 2016; Tijing et al. 2014a; Xianfeng Wang 2016; Yuan Liao et al. 2018). Then, others have reviewed membranes materials (polymer and more functionalization of nanomaterials) and the membranes fabrication methods for specific polymers via ES (Muhammad et al. 2019), (Yao et al. 2020), (Pan et al. 2019), (Zhou et al. 2021), (Lingling Zhong et al. 2021), (Ravi et al. 2020). Regrettably, they did not systematically analyze the properties of membranes fabricated using the ES technique in terms of membrane design and structure in detail.

Despite the unparalleled advantages of ENMs, reducing the permeability of the ENMs from wetting cannot be avoided. Therefore, new materials and membrane structures are needed to address the above limiting factors. We categorized the membrane with special wettability into three subgroups according to membrane structure: superhydrophobic membranes, multi-layered membranes (composite hydrophilic–hydrophobic/hydrophobic–oleophobic underwater membranes, superhydrophobic dual-layer, triple-layer membrane), omniphobic membrane (i.e., with the surface that possesses hydrophobic and oleophobic). First, this paper discussed the recent progress and challenges of the electrospinning technology to fabricate nanofiber. Second, this paper discussed fabrication methods of representative membranes fabricated with novel structural design via ES technology or the combination of ES and several surface modification methods and characteristics of these membranes for application in the MD process: (1) functional nanomaterials and doping methods to introduce roughness structures on the membrane surface and representative grafting materials; (2) grafting methods used in the surface modification to lower the surface tension of the MD membrane for prolonged operation. Thirdly, we made a prospect in electrospinning technology and the MD process.

We hope that this paper will inspire peer researchers in this field for the unique design and fabrication of high-performance ENM-based MD membranes.

**Electrospinning as promising nanomaterial manufacturing technology to fabricate the nanofiber membrane**

Nanotechnology, which manufactures nanomaterials with unique physical, chemical, and biological properties compared to macroscale mass materials, is attracting great attention as a basic core technology that can solve challenges that could not be solved by conventional methods.

Numerous techniques have been used to fabricate membranes with high hydrophobicity (Ma and Hill 2006; Qian and Shen 2005): lithography, plasma treatment, sol–gel method, phase separation, and electrospinning. Among them, electrospinning technology is a versatile and indispensable technique with low cost, vast material selectivity, versatility, multifunction, and high speed. Compared to the membranes produced from these conventional fabrication methods, the membranes fabricated by electrospinning methods have higher porosity and excellent permeability owing to interconnected open-pore architecture and steerable membrane thickness. This superior ES technology has been developed via many kinds of research and efforts to attract significant attention as a powerful candidate for fabricating nanofibrous membranes (Fig. 2).

The electrospinning process usually consists of a high voltage power supply system, a syringe pump, a syringe, a rotating drum as a collector, and a needle. It is based on the uniaxial stretching of an injection ejected from the surface of a charged long-chain polymer solution with sufficient molecular entanglements under the action of a strong electric field (usually 10⁵–10⁶V m⁻¹) between the emitter and a conductive collector. When the electrostatic power acting on the polymer solution’s surface is beyond the polymer solution’s surface tension, a charged liquid injection is attracted to the Taylor cone and spun toward the target collector. The solvent concurrently evaporates during the electrospinning process while the fluid injection travels from the spinneret to a collector (Manley and Larrondo 1981). The fiber morphology is
dependent on parameters including the applied electric field voltage, the distance between the spinneret and the collector, atmosphere temperature, flow rate, humidity, properties of the feed materials such as the polymer, concentration, surface tension, conductivity, and a viscosity (Burger et al. 2006). The single nozzle electrospinning process is a simple technique. However, industrialization for this process is limited due to low productivity. The following picture shows the possible geometries of electrospinning spinneret (Persano et al. 2013) (Fig. 3).

Recently, multi-needle and needleless electrospinning have been developed for mass production (Nayak et al. 2012; Zhou et al. 2009). However, nanofiber’s morphology control in multiple-needle electrospinning requires numerous architecture optimization and modeling works due to cross-talk between neighboring needles and interactions. The mutual repulsion between charged polymeric injections and continuous production at this process may be limited due to polymer plugging at the spinneret jet. The multiple-needle electrospinning based on multi-emitter components can be employed to augment the overall throughput per setup and the thickness of resultant mats and be useful for depositing large area surfaces and producing composite fibers composed of different materials (Ding et al. 2004).

Figure 4 shows a geometric structure of the representative multiple-needle electrospinning setup (Al-Mezrakhi 2018). The needleless electrospinning process to eject multipolymeric jets from polymer solution’s surface concurrently has attracted significant attention due to these disadvantages of the multi-needle electrospinning plants. Figure 4 shows the geometric architecture of the representative needleless electrospinning plants (Fig. 5).
The electrospinning methods can be divided into melt spinning, solution spinning, and emulsion spinning according to the material’s state to eject. Melt electrospinning does not require the utilization of solvents compared to traditional solution electrospinning. It can avoid the residual, recovery, and treatment of toxic solvents. It is considered the development direction of green manufacturing of polymer nanofibers. However, due to the complicated equipment and process delaying, melt electrospinning has been facing difficulties in realizing fiber refinement and low preparation efficiency. In the past period, solution electrospinning technology has successfully manufactured nanofibers of hundreds of materials and has initially realized a commercial application (Persano et al. 2013). However, the solvents used for solution electrospinning, such as chloroform and methylene chloride, are mostly toxic. Therefore, in the mass production process, the preparation, removal, and recovery of poisonous solvents increase equipment costs. Thermoplastic materials do not have suitable solvents at room temperature, making it challenging to prepare nanofibers by solution electrospinning. A non-melting and insoluble compound is usually spun by using emulsion spinning. This method is employed to produce fibers consisting of fluorocarbons with a high melting point, inorganic materials like ceramics, and blends possessing flame-retardant properties (Persano et al. 2013).
Most of the nanofibers are fabricated from the electrospinning (ES) technique. However, this method also has got a few drawbacks, such as dependency on electrical characteristics of dope solutions, many other safety issues, including electrical shock risks and high electric field requirements, and low productivity per spinneret. Among many methods, centrifugal spinning (CS) uses centrifugal force instead of electrostatic power. It is considered a nanofiber fabrication strategy, ES’s promising candidate, and it has received great attracts because of its excellent products, which are almost 50 times higher than the conventional ES technique (Ren et al. 2014). CS process can be employed to fabricate nanofibers by using polymer solutions or polymer melts without dependency on the dielectric constant and the requirement of a high voltage electric field (Saleem et al. 2020). The following picture shows a schematic representation of the experimental plant of a centrifugal spinning method (Gundogdu et al. 2018) (Fig. 6).

In addition to the CS method, new methods such as plasma-induced synthesis (Hu et al. 2014) and solution blow spinning (SBS) (Polat et al. 2016) to overcome several restrictions, including the requirement of higher voltage, solvent recovery problems, and low productivity of the ES processes, have been developed for efficient nanofiber fabrication in the recent years.

The ES technology has demonstrated excellent potential in many applications requiring high porosity, high specific surface area, and easy functionalization, especially in the MD process.

Configuration of MD setup

Without consuming much energy to evaporate water, the MD process can treat brine at comparatively low temperatures and pressure using solar and low-grade heat energy such as industrial waste heat. The MD process’s driving force is not an absolute pressure difference, a concentration gradient, or an electrical potential gradient. A vapor pressure difference across the hydrophobic porous membrane as a barrier between the feed and permeate sides plays a vital role (Lawson and Lloyd 1997; Schneider and van Gassel 1984). MD configurations usually are composed of DCMD (direct contact membrane distillation), AGMD (air gap membrane distillation), VMD (vacuum membrane distillation), and SGMD (sweeping gas membrane distillation) (Dong et al. 2015a; Efome et al. 2016; Prince et al. 2012) (Fig. 7).
DCMD

The membrane in the DCMD process is positioned between the feed and permeate sides, and the membrane gets in contact with both the hot feed solution and cold permeate stream. The driving force, the vapor pressure of the DCMD process, is generated from the heat difference between both sides of the membrane. The water vapor in the DCMD process passes through the hydrophobic membrane pores by diffusion or convection. DCMD process of high water flux is usually considered the most straightforward process and is used mostly. A heat loss is higher than the other configurations because hot streams are in direct contact with cold streams (Jafari et al. 2018).

AGMD

A gap is placed between the permeate side and membrane for the AGMD process. The membrane gets in direct contact with the hot feed solution, and the water vapor passes through the hydrophobic membrane and is condensed on the cold condenser surface via an air gap. The filtrated liquid is achieved between hot feed and permeate solution. The critical advantage of AGMD over DCMD is the lessening of the heat loss from the membrane of the condensing surface because of the introduction of the stagnant air layer between the membrane and condensate side, which makes AGMD possess a higher potential for commercialization (Attia et al. 2017a; Jafari et al. 2018). Also, it is more available than VMD owing to an internal condenser (air gap) (Alklaibi and Lior 2007). However, AGMD experiences low permeate flux than DCMD owing to the augmentation of mass transfer resistance by the separating air gap.

VMD

The VMD process does not have a cooling system. The use of a vacuum pump endows a lower vacuum pressure on the permeate side. The feed side has higher saturation pressure, resulting in the separation of the volatile molecules from the hot feed solution (Yalcinkaya 2019). The condensation is performed outside of the MD module. The condensation process enables the heat conduction loss to reduce on the feed solution side (Dao et al. 2013; Sarbatly and Chiam 2013; Wang and Chung 2013). A higher permeate flux can be achieved due to a higher pressure difference between the two sides of the membrane other configurations (Wang and Chung 2013). However, in the VMD process, the relatively high trans-membranous hydrostatic pressure is inadequate for some membrane systems possessing low feed LEP (Zhou et al. 2014).

SGMD

SGMD is relatively less investigated in the MD process because the system is intricate. A cold inert gas sweeps in the hydrophobic membrane’s permeate side instead of a cold feed solution in the SGMD process. The volatile liquid molecules pass through hydrophobic membrane pores toward the cold inert gas side, and then condensation is performed outside of the MD module (Yalcinkaya 2019). SGMD and VMD require additional condensers to convert the permeated vapor to liquid, increasing the cost and complicating these processes. However, SGMD was proved to possess the merits of a comparatively low conductive heat loss and a decreased mass transfer resistance (Zhang et al. 2017).

Despite the MD process’s superb characteristics, the MD process still has not been commercialized because of wetting, low permeability, and poor mechanical properties of the membrane.

Membrane structural designs to be adopted in the MD process

Current commercially available membranes inevitably experience membrane wetting over operation duration in the MD process. Therefore, it is imperative to develop a membrane designed so as to satisfy the MD process: superhydrophobicity or superomniphobicity, high porosity, good thermal stability, excellent chemical resistance, and good mechanical strength.

The main factors influencing the hydrophobicity of membrane, the most important factor in the MD process, can be classified as polymer, fillers, and the method used for membrane fabrication. These porous hydrophobic membranes have been usually produced from the hydrophilic materials (poly(vinyl alcohol) (PVA) (Dong et al. 2015b), polycrylonitrile (PAN) (Cai et al. 2018), and polysulfone (PSF) (Khayet et al. 2019)) and the hydrophobic materials (polypropylene (PP), poly(vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP), polyethylene (PE), polytetrafluoroethylene (PTFE), and polyvinylidene fluoride (PVDF) (Ahmed et al. 2015; El-Bourawi et al. 2006; Elmarghany et al. 2020)). The additives can be classified as one-dimensional (for example, nanotubes and fibers), two-dimensional (clay), or three-dimensional (spherical particles) (Bhattacharyya 2016) and could be organic (for example, carbon black, cellulosic nanofiller) and inorganic (SiO₂, Al₂O₃, TiO₂, ZnO) in nature.

According to the membrane’s design method, the available ENMs for MD application could be classified as a superhydrophobic single layer, multi-layer (composite hydrophilic–hydrophobic/hydrophobic–oleophobic...
underwater dual-layer, superhydrophobic dual-layer, triple-layer nanofiber membrane), and omniphobic nanofiber membrane.

**Superhydrophobic membranes**

The first experiment in applying electrospun nanofiber membrane in MD processes (i.e., AGMD) was reported by Matsuura (Feng et al. 2008). The hydrophobicity is usually estimated according to the water contact angle (WCA). Sixty-five degrees has been defined as the boundary angle between hydrophilicity (WCA < 65°) and hydrophobicity (WCA > 65°) based on the difference in the architecture of interfacial water (Tian and Jiang 2013; Vogler 1998). Figure 8 shows schematic portrayals of different superhydrophilic, hydrophilic, hydrophobic, and superhydrophobic surfaces according to the WCA (left to right, respectively) (Tili and Alkanhal 2019).

From the above picture, a superhydrophobic surface displays a contact angle greater than 150°, and a superhydrophilic surface exhibits a contact angle less than 5°. The highly water-repellent superhydrophobic surfaces possessing water contact angles bigger than 150° have been investigated and designed by simulating the self-cleaning property of lotus leaves (Zhang et al. 2008). The hydrophobicity of any solid surface depends on its surface energy and geometrical architecture, such as porosity and roughness. Therefore, superhydrophobic surfaces could be achieved by introducing a rough surface on hydrophobic materials and modifying a rough surface by utilizing a low surface energy material.

**Producing a rough surface on hydrophobic materials**

Although ENMs have outstanding properties such as excellent hydrophobicity, good porosity, and interconnected structure, the smooth ENMs manufactured only by hydrophobic polymers generally exhibit strong water adhesion despite their high contact angles (Liao et al. 2013). The superhydrophobic membranes have been developed to alleviate membrane wetting in the MD process, and the superhydrophobicity can impart less pore-wetting problems, improved LEP and enhanced water vapor flux, and excellent salt rejection than hydrophobic membranes (Lee et al. 2016a; Tijing et al. 2014a). Based on the Cassie–Baxter model, constructing a rough membrane surface is vital in achieving a superhydrophobic membrane (Cassie and Baxter 1944). Recently, various methods have mainly been adopted to introduce a rough surface on the membrane.

The first method is incorporating nanoparticles into the previously prepared solutions to prepare membranes directly (Dong et al. 2015a; Moradi et al. 2018). It is well known that inorganic nanoparticles, including Al2O3, SiO2, and TiO2, enhance the electrical conductivity of polyelectrolyte, especially the photocatalytic activity of TiO2 has the potential to improve the membrane fouling properties (Chung et al. 2001; Madaeni and Ghaemi 2007). Numerous superhydrophobic membranes by using unique properties of nanoparticles such as PVDF-functionalized SiO2 (Nthunya et al. 2019), PVDF-clay (Prince et al. 2012), PVDF-HFP-functionalyzed TiO2 (Lee et al. 2016a), PVDF-graphene quantum dots (GQDs) (Jafari et al. 2018), PVDF-functionalized Al2O3 (Attia et al. 2017a), and PVDF-HFP-graphene (Woo et al. 2016) were prepared via one-step electrospinning to display excellent performances in the MD process.

The second method is to fasten inorganic nanoparticles such as TiO2, Al2O3, SiO2, and Ag, on the membrane surface, followed by post-treatment (Boo et al. 2016; Lee et al. 2016a; Shan et al. 2018). A superhydrophobic membrane with a hierarchical structure (Attia et al. 2018b) was fabricated by spraying a mixture of non-fluorinated alumina (Al2O3) NPs on an electrospun base membrane produced from PVDF via electrospinning. Alumina (Al2O3) NPs were functionalized with isostearyl acids and PVDF. The choreographed membranes properties: 87.5% of porosity, 0.39 μm of mean pore size, 25psi of LEP, and WCA of 154°. Then, many superhydrophobic membranes such as PTFE-PVA (Zhou et al. 2014), PVDF-PTFE (Li et al. 2019a), PVDF-TBAC (tetrabutylammonium chloride)-FA (fluorinated acrylate copolymer) (Li et al. 2019c), and PTFE-PVA (Zhou et al. 2020) were fabricated by combining electrospinning and post-treatment such as sintering, heat-press, ultrasonic treatment, and vacuum sintering to demonstrate applicable properties for MD process.

The third method is to manufacture a superhydrophobic membrane possessing a hierarchical structure via colloid or emulsion electrospinning followed by post-treatment or without it, such as sintering like PVDF-hydrophobic silica (Li et al. 2015) and PTFE-PEO (Su et al. 2019).
Many ENMs with superhydrophobicity, like PDMS (polydimethylsiloxane)-PMMA (polymethyl methacrylate) (Ren et al. 2017b), a copolymer of tetrafluoroethylene, hexafluoropropylene, and vinylidene fluoride (THV) (Zhang et al. 2017) and PVDF-HFP-PET (polyethylene terephthalate) (An et al. 2020), were fabricated from various kinds of polymers on the base of the unique hydrophobic properties of these polymers (Fig. 9).

The effects of additives affecting the superhydrophobic ENMs performance, such as PVDF-LiCl (Liao et al. 2013) and PVDF-PTFE-IL (Li et al. 2020b) (ionic liquid (BMIMPF6: 1-butyl-3-methylimidazolium hexafluorophosphate)) were investigated in the MD process.

The effects of pre-treatment on the ENMs performance possessing superhydrophobicity during the MD process were also studied. A superhydrophobic TiO2 electrospun membrane (E-TiO2) (Guo et al. 2019) was developed via electrospinning by using PVDF-HFP, followed by coating with TiO2 nanoparticles using electrospraying. TiO2 nanoparticles were functionalized with a 1H, 1H, 2H, 2H-perfluorooctyltriethoxysilane (FTES). The membrane antifouling control was achieved by combining a ferrate pre-treatment and subsequently dissolved air flotation (DAF) in the DCMD process. The membrane regeneration was performed with easy physical water flushing.

Also, many studies on the mathematical modeling of the MD process were performed. A superhydrophobic ENM (Attia et al. 2017b) was fabricated from PVDF polymer and eco-friendly superhydrophobic alumina functionalized with isostearyl acids via electrospinning to remove heavy metal lead from the feed side of AGMD. Then, they used various models to calculate membrane flux on the base of mass and heat transfer balance in the case of AGMD. The experimental results demonstrated that membrane flow rate increased exponentially according to augmentation of feed solution temperature and slightly with an enlargement of feed flux. However, the flow rate decreased according to increasing feed solution concentration and coolant temperature. In Fig. 10, $T_f$, $T_{mf}$, $T_{mp}$, $T_{cd}$, $T_{ca}$, $T_{cp}$, and $T_p$ are the feed side inlet temperature, the feed side membrane temperature, the air gap side membrane’s temperature, the thin film condensate temperature, the cooling plate (permeate side) temperature, the cooling plate (coolant side) temperature, and the coolant temperature respectively.

The purpose of forming a rough surface on the hydrophobic material by incorporating nanomaterials is to produce a Cassie–Baxter state, which creates an air gap between the water droplet and the superhydrophobic surface, thereby increasing the allowable pore diameter of the membrane and improving the permeate flow (Dong et al. 2015a). The purpose of introducing a rough surface on the hydrophobic material by incorporating post-treated nanomaterials is to

Fig. 9 Diagrammatic electrospinning process of iHFC (interweaving hierarchical fibrous composite) membrane preparation from PET and PVDF-HFP solutions (An et al. 2020)

Fig. 10 The vapor pressure and temperature diagram in the AGMD process (Attia et al. 2017b)
enhance the stability of the resultant membrane by strengthening the adhesion between the nanomaterial and the substrate and its overall performance of it (Ren et al. 2017a) (Fig. 11).

However, the existence of nanoparticles inlaid into the membrane substrate useless for roughness structure adversely may influence the prepared membrane’s physical and chemical properties. The low adhesion force between these inorganic constituents and the membrane matrix makes the nanoparticles easily separate from the membrane surface (Zhong et al. 2019).

Then, post-processing results in undesirable effects like pore-clogging and the possibility of destroying the nanofiber architecture. It is difficult to steer the thickness and amount of functional groups on the nanofiber surface in this process (Khayet et al. 2019).

**Modification of a rough surface by utilizing a material with low surface energy**

A pore wetting of the membranes can be alleviated by enhancing surface hydrophobicity or reducing pore diameter (Gryta and Barancewicz 2010): broader pore diameter results in higher vapor flux. However, the allowable pore sizes of existing membranes are limited to the range of 50 to 200 nm, so the membrane hydrophobicity by reducing pore diameter is restricted (Ma et al. 2009). As compared to reducing the pore diameter of the membrane, it can be considered a rational way to enhance surface hydrophobicity to abate pore wetting because decreased pore size would lower permeability.

The as-prepared nanofiber layers via electrospinning possess excellent porosity and uniform pore size distribution. The interconnected porous architecture of electrospun membranes as the path to transfer water vapors enhances the membrane permeability. It is susceptible to functionalizing the membrane due to the high surface area. ENMs have excellent advantages such as multiple-scale roughnesses (Zhou et al. 2014), high hydrophobicity, interconnected structure, and high porosity (An et al. 2017; Dong et al. 2015b; Feng et al. 2008; Guo et al. 2015a; Tijing et al. 2014b) compared to traditional membranes (Tadanaga et al. 2003) to generate superhydrophobic surfaces for MD process. Many methods have been developed for surface modification, such as CF₄ plasma (Tian et al. 2015), fluorosilanization (Fang et al. 2012), and hydrophobic nanoparticles (Wang et al. 2011).

Many studies for preparing superhydrophobic ENMs were performed via fabrication of functional polymers with low surface energy functional groups using various methods such as free radical polymerization and atom transfer radical polymerization followed by one-step electrospinning of them (Guo et al. 2015b).

The surface modifications were achieved via electrospinning of hydrophilic (PAN, PSF) or hydrophobic (PVDF) polymers followed by simple dip-coating by using materials with low surface energy such as 1H,1H,2H,2H-perfluorodecyl acrylate (PFDA) monomer, and PDMS and post-treatment such as cold-press post-treatment or without it (Cai et al. 2018; Jiao et al. 2020; Li et al. 2017).

Then, the surface modifications were performed by hydrophobization with materials such as (heptadecafluoro-1,1,2,2-tetradeacyl) trimethoxysilane (FAS-17); PDMS; and 1H, 1H, 2H, 2H-perfluorododecyl-trichlorosilane (FTCS) fluorination (Dong et al. 2015b; Ren et al. 2017a; Zhong et al. 2019).

Novel superhydrophobic ENMs (Dong et al. 2015b) were fabricated via the electrospinning of hydrophilic PVA followed by chemical cross-linking using glutaraldehyde. Finally, surface modification through fluoroalkylsilane ((heptadecafluoro-1,1,2,2-tetradeacyl) trimethoxysilane (FAS-17)) with low surface energy. The resultant membrane displayed excellent properties like the following: WCA of 158°, SA of 4°, stable permeate flux of 25.2 kg/m²·h, and excellent permeate conductivity (<5 μS/cm).

A novel superhydrophobic surface-modified nanofiber (Khayet et al. 2019) was prepared from blends of a hydrophilic PSF as host polymer, and small quantities of a fluorinated polyurethane (FPA) as an additive via one-step electrospinning: high permeate fluxes of 53.8 kg/m²·h and stable low permeate conductivities (<5.1μS/cm).

A novel superhydrophobic PVDF membrane with a microsphere/fiber porous structure (Su et al. 2020) prepared from premixed solutions composed of the polymer (PVDF), a suitable solvent (NMP), and a nonsolvent (H₂O) by combining NIPS and electrospinning followed by simple submerging in fresh FDTS (1H,1H,2H,2H-perfluorodecyltrichlorosilane) solution for the MD application. The
experimental results revealed that adding a small quantity of water into the NMP + PVDF casting solution made phase separation happen earlier the formation of more nanoscale pores and microscale spheres, and the surface would become rougher than the absence of water to make the surface possess more hydrophobic. Then, the resultant membrane exhibited a high contact angle of 152.4° and an applicable permeability.

Recently, the primary methods for surface modification of electrospun membranes are to adopt fluorinated additives that can move to the nanofiber’s surface to be separated spontaneously from the surface, and it makes the surface possess lower surface energy. The main disadvantage of surface modification using materials with low surface energy like fluoride, silane, and silicon compounds is to use silane and fluorinated materials with potential environmental hazards.

Composite hydrophilic–hydrophobic/hydrophobic–oleophobic underwater and multi-layer nanofiber membranes have been developed to enhance the MD membrane design for better MD performance (for example, high permeability, high mass transfer, low thermal conductivity, mechanical durability) (Table 1).

**Multi-layer nanofiber membranes**

**Composite hydrophilic–hydrophobic/oleophobic underwater-hydrophobic membrane**

High mass fluxes and low heat transfer in DCMD are considered preferable properties to improve the vapor permeation flux and sustain the driving force occurring from the temperature difference (Yang et al. 2017). Therefore, thin membranes with suitable porous are preferred to achieve high mass transport coefficients. Then, thick membranes usually warrant excellent thermal efficiency, mechanical strength, and physical robustness. To resolve the issues mentioned above, reducing the vapor transport distance through a possibly thin hydrophobic layer is preferable (Liu et al. 2018), while sustaining the whole membrane thickness through a thick hydrophilic layer to decrease the temperature polarization effect (Qtaishit et al. 2009).

The ideal design of the composite hydrophilic–hydrophobic is to ensure the hydrophobic layer keeps dry to enable desalination while the hydrophilic layer is completely wetted to strengthen the flux (Jiaming Zhu 2015). A dual-layer membrane with hydrophobicity and hydrophilicity can be considered a Janus membrane. This dual-layer membrane’s main feature is to possess the opposite properties of both hydrophilicity and hydrophobicity, or negative and positive charges (Yang et al. 2016). In the 1980s, Cheng and Wiersma developed the dual-layer membrane patent composed of a top layer with hydrophobicity and a sublayer with hydrophilicity (Cheng and Wiersma 1982; Cheng and Wiersma 1983). They first discovered the concept of Janus membrane to MD in 1982 (Cheng and Wiersma 1982). A composite hydrophilic–hydrophobic membrane with asymmetric wettability has received significant attention in the application of MD.

At least one layer among the MD membrane should possess hydrophobicity or possibly superhydrophobicity to avoid pore wetting of the membrane (Liao et al. 2014b). While the hydrophilic layer in the composite hydrophilic–hydrophobic membrane is wetted with liquid (usually water), vapor transmission occurs in the hydrophobic layer. The dual-layer membrane with asymmetric wettability in the MD process results in higher mass flux because of the vapor’s shorter moving path between the liquid/vapor interfaces. The dual-layer membrane with asymmetric wettability was considered a more suitable way to solve the membrane thickness issue and displayed positive enhancement because the thicker hydrophilic layer as a support layer can mechanically hold the weak, thin hydrophobic layer. In contrast, the weak, thin hydrophobic layer effectively decreases the mass transfer resistance and results in a higher vapor flux (Bonyadi and Chung 2007). In this membrane, vapor condensation occurs at the interface of hydrophobic and hydrophilic layers. The mass transfer resistance between the evaporation and the condensation side may be significantly decreased due to the hydrophilic layer’s existence compared to the neat hydrophobic membrane with the same thickness (Zhao et al. 2020). Furthermore, a hydration layer is created on the hydrophilic skin layer of the hydrophobic/hydrophilic membranes due to the robust interaction between the water and the hydrophilic layer through hydrogen bonding, resulting in powerful underwater fouling resistance (Chen et al. 2010).

Many dual-layer composite nanofiber membranes were fabricated for the MD process via electrospinning of hydrophobic polymer (for example, PVDF-HFP, PTFE) or hydrophobic polymer-hydrophobic additives (for example, activated carbon (AC)) blend solution as the top active layer and hydrophilic polymer (for example, PVA, nylon-6 (N6), PAN, PSF) or hydrophilic polymer-hydrophilic additives (for example, cellulose acetate (CA), silica NPs) dope solution as bottom supporting layer followed by post-treatment or without it (Hou et al. 2018; Khayet et al. 2018; Woo et al. 2017; Zhao et al. 2018).

Figure 12 schematically demonstrates how AC nanoparticles affect the water contact angles of the membranes. AC enhanced hydrophobic/hydrophilic dual-layer nanofiber composite membranes were fabricated for DCMD (Zhao et al. 2018). Firstly, the commercial hydrophilic nylon 6.6 membrane was fixed onto the surface of the rotating drum collector. Then, a doping solution composed of the hydrophobic PVDF-HFP and different concentrations (0–3.0 wt%) of AC nanoparticles was electrospun on top of the nylon
Table 1 The characters of representative superhydrophobic single-layer nanofiber membrane and the performance in the MD process

| Polymer           | Solvent                  | Additives                         | Feed side temperature (°C) | LEP (kPa) | Operation time (h) | Mean pore size (μm) | WCA (°) | Feed solution                      | Feed solution                      | MD type/reference            |
|-------------------|--------------------------|-----------------------------------|----------------------------|-----------|--------------------|---------------------|---------|------------------------------------|------------------------------------|-----------------------------|
| PVDF              | Acetone; N, N-dimethyl acetamide (DMAc) | Clay                              | 80                         | 200±6     | 8                  | 0.64±0.22          | 154.20±3.04° | 3.5wt% NaCl | DCMD (Prince et al. 2012) |                           |
| PVDF              | DMAc; N, N-dimethylformamide (DMF); acetone | Lithium chloride (LiCl)           | 50                         | 350       | 15                 | 0.3                | >135°      | 3.5wt% NaCl | DCMD (Liao et al. 2013)  |                           |
| PTFE emulsion (FR301B); PVA |                         | Lithium chloride (LiCl)           | 80                         | 165       | 10                 | >150°              | Pb concentrations (500, 1000, 1500, 2000 mg/l) | VMD (Zhou et al. 2014) |                           |
| PVDF              | DMF                      | SiO₂                              | 60                         | 240±10    | 24                 | 0.1479–1.9339      | 155.6     | 3.5wt% NaCl | DCMD (Li et al. 2015)  |                           |
| PVDF-HFP          | DMF; acetone             | TiO₂, LiCl                        | 60–61                      | 194.5     | 48                 | 0.3–0.6            | 149       | 7.0 wt% NaCl | DCMD (Lee et al. 2016a) |                           |
| PVDF              | DMF; acetone             | Al₂O₃, hexadecyl trimethyl ammonium bromide (HTAB) | 70                         | 186.2     | 5                  | 0.47–0.715         | 150       | Pb concentrations (1000 mg/l) | AGMD (Attia et al. 2017a) |                           |
| PVDF              | DMF                      | Al₂O₃                             | 70                         | 186.2     | 5                  | 0.37–0.467         | 150       | Pb concentrations (1000 mg/l) | AGMD (Attia et al. 2017b) |                           |
| PDMS; PMMA        | DMF; tetrahydrofuran (THF); acetone | SiO₂ NPs                         | 70                         | 13        | 24                 | 9.15–13.43         | 163       | 3.5wt% NaCl | DCMD (Ren et al. 2017b) |                           |
| PVDF              | DMAC; acetone            | SiO₂ NPs                          | 60                         | 72.3±2.3–84.2±2.8 | 150               | 1.24–1.41          | 150       | 3wt% NaCl | DCMD (Nthunya et al. 2019) |                           |
| PVDF; fluorinated acrylate copolymer (FA) | DMF; acetone | Tetrabutylammonium chloride (TBAC) | 60                         | 200       | 9                  | 0.21–0.26         | 137±3     | 3.5wt% NaCl | DCMD (Li et al., 2019c) |                           |
| PVDF-HFP          | DMF; acetone             | TiO₂, LiCl                        | 65                         | 65        | 24                 | 0.52               | 157±1.6   | A synthetic AOM feed solution (algae organic matter: AOM) | DCMD (Guo et al. 2019) |                           |
| PTFE emulsion; PVA |                         |                                   | 60                         | 205±15    | 10                 | 0.55±0.05          | 161.5±2.4 | 3.5 wt% NaCl; 0.1 mM sodium dodecyl sulfate (SDS) | VMD (Zhou et al. 2020) |                           |
| PVDF-HFP; PET     | DMAC; acetone; trifluoracetic acid (TFA) |                                  | 65                         | 38.3      | 60                 | 1–1.5              | 146       | 3.5wt% NaCl | DCMD (An et al. 2020)  |                           |
| PVDF              | DMF                      | Graphene quantum dots (GQDs)      | 60                         | >135      | 60                 | 4900               | >125      | 3.5wt% NaCl | AGMD (Jafari et al. 2018) |                           |
| PVDF-HFP          | DMF; acetone             | Graphene                          | 60                         | >186      | 60                 | 0.86±0.02          | >162      | 3.5wt% NaCl | AGMD (Woo et al. 2016) |                           |
6,6 substrate. All of the AC-incorporated membranes in the experiments exhibited higher water contact angles as the micro-wrinkles and AC protrusions enhanced the surface hydrophobicity than the membrane without AC addition. It is expected that the PVDF-HFP/AC nanofibers with the hierarchical roughness structure composed of micro-wrinkles and AC prominences would decrease the actual contact area between the water droplet and the hydrophobic surface to result in enhanced hydrophobicity of the membranes.

A novel nanofibers-covered hollow fiber membrane (N-HFM) (Su et al. 2018) was fabricated from a commercial support woven tube and PVDF-HFP via non-rotational electrospinning for the DCMD process to combine the unique advantages of electrospun nanofibers and hollow fiber membrane (Fig. 13). The nanofibers film covered on the supporting woven tube via electrospinning acts as the skin layer of the resultant N-HFM. The fabricated hollow fiber membrane’s mechanical strength was then enhanced by a solvent vapor welding that fuses the nanofibers at their cross-points to maintain high porosity. The experimental results demonstrated that after a 40-min fusing, the strain at break, tensile strength, and Young’s modulus of the welded N-HFM increased by 79%, 90%, and 117%, respectively, compared to the pristine N-HFM.

A novel mathematical model (Zhao et al. 2020) on the heat and mass transfer mechanism was developed for the membrane distillation with hydrophobic/hydrophilic dual-layer composite membranes in DCMD mode. The primary purpose of this work is to explore the effect of the hydrophilic layer on the flux rate of the hydrophobic/hydrophilic dual-layer composite membranes. The parameters are the same as following: total thickness ($\delta$), hydrophobic layer ($\delta_o$) and hydrophilic layer ($\delta_i$) thickness, hydrophobic layer mean pore diameter ($d_o$), hydrophobic layer ($\varepsilon_o$) and hydrophilic layer ($\varepsilon_i$) porosity, and hydrophobic surface water contact angle ($\theta$). They fabricated a new single and dual-layer hydrophobic/hydrophilic membrane with total thicknesses (240 μm, 260 μm, and 285 μm) and different thickness ratios ($\delta/\delta_o=3.69, 2.48, \text{and } 2.19$) through electrospinning of hydrophobic PVDF-HFP solution on the commercial hydrophilic nylon 6,6 membrane substrate. Then, by using the proposed simultaneous heat and mass transfer theoretical model, they derived a standard parameter ($\beta$) to determine the augmented degree of the flux for the resultant hydrophobic/hydrophilic composite membranes. Furthermore, they theoretically derived a flux ratio model ($\gamma_{\text{DL=SL}}$) and a critical value of the thickness ratio ($\chi=1+1/\beta$) to systematically investigate the flux performance of a hydrophobic/hydrophilic dual-layer composite membrane to the single-layer hydrophobic membrane with equal total thickness and validated through experiments.

Then, the pores of the hydrophobic membranes adopted in the MD process are susceptible to being wetted or fouled

| Table 1 (continued) | Polymer | Solvent | Additives | Feed solution | MD type/ reference |
|---------------------|---------|---------|-----------|---------------|-------------------|
| PVDF | DMF; acetone | Distilled water | | | |
| PTFE; PEO | THV | DMF | Ionic liquid (BMIMPF6) | | |
| PVDF; PTFE | | | | | |

| Feed side temperature (°C) | 60 | 65 | 80 | 60 |
|-----------------------------|----|----|----|----|
| LEP (kPa) | 106.9 | 245.7 | 118.0 | 83 |
| Operation time (h) | 30 | 16.6 | 6 | 26 |
| Mean pore size (μm) | 0.307 | 0.41 | 0.79 | 0.93 |
| Feed solution | MD | AGMD (Atta et al. 2018b) | DCMD (Su et al. 2019) | SGMD (Zhang et al. 2017) | DCMO (Li et al. 2020b) |
| WCA (°) | >154 | >164 | 130.7 | 146.4±1.8 | 3.5wt% NaCl AGMD (Attia et al. 2018b) | 3.5wt% NaCl DCMD (Su et al. 2019) | 3.5wt% NaCl SGMD (Zhang et al. 2017) | 3.5wt% NaCl DCMO (Li et al. 2020b) |
by oil because of long-range hydrophobic–hydrophobic interactions that result in fouling or a loss of selectivity of the membranes (Olawale Makanjuola 2019). This prevents the application of the MD in the treatment of oil-containing wastewater. It is very crucial to develop a membrane with repellency for both water and oil to utilize MD in the treatment of oil-containing wastewater. The composite hydrophilic–hydrophobic dual layer and omniphobic membranes have been recognized as promising methods. In the composite hydrophilic–hydrophobic membrane, the hydrophilic surface, which becomes oleophobic underwater, interacts with the oily feed solution and inhibits the passage of oil to the hydrophobic sublayer.

The dual-layered membrane has been fabricated via electrospinning for oily wastewater treatment, which is consisted of a hydrophobic electrospun PVDF-HFP membrane as a bottom layer and a hydrophilic electrospun PVDF-HFP membrane modified by regenerated cellulose as a top layer. The experimental results exhibited that the resultant membrane produced a freshwater flux of 12.8 kg m\(^{-2}\) h\(^{-1}\) for saline feed solution containing 1000 ppm of oil while completely rejecting salt in the DCMD process (Olawale Makanjuola 2019).

The purpose of adding hydrophilic additives into a hydrophilic polymer of composite membranes is to improve the surface roughness for hydrophilicity and to ensure that the hydrophilic layer adheres well to the hydrophobic layer.

One challenge that the composite hydrophilic–hydrophobic membranes face is the possibility that wetting faults between hydrophilic skin and the hydrophobic substrate can be introduced into the inner pores due to the coating of a hydrophilic layer onto a hydrophobic matrix. Then, a conductive heat loss is increased because of the hydrophobic layer’s introduction with a thinner thickness, and the hydrophilic layer produces a further heat transfer resistance by increasing the undesired temperature polarization, resulting in the reduction of the flux.

Superhydrophobic dual-layer nanofiber membranes have been developed to improve wetting repellent characteristics, surface’s interface stability, and the mechanical rigidity of ENMs (Table 2).

**Robust superhydrophobic dual-layer membrane**

Inspired by the appealing self-cleaning characters of the silver ragwort leaf, lotus leaf, and water strider leg in the natural world, these prominent superhydrophobic surfaces have attracted significant attention. They have been widely investigated because of their promising applications in water harvesting, antifogging surfaces, and self-cleaning materials, especially desalination (Celia et al. 2013).

A three-dimensional (3D) superhydrophobic materials possess specific properties to maintain the air at both the surface and within the material’s bulk. A new interface between water, air, and material can be continuously provided as water penetrates it (Liao et al. 2014a). Two kinds of superhydrophobic dual-layer membranes (Liao et al. 2014a) were prepared via electrospinning for the MD process: (1) to form
an ultrathin 3D superhydrophobic selective skin through electrospinning of FS10 (α,ω-triethoxysilane-terminated perfluoropolyether ((EtO)3Si-PFPE-Si(OEt)3))-modified silica and PVDF dope solutions on a porous PVDF nanofibrous support; (2) to form a thicker 3D superhydrophobic selective skin by electrospinning FS10-modified silica and PVDF dope solutions on commercial PET nonwoven support. The results showed that the water contact angles of the superhydrophobic dual-layer are above 150°. So, they exhibited excellent superhydrophobicity against numerous kinds of liquid, including coffee, juice, milk, and oil-in-water emulsion as well as water.

The superhydrophobic dual-layer membranes were fabricated from a hydrophobic polymer or hydrophilic polymer-hydrophobic additive (for example, modified SiO2 NPs, functional alumina NPs, functionalized GO) blend solution as a skin layer on a commercial hydrophobic membrane substrate or hydrophobic ENMs or hydrophobic membrane prepared by various methods such as phase inversion method as supporting layer via electrospinning (Attia et al. 2018a; Du et al. 2019; Efome et al. 2016; Li et al. 2020a; Liao et al. 2014b). A novel composite membrane (Li et al. 2019b) was fabricated through PVDF fibrous coatings as the hydrophobic functional layer via electrospinning. They used two kinds of nonwoven fabrics and two kinds of spacers as the substrate to achieve high mechanical strength and excellent permeate flux of the membrane. The experimental data displayed that at the feed temperature of 80 °C, the permeate flux reached 49.3 kg/m²·h during the DCMD test. The spacer fabrics as substrates had minor less resistance to mass transfer than the nonwoven fabrics.

Many kinds of research for a triple-layer nanofiber membrane have been conducted to improve further the performance of the single-layer and dual-layer nanofiber membranes in MD application (Table 3).

### Triple-layer nanofiber membrane

Each layer in the triple-layer nanofiber membrane has a specific function.

A novel triple-layer membrane (Prince et al. 2013) was prepared by electrospinning PVDF solution on casted microporous PVDF membrane onto a PET substrate for AGMD application. The results showed that the formation of a thin hydrophobic nanofiber layer on the dual-layer membrane resulted in augmentation of the flux, salt rejection efficiency, and long-time performance due to enlargement of the LEP and hydrophobicity of the resultant membrane than the single-layer and dual-layer nanofiber membrane.

A triple-layer nanofiber-based membrane (Prince et al. 2014) was manufactured by wet casting and electrospinning method. (1) The middle layer was manufactured by the conventional phase inversion method while PVDF was dissolved in DMAc/ethanol solvent mixture. Then PVP (poly(vinyl pyrrolidone)) as pore former was added to prepare the casting polymer dope. Then, a small amount (0–3wt%) of surface modifying macromolecule (SMM (hydrophobic)) was added to the above mixture to alter the membrane surface. (2) PVDF-SMM(hydrophilic) composite nanofibers coated the bottom side of the intermediate layer via electrospinning. (3) The top side of the middle layer was coated with PVDF nanofibers via electrospinning.
A novel triple-layer nanofiber membrane possessing a diameter gradient (Ebrahimi et al. 2018) was fabricated: outer layers with bead-free and thinner diameters manufactured with the minimum concentration of PVDF (20wt%) and middle layer with thicker diameters produced with higher polymer concentrations (21.5–26wt%) via electrospinning for DCMD application. The results showed that all prepared membranes displayed about two times the permeate flux than a single-layer membrane while maintaining salt rejection above 99.9% due to lower heat loss and mass transfer resistance of the proposed membrane attributed to the increased pore size of the middle layer. The results showed that a permeate flux of the resultant membranes (27.8–31.5 kg/m²·h) was higher than 15.4 kg/m²·h for single-layer membranes under 42 g/L NaCl of feed solution.

A triple-layer nanocomposite membrane, which is composed of polyethersulfone (PES)/carbon nanotubes (CNTs) as a core and PVDF-HFP/CNTs as the bottom and top surfaces of the membrane (Elmarghany et al. 2020) was fabricated via electrospinning method, and the DCMD test was conducted.

A novel triple-layer membrane comprised of an electrospun PVDF-PTFE hydrophobic layer, a PET middle support layer, and an electrospun chitosan–polyethylene oxide (CS-PEO) hydrophilic layer (Li et al. 2020c) was developed to improve wetting resistance and water flux because a hydrophobic membrane via electrospinning only is difficult to guarantee a high flux. The experimental results revealed that the fabricated triple-layer composite membrane with an average flux of 19 kg/m²·h and rejection rate of 99.92% displayed better performance than the dual-layer membrane without a hydrophilic layer possessing an average flux of 15 kg/ m²·h and rejection rate of 99.88%. The PVDF-PTFE hydrophobic layer did not allow the water molecules to pass through the membranes. Then, CS-PEO hydrophilic layer will attract the water vapor from the PET supporting layer in time to enhance MD flux and delay the pore wetting.

However, the amphiphilic organic contaminants and low surface tension surfactants exist everywhere in hypersaline industrial effluents, like shale gas effluent or electroplating effluent, make superhydrophobic membranes susceptible to membrane wetting by significantly reducing the LEPw (Rezaei et al. 2018; Zheng et al. 2018). Therefore, superhydrophobic membranes lose rejection characters. Therefore, to extend the MD application for challenging wastewater’s desalination, a robust omniphobic membrane has been developed and widely investigated as a promising MD membrane that can resist wetting to water and low surface tension liquid.

### Omniphobic membrane

MD, as a hybrid thermal/membrane separation process, allows only water vapors to pass through a hydrophobic membrane by a vapor pressure gradient (Wang and Chung 2015), and salt is rejected regardless of salt concentration. The available MD membranes show excellent hydrophobicity and can be successfully employed to demineralize relatively clean waters like seawater and saline water (Hou et al. 2010). A wetting resistance of the substrate pore in the hydrophobic membrane is ensured at the MD process’s beginning step. The chemical and physical properties at the interface between the membrane and aqueous solutions are modified as the feed chemicals (for example, surfactants and other organic materials) and the membrane materials interact, resulting in fouling/wetting.

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**Table 3** The characters of representative superhydrophobic dual-layer nanofiber membrane and the performance in the MD process

| Polymer (bottom layer) | Polymer (top layer) | Flux, kg/m²·h | Feed side temperature (°C) | LEP (kPa) | Operation time (h) | WCA (°) | Feed solution | MD type/reference |
|------------------------|---------------------|---------------|-----------------------------|-----------|---------------------|--------|---------------|------------------|
| PVDF                   | PVDF                | 3.2           | 27.5                        | 379–565   | 6                   | 139 ± 5 | 3.5wt.% NaCl  | DCMD and VMD (Efome et al. 2016) |
| PVDF                   | PVDF                | 18.9          | 60                          | 179 ± 7   | 50                  | > 153.9 | 3.5wt.% NaCl  | DCMD (Liao et al. 2014b)          |
| PET                    | PVDF                | 24.6 ± 1.2    | 60                          | 150       | 40                  | > 150  | 3.5wt.% NaCl  | DCMD (Liao et al. 2014a)          |
| PVDF                   | PVDF                | 23            | 30–80                       | 144.79    | 5                   | 150 ±0.3 | 2.5wt.% metal concentration (Zn, Cd, Pb, Cu, Ni) | AGMD (Attia et al. 2018a) |
| PP                     | PVDF                | 36.4          | 50                          | 233.9 ± 7.3 | 60                  | 140.5  | 3.5wt% NaCl   | VMD/ (Li et al. 2020a)            |
| Additives              | Additives           |               |                             |           |                     |        |               |                                |
| PVDF                   | Silica particles;   |               |                             |           |                     |        |               |                                |
| PVDF                   | Silica particles    |               |                             |           |                     |        |               |                                |
| PET                    | Silica particles    |               |                             |           |                     |        |               |                                |
| PVDF                   | Alumina NPs        |               |                             |           |                     |        |               |                                |
| PP                     | GO                  |               |                             |           |                     |        |               |                                |
Usually, the superhydrophobic surface exhibits a high water contact angle of above 150° and a water SA of below 10°. However, those values are measured by using high purity water in the absence of any surfactants or contaminants with low surface tension. Although surfactants are fusible in water, they usually exist as oil-in-water emulsions in the effluent from oil/gas and chemical industries, so they are an essential factor to influence membrane wetting (Chen et al. 2017).

Numerous MD membranes, i.e., superhydrophobic (Celia et al. 2013), composite hydrophilic–hydrophobic (Edwie et al. 2012; Peng et al. 2005), and omniphobic (possessing hydrophobic and oleophobic) membranes (Wang et al. 2016) have been specifically designed and developed to prevent surfactant and other low surface-tension materials wetting. Superhydrophobic membranes essentially improve the anti-wetting properties, but unavoidable electrostatic interaction makes them easily wet by surfactants, resulting in the reduction of the MD performance for the more prolonged operation (Chen et al. 2017). Then, in the composite hydrophilic–hydrophobic membranes, the hydrophilic side contacts the hot feed, and the hydrophobic side contacts the cold permeate. They can prevent the wetting problem and enhance permeation flux. The biggest challenge is to possess the possibility of producing wetting defects owing to the possible coating of the inner pores within the hydrophobic membranes (Khayet et al. 2018). An active layer in the composite hydrophilic–hydrophobic membranes may be delaminated from the support layer because of the difference in the interfacial tension (Tijing et al. 2014b). Omniphobic membranes prone to repel water (hydrophobic) and low-surface-tension liquids like oil (oleophobic) have demonstrated a stable performance for the MD process under the surfactant’s existence in an aqueous solution for a long time (Boo et al. 2016). The omniphobicity that repels water and low surface tension liquids such as oil is created via producing surfaces possessing low surface tension and multilevel re-entrant structures that together promote the existence of the metastable Cassie–Baxter state for interfacial contact between liquid, solid, and vapor phases (Anish Tuteja et al. 2008; Butt et al. 2013; Tuteja et al. 2008). The superhydrophobic surface could be realized by a cooperation of roughness (nano/macroscale architectures) and a low surface energy chemistry (Li et al. 2008). However, an omniphobic surface needs a more accurate micro-/nano-scaled hybrid architecture design than a superhydrophobic surface (Schlaich et al. 2016). Although the roughness of a surface possessing a re-entrant morphology is not high enough, it will result in omniphobicity if the material has low surface energy (Anish Tuteja et al. 2007).

An omniphobic surface possessing a re-entrant texture that can support strongly metastable composite solid–liquid-air interfaces with both polar and non-polar liquids maintaining low surface tensions was developed (Tuteja et al. 2008) (Fig. 14). The experimental results revealed that in case of a liquid drop placed on the resultant surfaces keeping re-entrant texture ($\psi < 90^\circ$), the interacting traction upon the liquid–vapor interface is directed upward to support the metastable Cassie state for the composite solid–liquid-air interface, even though $\theta < 90^\circ$.

Many omniphobic membranes have been fabricated via deposition of nanoparticles to produce re-entrant micro/nano-structures on an electrospun substrate membrane surface, followed by surface fluorination to lower surface tension energy (Dizge et al. 2019; Hou et al. 2019). An omniphobic SiNP (silica nanoparticle) modified electrospun cellulose nanofiber membranes have been fabricated through three steps for the DCMD process: fabrication of cellulose nanofiber membranes by electrospinning; achievement of SiNPs modified nanofiber membranes by a sol–gel method; silanization using fluorinated alkylsilanes onto SiNPs modified nanofiber membranes to obtain the membrane with low surface energy via chemical vapor deposition (CVD). Heptadecafluoro-1,1,2,2-tetrahydrodecyl trichlorosilane (FDTS) was used for silanization (Dizge et al. 2019).

Next, various omniphobic membranes have been manufactured by electrospinning of hydrophobic polymer solution as substrate membrane, followed by surface fluorination to lower surface tension energy via solution submerging without any assistance of roughening treatments (i.e., the auxiliary nanoparticles) and thermal treatment (An et al. 2018; Deng et al. 2018; Qing et al. 2020). A novel amphiphobic PVDF-HFP nanofibrous membrane (An et al. 2018) was prepared via electrospinning and followed by the surface

![Fig. 14](image.png)  
**Fig. 14** a) and b) Schematic portrayals illustrating possible liquid–vapor interfaces on two different surfaces possessing the same solid surface energy and the same equilibrium contact angle ($\theta$), but different geometric angles ($\psi$) (Tuteja et al. 2008)
coating by 1H,1H,2H,2H-perfluorodecyl-triethoxysilane (FAS) through a facile immersion-coating process and thermal treatment. The results showed that the resultant FAS-coated PVDF-HFP nanofibrous membranes displayed prominent amphiphobicity against both water and oil even under rigorous conditions without much reduction of permeate flux and salt rejection of the consequent membrane by FAS coating in the DCMD process. A new nanoparticle-free omniphobic PVDF nanofibrous membrane has been fabricated through three steps for the DCMD process: the fabrication of PVDF nanofibrous membrane via electrospinning; the creation of multiscale hierarchical nanofin structures on electrospun PVDF nanofibers by solvent-thermal-induced roughening method; polydopamine-anchored surface fluorination to lower the surface energy of the nanofibrous membrane (Qing et al. 2020). 1H,1H,2H,2H-perfluorooctyltrichlorosilane (PFTS) was used for fluorination treatment. The experimental results demonstrated that the resultant membrane displayed a contact angle of 173.2° and 153.8° for water and mineral oil.

Then, some omniphobic membranes have been manufactured via simple one-step electrospinning. A novel omniphobic F-POSS/PVDF membrane (Lu et al. 2018) fabricated from PVDF-HFP and fluorinated-decyl polyhedral oligomeric silsesquioxane (F-POSS) colloidal suspension via one-step electrospinning. The experimental results revealed that the resultant omniphobic F-POSS/PVDF-HFP membrane had uniform fiber structures and very high F-POSS concentration on the surface. Furthermore, this membrane displayed excellent omniphobicity with a contact angle of 128.2° toward several low surface tension liquids such as ethanol and surfactant (sodium dodecyl sulfate, SDS).

And then, various omniphobic membranes have been manufactured via surface modification methods to produce re-entrant micro/nano-structures on an electrospun substrate membrane surface, followed by surface fluorosilanization and fluorination to lower surface tension energy (Jongho Lee et al. 2016; Koh and Lee 2021; Lee et al. 2016b; Li et al. 2019). A new omniphobic PVDF-HFP nanofibrous membrane with pine-needle-like hierarchical TiO₂-nanorods has been fabricated by using electrospinning, hydrothermal technique with polydopamine, and a fluorination treatment for the DCMD process (Li et al. 2019). Trichloro(1H,1H,2H,2H-tridecafluorooctyl) silane (FOTS) was used for fluorination. The experimental results demonstrated that the TiO₂ nanorods form uniform pine-needle-like hierarchical nanostructure on PVDF-HFP nanofibers. Then, the resultant membrane exhibited high contact angles of 168° and 153° towards the water and mineral oil, respectively.

A new omniphobic polyamide 6 (PA6)-based nanofibrous membrane has been fabricated by chemical surface modification methods for the MD process (Koh and Lee 2021). PA6 nanofibrous membrane was fabricated via electrospinning, and electrospun PA6 nanofibrous membrane was treated with trichloro(1H,1H,2H,2H-perfluoroctyl) silane (F-POSS) to endow a hydrophobic property. The fluorine-treated PA6 nanofiber membrane was altered with the PVDF-g-F-POSS solution by the grafting reaction between PVDF and F-POSS, and the polymer chains were flocculated to create Si–F nanoparticles (NPs). The resultant membrane displayed the omniphobicity against low surface tension liquids thanks to the formation of Si–F NPs on the membrane surface.

Due to its excellent oleophobic property, robust mechanical property, low water-adhesion property, and good durability, the omniphobic membrane has fulfilled unique potential in the MD process. The omniphobic membrane’s manufacturing process contains hierarchical re-entrant structures and surface fluorination like fluorosilanization and fluorination to lower the resultant membrane’s surface energy with the hierarchical re-entrant structures (Table 4).

Remarks of electrospinning technology and MD process

Current status and challenges of electrospinning technology

Many fusible or soluble polymers, including proteins, polysaccharides, and nucleic acids, have been used for electrospinning by controlling process parameters and environmental conditions and selecting the appropriate solvents. Their physicochemical properties and their merit and demerit of them have been studied overall.

Based on recognizing the solvent’s importance during electrospinning, numerous solvents are distinguished from different characteristics such as boiling point, density, volatility, solubility, dipole moment, vapor pressure, and dielectric constant. Their effects on electrospun nanofiber’s characteristics (for example, electrospinnability, morphology, thermal characters, crystalline architecture, and chemical structure) have been discovered in detail.

In applying electrospinning technology to practical applications, there are many challenges to solve. Poor mechanical properties and low productivity are the main challenges limiting their application in practical industrial applications of ENMs. Then, another challenge is the tailored alignment of fabricated fibers, especially fabricating electrospun fibers to calibrate morphology to ensure electron transport to be maximum possibly. To obtain uniform nanofibres with a diameter below 50 nm is also a significant challenge. Continuous development of electrospinning equipment and adding chemical additives such as organosoluble salts (for example, tetrabutyl ammonium bromide (TBAB), lithium...
chloride (LiCl), and ionic liquid) are more practical to obtain uniform nanofibers.

Current status and challenges of the MD process

Numerous experimental and modeling studies for the MD process application such as DCMD, AGMD, VMD, and SGMD using the electrospun membranes have been carried out, and many mass and heat transfer mechanisms for each MD process using different modes of membranes (multi-layer, composite and omniphobic membranes) have been studied in detail (Fig. 15).

$q_f$, $q_p$, $q_0$, $q_s$ mean the heat transferred through the boundaries of the feed side and permeate side, and through the hydrophobic layer and hydrophilic layer of the membrane; $q_m$ corresponds to the overall heat transfer flux through the entire thickness of the membrane; $J_W$ indicates vapor permeation flux; $T_{b,f}$, $T_{m,f}$, $T_{m,p}$, $T_{b,p}$ indicate the temperature of the bulk solution in feed side, the membrane in feed side, the interface of the hydrophobic/hydrophilic layers, the membrane in permeate side and bulk solution in permeate side; $T_{b,f}$, $T_{m,f}$, $T_{m,t}$, $T_{m,2}$, $T_{s,p}$, $T_{b,p}$ correspond feed bulk temperature, the surface temperature in the hydrophobic layer, the surface temperature in the hydrophilic layer, the interface of the hydrophobic/middle layers, the interface of the middle/ hydrophilic layers and permeate bulk temperature; $P_1$ and $P_2$ indicate pressure on feed and permeate side of the membrane.

Inspired by natural phenomenons such as lotus leaf, fresh rose petal, rice leaf, Salvinia molesta, and sharkskin, many membranes with excellent characteristics such as superhydrophobic, superhydrophilic, superomniphobic, and superoleophobic properties have been developed. They also have been applied in the MD process to demonstrate their outstanding performances.

Many studies about the module design and module optimization in MD configuration (Zhao et al. 2013) and the membrane’s structural design have been performed: a superhydrophobic single layer, multi-layer (composite hydrophilic–hydrophobic/hydrophobic–oleophobic under-water dual layer, superhydrophobic dual layer, triple-layer nanofiber membrane), and omniphobic nanofiber membrane fabricated in various structure (hollow, core–shell, lotus, pillar, acicular, multilevel re-entrant, pine-needle-like hierarchical structure and so on).

Figure 16 shows the structure of a single stage in the V-MEMD module. V-MEMD modules are composed of a steam raiser, multiple stages, and a condenser. The single stage consists of foil frames that function as a condenser and “distillate channels,” and membrane frames that serve as “vapor channels.” The space between foil frames and membrane frames plays a role as “Feed channels.” The vapor that flows into the parallel foil frames heats the feed and is then condensed. A vacuum is applied to a small channel at the bottom of the frame to remove non-condensable gases. The condensed vapor then enters a “distillate channel.” The heat energy of condensation transported through the foil frame is converted into evaporation energy to generate new vapor in the vapor channel. The vapor leaves the vapor channels and flows into the next stage. This process is repeatedly performed in the following stages (Fig 17).

In order to mitigate the membrane wetting, many kinds of research for feed pre-treatment operations have also been performed widely: removal of the wetting constituents of

| Table 4 | The characters of representative omniphobic membrane and the performance in the MD process |
|---------|------------------------------------------------------------------|
| Polymer | Additives | Post-treatment agent | Flux, kg/m²·h | Feed side temperature (°C) | Operation time (h) | WCA (°) | Feed solution | MD type/reference |
|---------|-----------|---------------------|--------------|--------------------------|------------------|--------|--------------|-----------------|
| Cellulose acetate | 1H, 1H, 2H, 2H-perfluoro-decyl-triethoxysilane (PDTS) | 13.6 | 53 | 120 | 155.6 ± 3.9 (for water); 95.3 ± 2.5 (for decane) | 3.5wt% NaCl; SDS | DCMD (Hou et al. 2019) |
| Silica nanoparticles | PVDF | 1H, 1H, 2H-perfluoro-dodecyl-trichlorosilane (CF3(CF2)9CH2CH2SiCl3, FTCs) | 36.9 | 60 | 24 | > 150 | 3.5wt% NaCl; SDS | DCMD (Deng et al. 2018) |
| PVDF-HFP | 60 | 8 | 154.5 ± 2.6 (for water); 149.5 ± 4.7 (for 3 mM SDS) | 5.85wt% NaCl; 3 mM SDS | DCMD (Lu et al. 2018) |
| F-POSS | PVDF-HFP | 1H, 1H, 2H-perfluoro-decyl-triethoxysilane, (FAS) | 19 | 65 | 2 | 138 ± 2; 127 ± 3 (oil contact angles) | 3.5wt% NaCl; 0.1 mM SDS; | DCMD (An et al. 2018) |
Fig. 15 Schematic of heat and mass transfer portrayal in MD process of water transportation through single (a) (Zhao et al. 2020), composite (b) (Zhao et al. 2020), triple-layer (c) (Li et al. 2020c), and omniphobic membranes (d) (Hou et al. 2019)

Fig. 16 Schematic portrayal of streams in vacuum-multi-effect-membrane-distillate (V-MEMD) module (Zhao et al. 2013)
the feed solution before MD operation (Rezaei et al. 2018), filtering and boiling feed solutions containing protein (Gryta 2008), alleviating protein fouling by using ultrasonic waves (Hou et al. 2017), nanofiltration for less fusible complexes with divalent salts (Roy et al. 2017), aggregation and anaerobic/aerobic digestions (Noel Dow et al. 2017), and chemical adjusting of feed solution using antiscalant (Peng et al. 2015). Along with the development of new membranes with a new structure for MD applications, it is important to develop a pre-treatment technology to reduce the components as much as possible that cause membrane wetting according to the characteristics of industrial wastewater.

As mentioned earlier, the MD process has not yet been industrialized due to the lack of reasonably designed membranes that can satisfy the MD process. The design of a membrane that can satisfy the MD process faces two critical challenges: low permeate flux and membrane pore wetting. Fabricating membranes possessing high porosity, open-cell pore structures, and narrow pore size distributions, especially electrospun nanofiber membranes with hierarchical re-entrant structures, could be considered a more efficient method for higher flux and enhancing the wetting resistance of the prepared membrane. The omniphobic property depends greatly on the hierarchical re-entrant structures. The air trapped in hierarchical re-entrant structures performs a vital role in omniphobic membranes. However, because the captured air may get away from air pockets during long-time MD operations, it is imperative to develop the omniphobic membrane with new designs such as multi-layer and nanorods architecture to support the omniphobicity during long-time MD operations. On the other hand, membrane fouling is a crucial drawback of MD, causing a decline in permeate flux because of the accumulation of undesirable material on the membrane surface and pores. Therefore, pre-treatment of wastewater before applying MD should be performed to decrease fouling and wetting problems and to ameliorate energy consumption and efficiency in the treatment and recovery process.

The electrospinnable polymeric materials possessing inherent hydrophobicity are minimal. A superhydrophobic surface with hierarchical architecture would not be efficient in enhancing the VMD process’s membrane wetting because the membrane material is not inherently hydrophobic (Jiao et al. 2020). Therefore, it is crucial to develop novel electrospinnable membrane materials with intrinsic hydrophobicity. The water drops will be rolled/Slid off as soon as they contact the electrospin membrane surface, possessing a “lotus effect” or the self-cleaning property during the MD process. It helps to prevent membrane wetting. Therefore, it is important to fabricate membranes with low SA as well as high WCA.

Most fabricating superhydrophobic and omniphobic surfaces by reducing the surface energy depends on fluorinated materials that have potential environmental hazards. Therefore, research on developing eco-friendly materials such as non-fluorinated silicon compounds should be performed to fabricate these surfaces. Good selection and incorporation of suitable additives and appropriate post-treatment to improve
the MD process’s membrane performance during electrospinning or post-electrospinning are essential to satisfy the MD application’s desalination requirement. Since the electrospun membrane has poor mechanical strength, it is used as a functional layer on other substrates. Therefore, studies to develop a competitive electrospinning substrate should be performed in the future.

Conclusion and the future prospects

This review performed comparisons for membrane design manufactured in various structures (hollow, core–shell, lotus, pillar, acicular, multilevel re-entrant, pine-needle-like hierarchical structure, and so on). From the fact that MD has not yet been introduced into the water industry due to a lack of suitable membranes, it is very important to design and manufacture suitable ENMs that can meet the needs of MD so as to fulfill the advantages of MD. Because the MD process is a thermally driven process, research on the development of heat transfer and mass transfer models that can comprehensively predict the properties of the manufactured ENMs based on various conditions (feed concentration, flow rate, temperature difference over the membrane, feed temperature pore-wetting, long period performance, membrane fouling, and so on) for various MD processes should be carried out.

Due to the nanofiber membrane’s intrinsic properties, they demonstrated their notable performances in seawater desalination and wastewater remediation.

Then, the membrane’s fabrication methods with excellent characteristics such as superhydrophobic, superomniphobic, and superoleophobic characteristics via electrospinning, especially the application and the structural design of these membranes in the MD process, were discussed. At present, composite dual-layer or multi-layer membranes, especially omniphobic membranes, are regarded as the only solution. Therefore, research should be performed extensively to develop a composite membrane using the omniphobic membrane as a hydrophobic layer. Nano-additives with hydrophobicity and hydrophilicity in composite membranes and omniphobic membranes endow better permeability, good salt rejection and excellent stability, and good antifouling performance by improving the hydrophobicity and hydrophilicity of the membrane, so research on the development of effective nano-additives is very important.

In this review, we also emphasize the importance of pre-treatment with the development of an optimally designed membrane. If the pre-treatment of chemical components and materials in the feed solution affecting the wetting of the membrane before applying the MD process is performed, the designed membrane can display its potential by reducing the wetting elements on the membrane. Studies on a suitable post-treatment method for the ENMs and a suitable pre-treatment for the feed solution of the MD should be performed in the future.

The development of ENMs with antiviral, antibacterial, antifouling properties, and efficient filtration properties from the continuously increasing water pollution and global coronavirus disease (COVID-19) pandemic has recently attracted great interest. By incorporating a functionalized filler with antibacterial and antiviral properties such as graphitic carbon nitride (g-C3N4), Ag nanoparticles, and tourmaline nanoparticles into the ENMs, the ENMs have high potential as an antibacterial and antiviral material for water purification, air filtration, and protective clothing while maintaining the nanoscale properties. Therefore, studies on preparing ENMs for producing distilled water from wastewater containing bacteria and viruses through the MD process should be conducted in the future.

The cost of manufacturing nanofibrous membrane through electrospinning technology on a laboratory scale is estimated at about $200/m2, which is affordable (Liu et al. 2022). Reducing the manufacturing cost of the ENMs is very important in expanding the application potential of the ENMs.

Nature provides excellent clues to thought and creative inspiration. Therefore, developing biomimetic approaches is very important to design and fabricate a more suitable membrane in the MD process.

The challenges mentioned above in fabricating nanofiber membranes are complicated; however, they will be solved. It is undeniable that with the rapid development of science and technology, ENMs manufactured with optimized design will display their enormous potential for addressing numerous emerging challenges to humankind, such as seawater desalination, metal removal from wastewater, and wastewater purification.

Abbreviations

MD: Membrane distillation; DCMD: Direct contact membrane distillation; AGMD: Air gap membrane distillation; VMD: Vacuum membrane distillation; SGMD: Sweeping gas membrane distillation; ES: Electrospinning; RO: Reverse osmosis; PP: Polypropylene; PVDF-HFP: Poly (vinylidene fluoride-co-hexafluoropropylene); PE: Polyethylene; PTFE: Polytetrafluoroethylene; PVDF: Polyvinylidene fluoride; PVA: Poly(vinyl alcohol); PAN: Polyacrylonitrile; PSF: Polysulfone; PVP: Poly(vinyl pyrrolidone); PET: Polyethylene terephhalate; THV: Copolymer of tetrafluoroethylene, hexafluoropropylene, and vinylidene fluoride; PVDF-HFP: Poly(vinylidene fluoride-co-hexafluoropropylene); PDMS: Polydimethylsiloxane; PMMA: Poly (methyl methacrylate); ENMs: Electrospun nanofiber membranes; SA: Sliding angle; CNTs: Carbon nanotubes; PEO: Polyethylene oxide; GO: Graphene oxide; SDS: Sodium dodecyl sulfate; NIPS: Non-solvent induced phase separation; NMP: N-methyl-2-pyrrolidone; DMAc: N, N-dimethyl acetamide; DMF: N, N-Dimethylformamide; LiCl: Lithium chloride; HTAB: Hexadecyl trimethyl ammonium bromide; LEP: Liquid entry pressure of water; WCA: Water contact angle; LEP: Liquid entry pressure; LMH: L/m2 h; NPs: Nanoparticles; AC: Activated carbon.
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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication The participant has consented to the submission of the study to the journal.

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References

Ahmed FE, Lalia BS, Hashaikheh R (2015) A review on electrospinning for membrane fabrication: challenges and applications. Desalination 356:15–30

Alkudhiri A, Darwish N, Hilal N (2013) Treatment of saline solutions using air gap membrane distillation: experimental study. Desalination 323:2–7. https://doi.org/10.1016/j.desal.2012.09.010

Alklaibi AM, Lior N (2004) Membrane-distillation desalination: status and potential. Desalination 171:111–131

Alklaibi AM, Noam L (2007) Comparative study of direct-contact and air-gap membrane distillation processes. Ind Eng Chem Res 46:584–590

Al-Mezrakchi RYH (2018) An investigation into scalability production of ultra-fine nanoﬁber using electrospinning systems. Fiber Polym 19:105–115. https://doi.org/10.1007/s12221-018-7506-z

An AK, Guo JX, Lee EJ, Jeong S, Zhao YH, Wang ZK, Leiknes T (2017) PDMS/PVDF hybrid electropspun membrane with superhydrophobic property and drop impact dynamics for dyeing wastewater treatment using membrane distillation. J Membrane Sci 525:57–67

An XC, Liu YZ, Hu YX (2018) Amphiphobic surface modification of electropspun nanofibrous membranes for anti-wettability performance in membrane distillation. Desalination 432:23–31

An XC, Bai YL, Xu GR, Xie BL, Hu YX (2020) Fabrication of interwoven hierarchical fibrous composite (iHFC) membranes for high-flux and robust direct contact membrane distillation. Desalination 477:8. https://doi.org/10.1016/j.desal.2019.114264

Anish Tuteja WC, Ma M, Mahry JM, Mazzella SA, Rutledge GC, McKinley GH, Cohen RE (2007) Designing superoleophobic surfaces. Science 318:1618–1622

Anish Tuteja WC, McKinley GH, Cohen RE, Rubner MF (2008) Design parameters for superhydrophobicity and superoleophobicity. Mrs Bull 33:752–758

Attia H, Alexander S, Wright CJ, Hilal N (2017) Superhydrophobic electropspun membrane for heavy metals removal by air gap membrane distillation (AGMD). Desalination 420:318–329

Attia H, Osman MS, Johnson DJ, Wright C, Hilal N (2017b) Modeling of air gap membrane distillation and its application in heavy metals removal. Desalination 424:27–36

Attia H, Johnson DJ, Wright CJ, Hilal N (2018) Comparison between dual-layer (superhydrophobic-hydrophobic) and single superhydrophobic layer electropspun membranes for heavy metal recovery by air-gap membrane distillation. Desalination 439:31–45

Attia H, Johnson DJ, Wright CJ, Hilal N (2018b) Robust superhydrophobic electropspun membrane fabricated by combination of electrospinning and electrospraying techniques for air gap membrane distillation. Desalination 446:70–82

Bhattacharya M (2016) Polymer nanocomposites—a comparison between carbon nanotubes, graphene, and clay as nanofillers. Materials 9:35. https://doi.org/10.3390/ma9040262

Bonyadi S, Chung TS (2007) Flux enhancement in membrane distillation by fabrication of dual layer hydrophilic-hydrophobic hollow fiber membranes. J Membrane Sci 306:134–146. https://doi.org/10.1016/j.memsci.2007.08.034

Boo C, Lee J, Elimelech M (2016) Omniphobic polyvinylidene fluoride (PVDF) membrane for desalination of saline gas produced water by membrane distillation. Environ Sci Technol 50:12275–12282

Burger C, Hsiao BS, Chu B (2006) Nanofibrous Materials and Their Applications. Annu Rev Mater Res 36:333–368

Butt H-J, Semprebon C, Papadopoulos P, Vollmer D, Brinkmann M, Ciccotti M (2013) Design principles for superamphiphobic surfaces. Soft Matter 9:418–428. https://doi.org/10.1039/c2sm27016a

Cai JC, Liu XH, Zhao YM, Guo F (2018) Membrane desalination using surface fluorination treated electropspun polycryliclontite membranes with nonwoven structure and quasi-parallel fibrous structure. Desalination 429:70–75

Cassie ABD, Baxter S (1944) Wettability of porous surfaces. Trans Faraday Soc 40:546–551

Cela E, Darmanin T, de Givenchy ET, Amigonis S, Guittard F (2013) Recent advances in designing superhydrophobic surfaces. J Colloid Interf Sci 402:1–18

Chen SF, Li LY, Zhao C, Zheng J (2010) Surface hydration: principles and applications toward low-fouling/nonfouling biomaterials. Polymer 51:5283–5293

Chen Y, Tian MM, Li XM, Wang YQ, An AK, Fang JH, He T (2017) Anti-wetting behavior of negatively charged superhydrophobic PVDF membranes in direct contact membrane distillation of emulsified wastewaters. J Membrane Sci 535:230–238

Cheng DYW, Wiersma SJ (1982) Composite membrane for a membrane distillation system. US 4,114,040

Cheng DYW, Wiersma SJ (1983) Composite membrane for a membrane distillation system. US 4,136,772

Chung SH, Wang Y, Persi L, Croce F, Greenbaum SG, Scrosati B, Pilchta E (2001) Enhancement of ion transport in polymer electrolytes by addition of nanoscale inorganic oxides. J Power Sources 97–8:644–648

Connor R (2012) Managing water under uncertainty and risk. In: The United Nations World Water Development Report 4, vol 1. UNESCO

Criscaulo A, Zhong J, Figoli A, Carnevale MC, Huang R, Drioli E (2008) Treatment of dye solutions by vacuum membrane distillation. Water Res 42:5031–5037

Dao TD, Meric JP, Laborie S, Cabassud C (2013) A new method for permeability measurement of hydrophobic membranes in vacuum membrane distillation process. Water Res 47:2096–2104. https://doi.org/10.1016/j.watres.2013.01.040
Environmental Science and Pollution Research (2022) 29:82632–82659

Deng L et al (2018) Self-roughened omniphobic coatings on nanofibrous membrane for membrane distillation. Sep Purif Technol 206:14–25

Deshmukh A et al (2018) Membrane distillation at the water-energy nexus: limits, opportunities, and challenges. Energ Environ Sci 11:1177–1196. https://doi.org/10.1039/c8ee00291f

Ding B, Kimura E, Sato T, Fujita S, Shiratori S (2004) Fabrication of blend biodegradable nanofibrous nonwoven mats via multi-jet electrospinning. Polymer 45:1895–1902

Dizge N, Shauleisky E, Karanikola V (2019) Electrospun cellulose nanofibers for superhydrophobic and oleophobic Membranes. J Membrane Sci 590:9. https://doi.org/10.1016/j.memsci.2019.117271

Dong ZQ, Ma XH, Xu ZL, Gu ZY (2015a) Superhydrophobic modification of PVDF-SiO2 electrosprun nanofiber membranes for vacuum membrane distillation. Rsc Adv 5:67962–67970

Dong ZQ, Wang BJ, Ma XH, Wei YM, Xu ZL (2015b) FAS grafted electrosin propy(vinyl alcohol) nanofiber membranes with robust superhydrophobicity for membrane distillation. Acs Appl Mater Inter 7:22652–22659. https://doi.org/10.1021/acsami.5b07454

Dow N et al (2016) Pilot trial of membrane distillation driven by low grade waste heat: membrane fouling and energy assessment. Desalination 391:30–40

Du YX et al (2019) Electrospun nanofibrous polyphenylene oxide membranes for high-salinity water desalination by direct contact membrane distillation. Acs Sustain Chem Eng 7:20060–20069. https://doi.org/10.1021/acsSusChem.9b05805

Ebrahimii A, Karimi M, Ashtiani FZ (2018) Characterization of triple electrospin layers of PVDF for direct contact membrane distillation process J Polym Res 25:10. https://doi.org/10.1007/s10965-017-1437-7

Edwie F, Teoh MM, Chung TS (2012) Effects of additives on dual-layer hydrophobic-hydrophilic PVDF hollow fiber membranes for membrane distillation and continuous performance. Chem Eng Sci 68:567–578

Efome JE, Rana D, Matsuura T, Lan CQ (2016) Enhanced performance of PVDF nanocomposite membrane by nanofiber coating: a membrane for sustainable desalination through MD. Water Res 89:39–49

El-Bourawi MS, Ding Z, Ma R, Khayet M (2006) A framework for better understanding membrane distillation separation process. J Membrane Sci 285:4–29

Elmarghany MR et al (2020) Triple-Layer nanocomposite membrane prepared by electrospinning based on modified PES with carbon nanotubes for membrane distillation. Appl Membranes-Basel 10:19. https://doi.org/10.3390/membranes10010015

Fang H, Gao JF, Wang HT, Chen CS (2012) Hydrophobic porous alumina hollow fiber for water desalination via membrane distillation process. J Membrane Sci 403:41–46

Feng C, Khulbe KC, Matsuura T, Gopal R, Kaur S, Ramakrishna S, Khayet M (2008) Production of drinking water from saline water by air-gap membrane distillation using polyvinylidene fluoride nanofiber membrane. J Membrane Sci 311:1–6. https://doi.org/10.1016/j.memsci.2007.12.026

Gryta M (2008) Fouling in direct contact membrane distillation process. J Membrane Sci 325:383–394. https://doi.org/10.1016/j.memsci.2008.08.001

Gryta M, Baranczewicz M (2010) Influence of morphology of PVDF capillary membranes on the performance of direct contact membrane distillation. J Membrane Sci 358:158–167. https://doi.org/10.1016/j.memsci.2010.04.044

Gundogdu NAS, Akgul Y, Kilic A (2018) Optimization of centrifugally spun thermoplastic polyurethane nanofibers for air filtration applications. Aerosol Sci Tech 52:515–523. https://doi.org/10.1080/0278682X.2018.1433813

Guo F, Servi A, Liu AD, Gleason KK, Rutledge GC (2015a) Desalination by membrane distillation using electrosprun polyamide fiber membranes with surface fluorination by chemical vapor deposition. Acs Appl Mater Inter 7:8225–8232

Guo YD, Tang DY, Zhao EQ, Yu ZQ, Lv HT, Li XY (2015b) Controlled synthesis of amphiphilic graft copolymer for superhydrophobic electrosprun fibres with effective surface fluoro enrichment: the role of electric field and solvent. Rsc Adv 5:82789–82799

Guo JX, Deka BJ, Kim KJ, An AK (2019) Regeneration of superhydrophobic TiO2 electrosprun membranes in seawater desalination by water flushing in membrane distillation. Desalination 468:10. https://doi.org/10.1016/j.desal.2019.06.020

Hou DY, Wang J, Qu D, Luan ZK, Zhao CW, Ren XJ (2010) Desalination of brackish groundwater by direct contact membrane distillation. Water Sci Technol 61:2013–2020

Hou D, Lin D, Zhao C, Wang J, Fu C (2017) Control of protein (BSA) fouling by ultrasonic irradiation during membrane distillation process. Sep Purif Technol 175:287–297. https://doi.org/10.1016/j.seppur.2016.11.047

Hou DY, Wang ZX, Wang KP, Wang J, Lin SH (2018) Composite membrane with electrosprun multiscale-textured surface for robust oil-fouling resistance in membrane distillation. J Membrane Sci 546:179–187

Hou D, Ding C, Fu C, Wang D, Zhao C, Wang J (2019) Electrosprun nanofibrous omniphobic membrane for anti-surfactant-wetting membrane distillation desalination. Desalination 468 https://doi.org/10.1016/j.desal.2019.07.008

Hu XL, Zhang X, Shen XD, Li HT, Takai O, Saito N (2014) Plasma-induced synthesis of CuO Nanofibers and ZnO Nanoflowers in Water. Plasma Plasma Chem Process 34:1129–1139. https://doi.org/10.1007/s11090-014-9546-0

Jafari A, Kebrba MRS, Rahimpour A, Beker G (2018) Graphene quantum dots modified poly(vinylidene fluoride) (PVDF) nanofibrous membranes with enhanced performance for air gap membrane distillation. Chem Eng Process 126:222–231

Jiaming Zhu LJ (2015) New insights into fabrication of hydrophobic/hydrophilic composite hollow fibers for direct contact membrane distillation. Chem Eng Sci 137:79–90. https://doi.org/10.1016/j.ces.2015.05.064

Jiao L, Yan KK, Wang J, Lin SS, Li G, Bi F, Zhang L (2020) Low surface energy nanofibrous membrane for enhanced wetting resistance in membrane distillation process. Desalination 476:8. https://doi.org/10.1016/j.desal.2019.114210

Joachim Koschikowski MW (2003) Solar thermal-driven desalination plants based on membrane distillation. Desalination 156:295–304

Jongho Lee CB, Ryu W-H, Taylor AD, Elimelech M (2016) Development of omniphobic desalination membranes using a charged electrosprun nanofiber scaffold. Acs Appl Mater Inter 8:11154–11161. https://doi.org/10.1021/acsami.6b02419

Khalfia AE, Alawad SM (2018) Air gap and water gap multistage membrane distillation for water desalination. Desalination 437:175–183

Khayet M, Garcia-Payo MC, Garcia-Fernandez L, Contreras-Martinez J (2018) Dual-layered electrosprun nanofibrous membranes for membrane distillation. Desalination 426:259–304

Khayet M, Garcia-Payo C, Matsuura T (2019) Superhydrophobic nanofibers electrosprun by surface segregating fluorinated amphiphilic additive for membrane distillation. J Membrane Sci 588:11. https://doi.org/10.1016/j.memsci.2019.117215

Koh E, Lee YT (2021) Preparation of an omniphobic nanofiber membrane by the self-assembly of hydrophobic nanoparticles for membrane distillation. Sep Purif Technol 259https://doi.org/10.1016/j.seppur.2020.118154
Noel Dow JVG, Niaadlo L, Milne N, Zhang J, Gray S, Duke M (2017) Demonstration of membrane distillation on textile waste water: assessment of long term performance, membrane cleaning and waste heat integration. Environ Sci-Water Res Technol 3:433–449

Nthinuya LN, Gutierrez L, Verliefde AR, Mhlanga SD (2019) Enhanced flux in direct contact membrane distillation using superhydrophobic PVDF nanofibre membranes embedded with organically modified SiO2 nanoparticles. J Chem Technol Biot 94:2826–2837

Olawale M, Ahmed F, Janajreh I, Hashaikhe R (2019) Development of a dual-layered PVDF-HFP/cellulose membrane with dual wettability for desalination of oily wastewater. J Membrane Sci 570–571:418–426. https://doi.org/10.1016/j.memsci.2018.10.028

Pan C-Y, Xu G-R, Xu K, Zhao H-L, Wu Y-Q, Su H-C, Xu J-M, Dasb R (2019) Electrosprun nanofibrous membranes in membrane distillation: recent developments and future perspectives. Sep Purif Technol 221:44–63. https://doi.org/10.1016/j.seppur.2019.03.080

Peng P, Fane AG, Li XD (2005) Desalination by membrane distillation adopting a hydrophilic membrane. Desalination 173:45–54

Peng Y, Ge J, Li Z, Wang S (2015) Effects of anti-scaling and cleaning chemicals on membrane scale in direct contact membrane distillation process for RO brine concentrate. Sep Purif Technol 154:22–26. https://doi.org/10.1016/j.seppur.2015.09.007

Persano L, Campeseo A, Tekmen C, Pisignano D (2013) Industrial upscaling of electrosprinnning and applications of polymer nanofibers: a review. Macromol Mater Eng 298:504–520

Polat Y, Pampal ES, Stojanovska E, Simsek R, Hassanin A, Kilic A, Demir A, Yilmaz S (2016) Solution blowing of thermoplastic polyurethane nanofibers: a facile method to produce flexible porous materials. J Appl Polym Sci 133:9. https://doi.org/10.1002/app.43025

Prince JA, Singh G, Rana D, Matsuru T, Anbarhiasi V, Shanmugasundarm TS (2012) Preparation and characterization of highly hydrophobic poly(vinylidene fluoride) - clay nanocomposite nanofiber membranes (PVDF-clay NNM) for desalination using direct contact membrane distillation. J Membrane Sci 397:80–86

Prince JA, Anbarhiasi V, Shanmugasundaram TS, Singh G (2013) Preparation and characterization of novel triple layer hydrophilic-hydrophobic composite membrane for desalination using air gap membrane distillation. Sep Purif Technol 118:598–603

Prince JA, Rana D, Matsuru T, Ayyanar N, Shanmugasundaram TS, Singh G (2014) Nanofiber based triple layer hydrophobic-hydrophilic membrane - a solution for pore wetting in membrane distillation. Sci Rep-Uk 4:6. https://doi.org/10.1038/srep09049

Qian BT, Shen ZQ (2005) Fabrication of superhydrophobic surfaces by dislocation-selective chemical etching on aluminum, copper, and zinc substrates. Langmuir 21:9007–9009

Qing W et al (2020) Omniphobic PVDF nanofibrous membrane for superior anti-wetting performance in direct contact membrane distillation. J Membrane Sci 608 https://doi.org/10.1016/j.memsci.2020.118226

Quaismat M, Khayet M, Matsura T (2009) Guidelines for preparation of higher flux hydrophilic/hydrophobic composite membranes for membrane distillation. J Membrane Sci 329:193–200

Ravi J, et al (2020) Polymeric membranes for desalination using membrane distillation: a review. Desalination 490 https://doi.org/10.1016/j.desal.2020.114530

Ren LY, Ozisik R, Kotha SP (2014) Rapid and efficient fabrication of multilevel structured silica micro-/nanofibers by centrifugal jet spinning. J Colloid Interf Sci 425:136–142

Ren LF, Xia F, Chen V, Shao JH, Chen R, He YL (2017) TiO2-FTCS modified superhydrophobic PVDF electrosprun nanofibrous membrane for desalination by direct contact membrane distillation. Desalination 423:1–11

Ren LF, Xia F, Shao JH, Zhang XF, Li J (2017b) Experimental investigation of the effect of electrosprinning parameters on properties of superhydrophobic PDMS/PMMMA membrane and its application in membrane distillation. Desalination 404:155–166

Rezaei M, Warsinger DM, Lienhard JH, Duke MC, Matsuru T, Samhaber WM (2018) Wetting phenomena in membrane distillation: mechanisms, reversal, and prevention. Water Res 139:329–352

Roy Y, Warsinger DM, Lienhard JH (2017) Effect of temperature on ion transport in nanofiltration membranes: diffusion, convection and electromigration. Desalination 420:241–257. https://doi.org/10.1016/j.desal.2017.07.020

Saikat SR, Chen S-S, Li C-W, Nguyen NC, Nguyen HT (2016) A comprehensive review: electrosprinning technique for fabrication and surface modification of membranes for water treatment application. Rsc Adv 6:85495–85514. https://doi.org/10.1039/C6RA14952A

Salem H, Trabzon L, Kilic A, Zaidi SJ (2020) Recent advances in nanofibrous membranes: production and applications in water treatment and desalination. Desalination 478:40. https://doi.org/10.1016/j.desal.2019.114178

Sarbatly R, Chiam CK (2013) Evaluation of geothermal energy in desalination by vacuum membrane distillation. Appl Energ 112:737–746

Schlaich C, Carnacho LC, Yu LX, Achazi K, Wei Q, Haag R (2016) Surface-independent hierarchical coatings with superamphiphobic properties. Ac Appl Mater Inter 8:29117–29127. https://doi.org/10.1021/acsami.6b08487

Schneider K, van Gassl JT (1984) Membranedestillation. Chemie Ingenieur Technik 56:514–521

Shan HT, Liu J, Li XP, Li Y, Tezel FH, Li BA, Wang SC (2018) Nano-coated amphiphobic membrane for flux enhancement and comprehensive anti-fouling performance in direct contact membrane distillation. J Membrane Sci 567:166–180

Shengjie Peng GJ, Li L, Zhang J, Chen J (2016) Multi-functional electrosprun nanofibres for advances in tissue regeneration, energy conversion & storage, and water treatment. Chem Soc Rev 45:1225–1241. https://doi.org/10.1039/c5cs01577f

Shirazi MMA, Kargari A, Tabatabaei M (2014) Comprehensive review: electrospinning technique for fabrication and comprehensive anti-fouling performance in direct contact membrane distillation. Rsc Adv 4:155–166

Shukla AK et al (2018) Removal of heavy metal ions using a carboxylic-functionalized nanofibrous membrane. J Environ Sci 404:155–166

Shukla AK, Alam J, Ansari MA, Alhoshan M, Alam M, Kaushik A (2019) Selective ion removal and antibacterial activity of silver-doped multi-walled carbon nanotube/polyphenylsulfone nanocomposite membranes. Mater Chem Phys 233:102–112. https://doi.org/10.1016/j.matchemphys.2019.05.054
Su CI, Shih JH, Huang MS, Wang CM, Shih WC, Liu YS (2012) A study of hydrophobic electrospray membrane applied in seawater desalination by membrane distillation. Fiber Polym 13:698–702

Su CL et al (2018) Fabrication and post-treatment of nanofibers-covered hollow fiber membranes for membrane distillation. J Membr Sci 562:38–46

Su CL, Li YP, Cao HB, Lu C, Li YJ, Chang JJ, Duan F (2019) Novel PTFE hollow fiber membrane fabricated by emulsion electrospinning and sintering for membrane distillation. J Membrane Sci 583:200–208

Su QW, Zhang YJ, Zhang LZ (2020) Fouling resistance improvement with a new superhydrophobic electrospray PVDF membrane for seawater desalination. Desalination 476:15. https://doi.org/10.1016/j.desal.2019.114246

Suja PS, Reshmi CR, Sagitha P, Sujith A (2017) Electrospun nanofibrous membranes for water purification. Polymer Rev 57:467–504. https://doi.org/10.1080/15583724.2017.1309664

Tadanaga K, Kitamura K, Matsuda A, Minami T (2003) Formation of superhydrophobic alumina coating films with high transparency on polymer substrates by the sol-gel method. J Sol-Gel Sci Techn 26:705–708

Tian Y, Jiang L (2013) WETTING: intrinsically robust hydrophobicity. Nat Mater 12:291–292

Tian MM et al (2015) CF4 plasma modified highly interconnective porous polysulfone membranes for direct contact membrane distillation (DCMD). Desalination 369:105–114

Tijing LD, Choi JS, Lee S, Kim SH, Shon HK (2014a) Recent progress of membrane distillation using electrospray nanofibrous membrane. J Membrane Sci 453:435–462

Tijing LD, Woo YC, Johir MAH, Choi J-S, Shon HK (2014b) A novel dual-layer bicomponent electrospun nanofibrous membrane for desalination by direct contact membrane distillation. Chem Eng J 256:155–159. https://doi.org/10.1016/j.cej.2014.06.076

Tilili I, Alkanhal TA (2019) Nanotechnology for water purification: electrospun nanofibrous membrane in water and wastewater treatment. J Water Reuse Desal 9:232–248

Tomaszewska M, Gryta M, Morawski AW (1995) Study on the concentration of acids by membrane distillation. J Membr Sci 102(1995):113–122

Tun LL, Jeong D, Jeong S, Cho K, Lee S, Bae H (2016) Dewatering of source-separated human urine for nitrogen recovery by membrane distillation. J Membrane Sci 512:13–20

Tuteja A, Choi W, Mahy JM, McKinley GH, Cohen RE (2008) Robust omniphobic surfaces. P Natl Acad Sci USA 105:18200–18205

Vogler EA (1998) Structure and reactivity of water at biomaterial surfaces. Adv Colloid Interfac 74:69–117

Wang P, Chung TS (2013) A new-generation asymmetric multi-bore hollow fiber membrane for sustainable water production via vacuum membrane distillation. Environ Sci Technol 47:6272–6278

Wang P, Chung TS (2015) Recent advances in membrane distillation processes: membrane development, configuration design and application exploring. J Membrane Sci 474:39–56

Wang XF, Ding B, Yu JY, Wang MR (2011) Engineering biomimetic superhydrophobic surfaces of electrospray nanomaterials. Nano Today 6:510–530

Wang N et al (2013) Tailored fibro-porous structure of electrospray polyurethane membranes, their size-dependent properties and trans-membrane glucose diffusion. J Membrane Sci 427:207–217

Wang X, Yu J, Sun G, Ding B (2016) Electrospray nanofibrous materials: a versatile medium for effective oil/water separation. Mater Today 19:403–414. https://doi.org/10.1016/j.mattod.2015.11.010

Wang ZX, Elimelech M, Lin SH (2016) Environmental applications of interfacial materials with special wettability. Environ Sci Technol 50:2132–2150

Woo YC et al (2016) Water desalination using graphene-enhanced electrospray nanofiber membrane via air gap membrane distillation. J Membrane Sci 520:99–110

Woo YC et al (2017) Electrospray dual-layer nonwoven membrane for desalination by air gap membrane distillation. Desalination 403:187–198

Yalcinkaya F (2019) A review on advanced nanofiber technology for membrane distillation. J Eng Fiber Fabr 14:12. https://doi.org/10.1177/1558925018824901

Yan JJ, Shao SF, Wang JH, Liu JP (2007) Improvement of a multi-stage flash seawater desalination system for cogeneration power plants. Desalination 217:191–202

Yang HC, Hou J, Chen V, Xu ZK (2016) Janus membranes: exploring duality for advanced separation. Angew Chem Int Edit 55:13398–13407

Yang HC, Zhong WW, Hou JW, Chen V, Xu ZK (2017) Janus hollow fiber membrane with a mussel-inspired coating on the lumen surface for direct contact membrane distillation. J Membrane Sci 523:1–7

Yao MW, Tijing LD, Naidu G, Kim SH, Matsuyama H, Fane AG, Shon HK (2020) A review of membrane wettability for the treatment of saline water deploying membrane distillation. Desalination 479:22. https://doi.org/10.1016/j.desal.2020.114312

Yuan Liaolong C-HL, Tian M, Wang R, Fane AG (2018) Progress in electrospray polymeric nanofibrous membranes for water treatment: fabrication, modification and applications. Prog Polym Sci 77:69–94. https://doi.org/10.1016/j.progpolymsci.2017.10.003

Zarebska A, Nieto DR, Christensen KV, Nordahl B (2014) Ammonia recovery from agricultural wastes by membrane distillation: fouling characterization and mechanism. Water Res 56:1–10

Zhang X, Shi F, Niu J, Jiang YG, Wang ZQ (2008) Superhydrophobic surfaces: from structural control to functional application. J Mater Chem 18:621–633

Zhang Y, Yang B, Li KL, Hou DY, Zhao CW, Wang J (2017) Electrospray porous poly(tetrafluoroethylene-co-hexafluoropropylene-co-vinylidene fluoride) membranes for membrane distillation. Rsc Adv 7:56183–56193

Zhou L, Tan SH, Ahmad AL, Low SC (2021) High-flux strategy for electrospun nanofibers in membrane distillation to treat seawater desalination. Desalination 476:15. https://doi.org/10.1016/j.desal.2020.114312

Zhao LH, Wu CR, Lu XL, Ng D, Truong YB, Xie ZL (2018) Activated carbon enhanced hydrophobic/hydrophilic dual-layer nanofiber composite membranes for high-performance direct contact membrane distillation. Desalination 446:59–69

Zhao LH, Wu CR, Lu XL, Ng D, Truong YB, Zhang JH, Xie ZL (2020) Theoretical guidance for fabricating higher flux hydrophobic/hydrophilic dual-layer membranes for direct contact membrane distillation. J Membrane Sci 596:11. https://doi.org/10.1016/j.memsci.2019.117608

Zheng R, Chen Y, Wang J, Song JF, Li XM, He T (2018) Preparation of omniporous PVDF membrane with hierarchical structure for treating saline oily wastewater using direct contact membrane distillation. J Membrane Sci 555:197–205

Zhong LL et al (2019) One-step nanotopography construction by polyaniline polymerization for a superhydrophobic nanofibrous membrane towards direct contact membrane distillation. Environ Sci-Nano 6:2553–2564

Zhou FL, Gong RH, Porat I (2009) Mass production of nanofibre assemblies by electrostatic spinning. Polym Int 58:331–342

Zou H, Yao YY, Xiang RL, Wu YR (2014) Formation and characterization of polytetrafluoroethylene nanofiber membranes for vacuum membrane distillation. J Membrane Sci 453:402–408

Zhou L, Tan SH, Ahmad AL, Low SC (2021) High-flux strategy for electrospun nanofibers in membrane distillation to treat...
aquaculture wastewater: a review. J Chem Technol Biotechnol 96:3259–3272. https://doi.org/10.1002/jctb.6828
Zhou T, Zhong Q, Li J, Yao Y, Xiang R, Zhu P (2020) Superhydrophobic polytetrafluoroethylene nanofiber membranes prepared by vacuum sintering and their application in vacuum membrane distillation. J Appl Polym Sci 137 https://doi.org/10.1002/app.49060

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