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NONWOVEN MEMBRANES FOR SEAWATER DESALINATION: STRUCTURAL DESIGN, FUNCTIONALIZATION STRATEGIES, AND SYSTEM-LEVEL PERFORMANCE

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ABSTRACT

Nonwoven materials, characterized by high porosity, tunable fiber architecture, robust mechanical strength, and versatile surface functionalizability, have emerged as highly promising platforms for next-generation seawater desalination. This review comprehensively examines the structural design strategies and performance-regulation mechanisms of nonwoven membranes across major desalination technologies, including reverse osmosis (RO), forward osmosis (FO), membrane distillation (MD), and solar-driven interfacial evaporation (SIE). Particular emphasis is placed on the synergistic influence of fiber diameter, orientation, porosity, and multilayer composite configurations in determining key performance metrics, including water flux, salt rejection, wetting resistance, antifouling behavior, and long-term operational stability. Furthermore, we summarize recent advances in nonwoven fabrication techniques, including melt blowing, electrospinning, and centrifugal spinning, and discuss their integration with emerging functionalization approaches such as plasma modification, nanoparticle and 2D-material incorporation, polymer blending, and sustainable bio-based materials. By aligning nonwoven material design with the physicochemical requirements of different desalination pathways, this review highlights the technological potential of nonwoven membranes to enable high-efficiency, low-carbon, and environmentally sustainable desalination systems.

KEYWORDS: nonwoven material; seawater desalination; polymer composite; porous structure; surface functionalization

1. INTRODUCTION

Freshwater and energy are fundamental prerequisites for human survival and socio-economic development, yet readily accessible freshwater resources remain critically limited despite water covering nearly 70% of the Earth's surface. Less than 2.5% of global water is freshwater, and its distribution is highly uneven: ~68.7% is locked in glaciers and permanent snowpacks in remote polar regions, ~30.1% resides as deep groundwater with extremely slow recharge rates, and only a fraction, including shallow groundwater (~0.76%), surface water in lakes and rivers (~0.26%), and soil moisture and atmospheric vapor (~0.18%), is directly accessible for human use[1-3].Consequently, ***less than 1% of freshwater is available to support domestic, agricultural, and industrial demands***, a scarcity intensified by population growth, pollution, climate change, and expanding societal infrastructure, thereby making efficient freshwater acquisition with minimal energy consumption an urgent global priority[4, 5].

Given the vastness of seawater, desalination has become an increasingly indispensable strategy for augmenting freshwater supplies[6]. Rapid advancements in desalination technologies, particularly RO, MD, FO, and emerging SIE systems, have significantly improved desalination efficiency, though persistent challenges remain, including energy intensity, membrane fouling, wetting resistance, and brine management[7]. Across these technologies, nonwoven membranes have become essential

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functional components due to their high porosity, tunable architecture, mechanical strength, and ease of surface modification, enabling enhanced water transport, anti-wetting behavior, antifouling performance, and operational durability[8-10].

Although many reviews focus on membrane technologies for desalination applications[11, 12], there are limited efforts that focus on structure–property–process correlations in nonwovens (e.g., fiber diameter, alignment, and pore connectivity), as well as their scalability and integration with renewable energy systems. Sustainability considerations, such as bio-based nonwovens, recyclability, and life-cycle carbon impacts, also remain underexplored. To address these gaps, this review systematically evaluates the multi-scenario adaptability of nonwoven materials across RO, FO, MD, SIE, and emerging desalination platforms; elucidates how fiber-scale features, pore architecture, wettability, and hierarchical multilayer configurations dictate performance under distinct separation mechanisms; and highlights how advanced manufacturing (electrospinning, meltblowing), functionalization (nanocomposites, plasma treatment, Janus designs), and materials-level co-design can advance next-generation desalination systems. Most importantly, we outline future opportunities, including stimuli-responsive "smart" membranes, digital-twin-guided optimization, renewable energy coupling, and circular economy-aligned green fabrication, to establish a coherent materials design paradigm and technological roadmap for high-efficiency, low-carbon, and sustainable desalination. **Figure 1** shows the schematic diagram of seawater desalination technology.

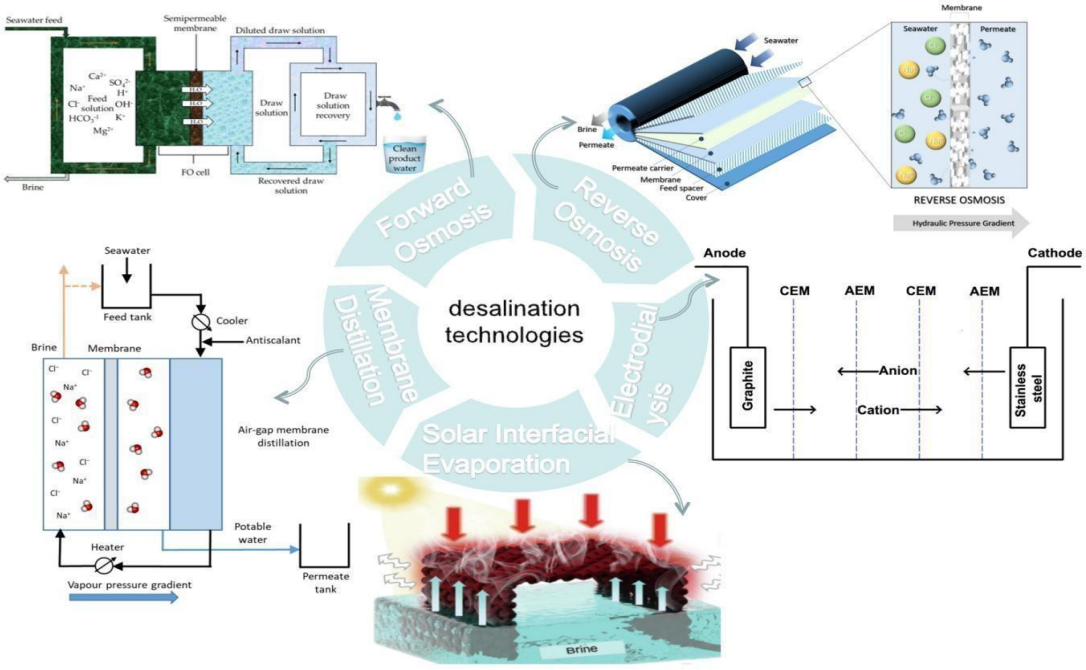

Figure 1. Seawater desalination technology schematic diagram [13-17].

2. FUNDAMENTALS OF NONWOVEN MEMBRANES FOR SEAWATER DESALINATION 2.1 STRUCTURAL CHARACTERISTICS

Nonwoven membranes are highly porous, fiber-based materials produced by consolidating randomly oriented or directionally aligned polymer fibers into a stable network, and they are widely fabricated from polymers such as polypropylene (PP), polyvinylidene fluoride (PVDF), polyester (PET), and other engineering plastics whose surface chemistry can be finely tuned through grafting, plasma activation, or functional ligand incorporation[18, 19]. Their performance in seawater desalination is governed by key structural parameters, including fiber diameter, specific surface area, pore-size distribution, total porosity, tortuosity, and membrane thickness, which can be engineered through processing routes such as meltblowing, electrospinning[20], or solution blowing to meet the flow, wetting, and mechanical demands of specific desalination technologies[21]. The ability to rationally tailor microstructural features (e.g., fiber orientation, inter-fiber bonding, pore connectivity) and macrostructural configurations (e.g., gradient or multilayer architectures, hierarchical porosity) enables

optimization of functional properties such as water permeation flux, vapor transport resistance, salt rejection, mechanical robustness, thermal stability, and fouling or wetting resistance. These structural–functional relationships are especially essential for advanced desalination methods, such as MD, FO, and SIE, where precise control over hydrophobicity, capillary pressure, heat localization, and mass-transfer pathways determines long-term operational stability.

2.1.1 FIBER DIAMETER AND ARRANGEMENT

The fiber diameter and spatial arrangement within nonwoven membranes are fundamentally dictated by the membrane fabrication method, as different web-forming and bonding techniques, such as spunbonding, meltblowing, and electrospinning, produce fibers over distinct dimensional scales and with characteristic three-dimensional architectures. Electrospinning, for example, enables the production of ultrafine fibers with diameters from tens of nanometers to approximately one micrometer[22, 23] , yielding highly interconnected networks with narrow pore-size distributions, large specific surface areas, and enhanced capillary and interfacial control[24-26]. The use of specialized collectors, such as high-speed rotating drums or patterned electrodes, can further induce partial or highly oriented fiber alignment[27], generating straight or low-tortuosity pore channels that reduce mass-transfer resistance and benefit processes such as MD or solar-driven evaporation. By contrast, spunbonded and meltblown nonwovens typically consist of randomly deposited microfibers, forming mechanically robust webs with high porosity yet more tortuous pore pathways that may impede efficient vapor or water transport. These structural distinctions, ranging from nanoscale fiber diameters to mesoscale orientation and macroscopic web architecture, critically influence membrane wettability, permeability, mechanical integrity, and overall desalination performance.

2.1.2 POROSITY

Porosity is a central structural parameter governing the performance of nonwoven membranes, and under identical fiber diameters and fabrication conditions, the spatial arrangement of fibers plays a decisive role in determining the overall void fraction. As demonstrated by Liu et al. [19], randomly oriented fiber networks exhibit substantially higher porosity than quasiparallel fiber (QPF) architectures due to predominant point contacts and a more open, loosely packed morphology, whereas QPF membranes form line contacts between aligned fibers that reduce pore volume and limit permeability. High-porosity nonwovens with 3D interconnected pore networks also display superior resistance to hydraulic compression, making them particularly advantageous for thermally or osmotically driven desalination processes, such as MD and FO, where efficient vapor or liquid transport requires minimal mass-transfer resistance [28, 29]. For desalination applications more broadly, achieving high porosity and large specific surface area enhances the membrane–water interfacial area, promotes capillary-driven liquid uptake,accelerates vapor diffusion, and facilitates surface functionalization[30]. These attributes are especially critical in interfacial evaporation or vapor-driven processes, such as MD and SIE, where interconnected pores provide multiple low-tortuosity escape pathways for vapor, minimize internal vapor pressure buildup, suppress premature condensation, and sustain rapid water transport [31-33].

2.1.3 MULTILAYERS

Multilayer nonwoven membranes have emerged as an essential materials platform for seawater desalination, offering modular, functionally graded architectures that overcome many of the intrinsic limitations of traditional single-layer polymeric membranes, such as the permeability–selectivity trade-off, susceptibility to fouling, structural collapse under hydraulic compression, and insufficient mechanical or thermal stability under high salinity, elevated temperature, or high-pressure conditions.

Fabricated through hybrid multistep approaches, the hierarchical structures enable the synergistic integration of mechanical reinforcement, optimized mass-transport pathways, tailored wettability, and enhanced chemical or photothermal functionalities. As a result, multilayer nonwoven composites are now widely employed across various desalination technologies, including MD, SIE, RO, and electrodialysis (ED), each of which imposes distinct structural and interfacial requirements based on its underlying separation mechanism. For example, MD relies on a vapor-pressure gradient across a hydrophobic porous membrane and therefore demands a composite design comprising (i) a mechanically robust hydrophilic support layer (e.g., PET or PP) for feed distribution, (ii) a moderately hydrophobic intermediate layer (e.g., meltblown PP or PVDF) to balance strength and vapor transport, and (iii) a superhydrophobic nanofibrous top layer, often electrospun from fluorinated PVDF or polytetrafluoroethylene (PTFE), to maintain liquid entry pressure (LEP) and ensure high vapor flux[8, 34, 35].

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In SIE systems, multilayer membranes serve primarily as hydrophilic water-transport scaffolds and photothermal platforms, typically adopting a tri-layer arrangement with a buoyant support, a highly hydrophilic intermediate layer (e.g., modified cellulose or PET) to ensure continuous capillary-driven supply, and a photothermal functional layer incorporating lightabsorbing nanomaterials (e.g., CNTs, graphene, or MXenes) to localize heat at the air–water interface[36]. In RO, the nonwoven fabric functions exclusively as a mechanical substrate, supporting a polysulfone (PSf) interlayer that smooths the surface for defect-free formation of the ultrathin polyamide (PA) selective layer while mitigating internal concentration polarization (CP); insufficient hydrophilicity in this interlayer would compromise PA crosslinking, leading to lower flux and poorer salt rejection[37, 38]. For ED, nonwoven structures can be engineered as ion-selective spacers or porous separators by tuning fiber diameter, surface charge, and thickness to reduce ohmic resistance and energy consumption, providing a low-cost alternative to conventional ion-exchange membranes[39].

2.2 PERFORMANCE PARAMETERS

2.2.1 HYDROPHOBICITY AND CONTACT ANGLE

Hydrophobicity is a critical performance parameter for nonwoven membranes used in seawater desalination, particularly in vapor-driven processes such as MD. Membrane hydrophobicity is commonly enhanced through two complementary strategies: (1) chemical modification, including fluorination, silanization, or grafting of low-surface-energy ligands[40-43], and (2) structural engineering that introduces micro- or nanoscale surface roughness[44, 45]. When hierarchical roughness forms groove-like or reentrant topologies, trapped air pockets reduce the effective solid–liquid interfacial area, causing water droplets to rest in the Cassie–Baxter state rather than fully penetrating the surface texture. This state enables the formation of superhydrophobic surfaces with water contact angles typically exceeding 150°, which dramatically improves the membrane's resistance to wetting and pore intrusion under high salinity or elevated-temperature conditions[46].

Beyond surface chemistry and roughness, pore size and pore-size distribution strongly influence the wetting stability of hydrophobic nonwoven membranes. Larger pores generally reduce LEP, making membranes more vulnerable to wetting; however, when LEP is sufficiently maintained through high hydrophobicity or hierarchical structuring, a moderate increase in pore size can substantially enhance vapor transport by lowering mass-transfer resistance[47]. This interplay between LEP, pore geometry, and surface hydrophobicity underscores the importance of joint optimization rather than single-parameter design. Recent work illustrates that membranes engineered with high water contact angles (>150°) and well-tuned pore structures can simultaneously achieve exceptional anti-wetting stability and high flux. For example, Liu et al.[19] reported that such synergistic structural–functional design reduced the unit cost of freshwater production in MD by nearly 70%, demonstrating the significant economic and operational advantages of integrated materials engineering in desalination applications. The finding highlights that hydrophobicity is not merely a surface property but a multi-scale design criterion that spans surface chemistry, fiber morphology, pore architecture, and thermodynamic stability.

2.2.2 WATER FLUX AND SALT REJECTION

Water flux is a fundamental indicator of freshwater production capacity in membrane-based desalination technologies, and it is governed by a coupled interplay of membrane microstructure, surface chemistry, and operating conditions. Nonwoven membranes—distinguished by their high porosity (typically >70%), 3D interconnected fibrous networks, and tunable hierarchical architectures, offer substantially lower mass-transfer resistance compared to conventional phase-inversion membranes[48]. This structural openness enables superior vapor or liquid permeability, particularly in thermally driven processes such as direct contact MD (DCMD). Prior studies have demonstrated that DCMD water flux increases nearly linearly with enhanced surface hydrophobicity and appropriately enlarged pore size, provided that the LEP remains sufficiently high to prevent pore intrusion[49, 50].

Experimental evidence further highlights the intrinsic advantages of nonwoven architectures. Wang et al.[51] developed a superhydrophobic electrospun poly(vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP) membrane with an average pore size of 0.45 μm and a porosity of 88%. Under DCMD conditions using a 3.5 wt.% NaCl feed at 60 °C and a permeate at 20 °C, the membrane achieved a stable water flux of 52.3 $L \cdot m^{-2} \cdot h^{-1}$, exceeding the performance of commercial PTFE and PP membranes (30–40 $L \cdot m^{-2} \cdot h^{-1}$) tested under the same conditions. Impressively, this flux was maintained for over 100 hours without observable wetting, attributed to the synergistic effects of fluorination-induced low surface energy, high porosity, and hierarchical nano/micro-scale surface roughness that reinforced the Cassie–Baxter wetting state.

Despite these advantages, the pursuit of ultra-high flux must be balanced against wetting resistance. Larger pore sizes and thinner membrane designs reduce mass-transport resistance but also lower LEP, increasing the risk of wetting when exposed to seawater containing surfactants, oils, or natural organic matter. Liu et al.[52] demonstrated that increasing the average pore size of meltblown PP nonwovens from 0.3 μm to 0.8 μm enhanced the DCMD flux by ~60% but simultaneously reduced the LEP from 110 kPa to 45 kPa, rendering the membrane significantly more susceptible to pore flooding under realistic conditions. These findings underscore the delicate balance between permeability and stability that must be maintained in desalination membrane design.

To overcome this trade-off, recent research has focused on graded multilayer architectures that decouple mechanical support, pore structure, and wetting resistance within a single composite membrane[10, 53, 54]. In such configurations, a mechanically robust microporous support layer provides structural integrity, while an ultrathin (<5 μm) electrospun top layer with submicron pores and superhydrophobicity (contact angle >150°) ensures high LEP and minimal vapor transport resistance. These engineered multilayer systems have achieved water fluxes exceeding 60 $L \cdot m^{-2} \cdot h^{-1}$ with near-perfect salt rejection (>99.99%) in laboratory-scale MD setups [37, 54, 56].

2.2.3 MECHANICAL STRENGTH

Mechanical strength is a key determinant of membrane durability and operational reliability[57] in seawater desalination, particularly because membranes are routinely exposed to harsh environments that involve high hydraulic pressures, elevated temperatures, thermal cycling, and abrasive particulate or biological fouling. In multilayer membrane systems, mechanical robustness is unevenly distributed across layers. Fatima Ghassan Alabtah et al.[58] demonstrated that thin-film composite (TFC) membranes derive the majority of their structural integrity from the PET nonwoven backing, whereas the intermediate PSf layer and the ultrathin PA selective layer possess fracture stresses that are typically an order of magnitude lower. Such mechanical anisotropy underscores the critical role of the nonwoven substrate in supporting filtration layers during fabrication and longterm operation.

Nonwoven supports produced via spunbonding, meltblowing, or electrospinning offer distinct mechanical advantages due to their interconnected fibrous networks, which accommodate deformation through fiber bending, sliding, and energy dissipation at bonding junctions. Their mechanical behavior is primarily governed by fiber material composition, diameter, bonding density, and network orientation, all of which can be engineered to meet the performance demands of different desalination systems.

In contrast, electrospun nanofibrous membranes often suffer from limited cohesive strength due to minimal fiber entanglement and weak physical bonding. Zhang et al.[59] reported that pristine electrospun PVDF nanofiber mats possessed a tensile strength of only ~2 MPa, far below that required for pressure-driven desalination processes. However, post-treatment techniques such as hot calendering, thermal annealing, or chemical crosslinking significantly improved mechanical strength (>15 MPa) while preserving porosity above 80%. These results demonstrate that mechanical reinforcement can be achieved without substantial compromise to mass-transfer performance, enabling broader use of nanofibrous architectures in composite membrane systems.

Thermal stability is equally important in thermally driven desalination processes. In DCMD, membranes must maintain their mechanical integrity through repeated cycles of heating and cooling. Liu et al.[60] compared meltblown PP nonwovens and electrospun nanofiber mats after 100 thermal cycles between 20–80 °C. Meltblown nonwovens retained more than 95% of their initial tensile strength and exhibited no noticeable fiber fusion or pore collapse. In contrast, electrospun structures exhibited approximately 40% strength loss due to partial fiber agglomeration at elevated temperatures. These findings highlight a fundamental trade-off between nanofiber-enabled permeability and microfiber-enabled thermo-mechanical resilience. Collectively, the mechanical performance of nonwoven membranes reflects the complex interplay of fiber-scale mechanics, bonding interactions, and structural hierarchy.

2.2.4 ANTIFOULING PROPERTIES

Membrane fouling continues to be one of the most significant barriers to the large-scale implementation of membrane-based seawater desalination technologies. Fouling originates from a combination of mechanisms, including contaminant adsorption within membrane pores, cake layer accumulation on the surface, and the development of CP layers, which collectively lead to sharp declines in water flux, reduced membrane lifespan, and compromised permeate quality[61]. These effects not only diminish operational efficiency but also substantially elevate cleaning frequency, chemical usage, and overall maintenance costs, making fouling control a central challenge in sustainable desalination operation[62]. Nonwoven-based ultrafiltration (UF) and composite desalination membranes are particularly prone to fouling due to the intrinsic hydrophobicity of common polymeric

materials, which facilitates the adhesion of natural organic matter, biological cells, oil droplets, and colloidal particles[63]. Therefore, modulating surface hydrophilicity, surface charge, and interfacial structure has become a critical strategy to mitigate fouling.

To address these concerns, a wide range of surface modification and functionalization strategies has been explored to impart fouling resistance to nonwoven membranes. Ying Liu et al.[64] demonstrated a combined "coagulation + membrane modification" methodology, where a nonwoven support was coated through co-deposition of PDA–PEI and zwitterionic molecules. This dual-layer coating significantly increased membrane hydrophilicity and introduced strong electrostatic repulsion, both of which suppressed the early-stage adsorption and deposition of foulants. Such zwitterionic or polyamine-based coatings are particularly effective because they generate a tightly bound hydration layer that acts as a physical and energetic barrier to contaminant adhesion.

Recent advances in molecular design and structural engineering have further expanded the antifouling potential of nonwoven membranes. Artificial water channels, constructed from simplified synthetic molecular frameworks, have been integrated into the PA selective layer of composite membranes[64, 66]. These nanoscale channels provide highly ordered pathways for rapid water transport while minimizing heterogeneous adsorption sites, thereby reducing the propensity for contaminant accumulation. Simultaneously, bioinspired asymmetric wettability designs have emerged as a powerful paradigm in fouling resistance. Zhu et al.[67, 68] developed a Janus-type nonwoven composite via the combination of electrospinning and electrospray deposition. The resulting membrane consists of a mechanically robust hydrophobic nanofibrous substrate topped with a Janus skin that exhibits extreme dual wettability, superhydrophobicity in air (water contact angle ≈ 166°) and underwater superoleophobicity (oil contact angle ≈ 164°). This asymmetric interface effectively repels oil, organic contaminants, and hydrophobic foulants while maintaining high water permeability, resulting in excellent antifouling behavior without sacrificing water flux. These innovations highlight a shift toward multifunctional antifouling strategies that integrate hydrophilic coatings, charge manipulation,nanochannel engineering, and asymmetric wettability.

2.3. DESALINATION MECHANISMS

Advances in seawater and brackish water desalination rely on multiple physical, chemical, and electrochemical separation mechanisms, each governed by a distinct driving force. Broadly, existing desalination technologies can be classified into six major categories: (1) size-exclusion-based sieving processes such as microfiltration (MF) and UF; (2) osmotic-pressure-driven separations including FO; (3) hydraulic-pressure-driven membrane processes such as RO and nanofiltration (NF); (4) thermal phase-change distillation methods including multi-stage flash (MSF), multi-effect distillation (MED), and MD; (5) selective adsorption using porous materials or ion-specific sorbents; and (6) electric-field-driven ion migration, exemplified by ED. Each mechanism exhibits distinct separation selectivity, energy demand, material requirements, and operational constraints, and nonwoven membranes can serve a variety of roles, from pretreatment filters and mechanical support layers to functional substrates in hybrid or composite desalination systems. Understanding the working principles of these mechanisms provides the foundation for rational membrane design, materials selection, and system-level optimization.

2.3.1 INTERFACIAL ADHESION MECHANISM: MF AND UF

MF and UF are pressure-driven membrane processes whose primary desalination mechanism is physical sieving, where suspended solids or macromolecules are retained based on size exclusion and interfacial adhesion forces[69]. MF employs microporous membranes with pore sizes typically ranging from 0.1 to 10 μm, enabling the effective separation of suspended particulate matter, bacteria, and turbidity-causing components[70]. UF operates with even smaller pore sizes, typically 0.01–0.1 μm and is used to remove high-molecular-weight solutes, viruses, colloids, and biopolymers, while permitting the passage of water and low-molecular-weight neutral solutes[70]. Although neither MF nor UF membranes can remove dissolved ions such as Na^+ or Cl^- due to their relatively large pore dimensions, these processes offer high permeability, low operating pressure, and excellent stability against fouling.

Because of their strong capability to remove particulates, organic macromolecules, and microorganisms, MF and UF serve as indispensable pretreatment stages for RO, NF, and ED desalination systems. Their function is crucial: by reducing colloidal load, preventing biofouling, and mitigating the accumulation of organic matter, they dramatically lower the fouling potential of downstream membranes[71]. This not only improves desalination efficiency and prolongs membrane lifespan but also reduces the frequency of chemical cleaning and associated operational costs. High-performance nonwoven-based MF/UF membranes, owing to their large porosity, interconnected pore network, and high mechanical robustness, enhance these

pretreatment benefits further, offering higher flux and more effective contaminant removal compared to many conventional polymeric substrates[72-74].

2.3.2 OSMOSIS-DRIVEN PROCESSES: FO

FO harnesses the natural osmotic pressure gradient across a semipermeable membrane to induce water transport from a lowosmolarity feed solution to a high-osmolarity draw solution[75]. Because FO does not require externally applied hydraulic pressure, it offers several significant advantages over conventional pressure-driven desalination methods. These include inherently lower energy consumption, reduced mechanical stress on the membrane, minimized compaction of support layers, and lower tendency toward irreversible fouling[76]. FO membranes also provide high rejection of salts, macromolecules, and contaminants, making them attractive for desalination, wastewater treatment, and hydration-driven processes[77, 78].

Despite these advantages, FO systems still face major technical barriers that limit their large-scale deployment. A central challenge is CP, which reduces the effective osmotic driving force. This includes (1) dilutive ICP (DICP) occurring inside the porous support layer as water dilutes the draw solution[79, 80], and (2) concentrative external CP (CECP) at the membrane–feed interface as rejected solutes accumulate[81, 82]. Both effects significantly diminish water flux and reduce overall system performance[83]. Additionally, reverse solute flux from the draw solution back into the feed can degrade feed quality, destabilize draw solution osmolarity, and increase operational cost due to the need for more frequent regeneration.

To establish FO as a competitive desalination strategy, advancements are required in three interconnected areas: (1) Membrane innovation, including the development of ultrathin selective layers, low-tortuosity support layers, nanostructured interfaces, and biomimetic nanochannel architectures to minimize mass-transfer resistance; (2) Draw solution engineering, focusing on highosmolarity solutes with low reverse salt flux, simple regeneration pathways, and good chemical stability; and (3) Process integration, particularly coupling FO with downstream separation technologies (e.g., RO, MD, ED) or renewable energy sources to reduce overall energy consumption[83].

2.3.3 HYDRAULIC PRESSURE–DRIVEN PROCESSES: RO AND NF

RO and NF are the most widely adopted pressure-driven desalination technologies, and their separation mechanisms rely on applying hydraulic pressure greater than the osmotic pressure of the feed solution[84-86]. This pressure forces water molecules through a dense or selectively charged PA layer while rejecting dissolved salts, multivalent ions, organic compounds, and microorganisms. RO is currently the dominant technology for seawater desalination, consistently delivering salt rejection rates of over 99%[87-89]. In contrast, NF, characterized by slightly larger effective pore sizes and charge-based selectivity, exhibits preferential rejection of divalent ions such as Ca^{2+} and SO_4^{2-}, making it ideal for water softening, partial desalination, and polishing industrial wastewater[90, 91].

While RO and NF have achieved technological maturity and global scale, several persistent challenges remain. The high hydraulic pressures required, particularly for seawater RO, lead to substantial energy consumption, making RO the most energyintensive membrane-based desalination method[92-94]. Furthermore, RO/NF membranes are prone to fouling by colloids, organic matter, biofilms, and inorganic scaling, all of which reduce water flux and necessitate frequent chemical cleaning [95-97]. Another critical bottleneck is brine management: the disposal of highly concentrated reject streams poses environmental and regulatory concerns, especially in coastal regions with sensitive ecosystems.

2.3.4 THERMAL-DRIVEN WATER SEPARATION

Thermal desalination technologies, including MSF distillation, MED, and mechanical vapor compression (MVC), operate on phase-change principles in which saline feedwater is heated to generate vapor that subsequently condenses as purified water. These processes are particularly advantageous for treating hypersaline or highly contaminated feedwaters, such as concentrated brines and industrial waste streams, where membrane-based technologies often struggle with scaling, fouling, or osmotic limitations[98]. Because thermal methods are not restricted by osmotic pressure, their separation efficiency remains high even at extreme salinity levels. Furthermore, MSF, MED, and MVC systems offer additional benefits when integrated into cogeneration facilities or solar-thermal power plants, enabling cascaded heat utilization and significantly improving overall energy efficiency through waste-heat recovery[99-101].

In addition to conventional distillation systems, emerging thermal-driven desalination approaches, notably interfacial solar evaporation and MD[102-104], have demonstrated substantial promise for sustainable and decentralized freshwater production.

Unlike bulk heating, these processes localize heat at the air–water interface or within a thin membrane region, thereby minimizing thermal losses and substantially improving energy efficiency. Advances in photothermal materials, nanostructured porous supports, and heat-localization strategies have enabled solar-thermal evaporators to achieve evaporation rates by approaching or surpassing the thermodynamic limit under one-sun illumination[105, 106]. Meanwhile, MD continues to gain traction due to its near-complete salt rejection, compatibility with low-grade heat sources, and robustness against high salinity[107, 108].

2.3.5 SELECTIVE ADSORPTION

Selective adsorption represents a fundamentally different desalination mechanism in which functional materials capture ions through chemical affinity, electrostatic interactions, or molecular recognition[109, 110]. Technologies based on this princip le include capacitive deionization (CDI), ion-imprinted polymers (IIPs), MOFs, and COFs. CDI, one of the most mature approaches, applies a low electrical voltage to charged porous electrodes, enabling the reversible electrostatic adsorption of both cations and anions[111]. Upon voltage reversal or short-circuit discharge, the stored ions are released, regenerating the electrodes for repeated cycles. CDI is particularly advantageous for low-salinity or brackish water, offering low energy consumption, mild operating conditions, and the absence of phase change.

Beyond desalination, selective adsorption technologies are increasingly being deployed for strategic resource recovery, particularly for high-value or supply-critical ions such as lithium, boron, rare earth elements, and nutrient species[112-114]. Continued advances in high-surface-area adsorbents, ion-selective chemical functionalities, and tunable pore architectures have significantly increased uptake capacity, selectivity, and cycling stability[115, 116].

2.3.6 ELECTROCHEMICAL DESALINATION

Electrochemical desalination technologies, including ED and electrodeionization (EDI), utilize an externally applied electric field to selectively drive ions across semipermeable ion-exchange membranes[117-118]. In ED, alternating cation-exchange and anion-exchange membranes create dilute and concentrate channels, allowing salts to be removed from the feedwater while concentrating ions in adjacent compartments[119-121]. The separation efficiency is strongly controlled by membrane properties such as fixed charge density, ion-exchange capacity, water uptake, and selectivity, which may respond differently depending on feedwater ionic composition and competing species[122]. ED is particularly effective for moderate-salinity feedwaters, brackish water treatment, and industrial wastewater polishing where energy requirements remain manageable[123-125].

EDI represents an advancement over traditional ED, integrating ion-exchange resins within the desalting compartments. Under an applied electric field, these resins are continuously regenerated in situ, eliminating the need for chemical regeneration and enabling uninterrupted production of ultrapure water. As such, EDI is widely used in electronics manufacturing, pharmaceuticals, and high-pressure boiler feed applications[126, 127]. Although energy consumption for ED and EDI increases with feed salinity, their modular design, precise ion removal capability, and chemical-free operation make them indispensable for specialized desalination and ultrapure water applications.

3. NONWOVEN MEMBRANES FABRICATION TECHNIQUES

3.1 TRADITIONAL NONWOVEN FABRICATION TECHNIQUES

3.1.1 MELT BLOWING

Melt blowing is a widely used one-step, direct web-forming nonwoven fabrication technology, and it plays a critical role in producing microfibrous membranes with tunable structural properties suitable for filtration, desalination pretreatment, and membrane support applications.The macroscopic performance of melt-blown nonwovens is intrinsically governed by their microstructure, particularly fiber diameter, porosity, and pore connectivity. These parameters directly influence essential functional metrics such as specific surface area, filtration efficiency, pressure drop, mechanical compliance, and air or vapor permeability[128].

Nanofibrous membranes have gained significant attention in the field of water purification and desalination due to their unique features[129], which enable rapid mass transport, enhanced adsorption or catalytic activity, and precise molecular-level separation, making nanofiber-based membranes ideal for applications ranging from pretreatment and contaminant removal to advanced desalination processes such as MD, FO, and hybrid separation systems. As a result, a variety of nanofiber fabrication

methods have been extensively explored, with electrospinning and centrifugal spinning representing two of the most widely used and technologically impactful approaches[130-132].

3.1.2 ELECTROSPINNING

Electrospinning is one of the most versatile and widely adopted nanofiber fabrication technologies, utilizing a high-voltage electrostatic field to draw ultrafine fibers from polymer solutions or melts[133]. This process enables the production of continuous nanofibers with diameters ranging from tens of nanometers to several micrometers[134]. To date, researchers have successfully electrospun nanofibrous membranes from hundreds of polymer types, including PVDF[135], polyacrylonitrile (PAN)[136], PA, polyurethane (PU), and numerous biopolymers[137], demonstrating its broad material compatibility and design flexibility[138].

In water purification and desalination, electrospinning has emerged as the dominant nanofiber fabrication technique, owing to its exceptional control over membrane architecture. By manipulating parameters such as solution viscosity, solvent volatility, applied voltage, tip-to-collector distance, and collector geometry, it is possible to tailor fiber diameter, pore structure, and membrane surface functionality with high precision[129]. This tunability enables the creation of membranes with large porosity, high selectivity, interconnected microporous pathways, and ease of functionalization with nanoparticles, catalysts, or hydrophilic/hydrophobic moieties[129]. Electrospun nanofibrous membranes have been successfully integrated into MD, RO support layers, FO substrates, and adsorptive filtration systems[139-143].

3.1.3 CENTRIFUGAL SPINNING

Centrifugal spinning is a high-throughput, needleless nanofiber fabrication technique driven by the centrifugal forces generated by rapid rotor rotation[144, 145]. In contrast to electrospinning, this method does not require a high-voltage electric field, making it inherently safer, simpler in design, and more suitable for industrial-scale production. As such, centrifugal spinning has emerged as a promising complementary or alternative nanofiber fabrication technology for applications requiring large-area nanofibrous membranes in water treatment, filtration, biomedicine, and energy systems.

The technique operates by rotating a polymer-containing reservoir or spinneret at high speeds, typically between 3,000 and 50,000 rpm, producing a strong centrifugal force that propels the polymer melt or solution radially outward through microorifices. Once ejected, the fluid jet undergoes significant elongation due to extensional and aerodynamic forces, while solvent evaporation (in solution spinning) or melt cooling (in thermal spinning) leads to rapid fiber solidification. The resulting solidified fibers are collected on a surrounding surface or enclosure, forming a nonwoven nanofibrous mat with high production throughput[131].

3.2 INTEGRATED TECHNIQUES

3.2.1 SOLAR-POWERED MD

Solar-driven MD (SMD) is an emerging sustainable desalination technology that couples renewable solar energy with a thermally driven membrane separation process. The operating principle involves heating saline feedwater using solar energy to generate vapor at the feed–membrane interface. A hydrophobic microporous membrane selectively allows water vapor to pass through its pores, driven by a vapor pressure gradient, while retaining liquid water and dissolved salts. The vapor subsequently condenses on the permeate side to yield potable water. **Figure 2** is a schematic diagram of a solar-driven membrane distillation (MD) configuration. SMD configurations are broadly divided into indirect systems, where solar energy is harvested by an external heat-collection unit to warm the feed stream, and direct systems, where solar absorbers are integrated directly into the membrane module to provide localized heating[146, 148]. Direct SMD has gained increasing attention due to its compact architecture, reduced thermal losses, improved heat–mass integration, and simplified operational infrastructure.

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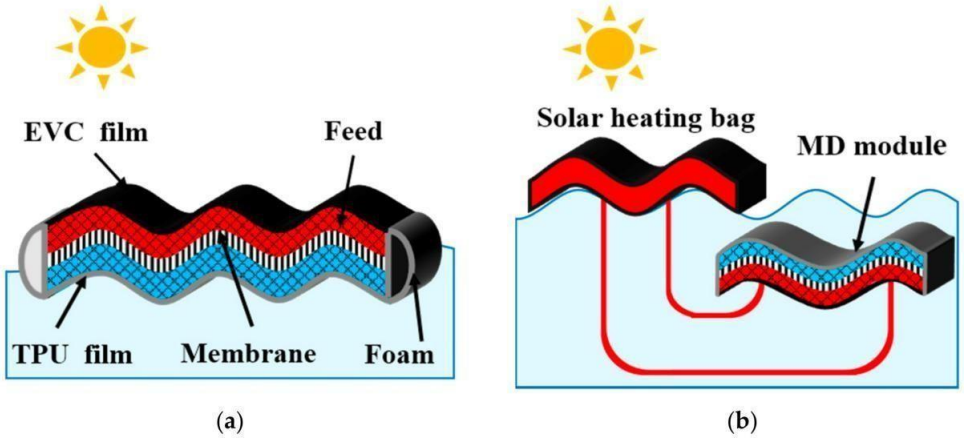

Figure 2. Schematic of solar-driven membrane distillation (MD) configurations [148], (**a**) simplest and (**b**) optimal.

In direct SMD systems, solar-to-thermal conversion is typically achieved using photothermal membranes or integrated absorber plates. Photothermal membranes incorporate nanostructured solar absorbers—such as carbon nanotubes, graphene derivatives[149], metallic nanoparticles, or plasmonic nanostructures—directly onto a hydrophobic membrane surface. These coatings convert incident sunlight into localized heat, thereby minimizing bulk water heating and reducing convective thermal losses. Alternatively, dark-colored absorber plates or coatings mounted beneath or adjacent to the membrane behave similarly to flat-plate solar collectors, promoting efficient interfacial evaporation. Chen and Ho demonstrated that incorporating solar-assisted heating into a flat-plate DCMD configuration improved process efficiency by ~16% [150]. Ma et al. [151] reported that a direct solar-powered vacuum MD (VMD) module could achieve a water productivity of ~8 $L \cdot m^{-2} \cdot d^{-1}$ (GOR = 0.71) at a 0.35 m^2 scale, further increasing to 32 $L \cdot m^{-2} \cdot d^{-1}$ when combined with a heat pump for improved thermal management.

To enhance thermal utilization and improve energy efficiency, multi-effect and multi-stage SMD designs have been developed. In these architectures, only the first stage is directly heated by solar energy; subsequent stages reuse the latent heat released during vapor condensation to preheat incoming feedwater. This cascading heat-recovery strategy significantly lowers the SEC and improves overall freshwater productivity. More recently, hybrid SMD–PV systems have emerged, in which PV panels serve simultaneously as solar absorbers and electricity generators. The waste heat generated during PV operation is harvested to drive MD, while the cooling effect of water evaporation enhances PV electrical efficiency. Such "solar–thermal–electric" cogeneration systems represent a promising pathway toward maximizing solar resource utilization[152].

Despite these advances, SMD still faces several technological barriers. First, thermal losses remain substantial, with ~63% of incident solar energy dissipated through convection, radiation, and conduction. Conductive losses through the membrane contribute up to 42% under low feed flow rates[153]. Second, mass-transfer resistance limits productivity, particularly in configurations such as air-gap MD (AGMD), where gas-phase diffusion often restricts fluxes to below 0.3 $kg \cdot m^{-2} \cdot h^{-1}$[150]. Additional limitations include temperature polarization, scaling and fouling at elevated temperatures, system durability under outdoor conditions, and challenges in scaling up membrane modules for large-area deployment.

Future development of SMD should focus on several directions: (1) designing advanced broadband photothermal materials with improved light absorption and thermal localization; (2) optimizing multi-effect architectures and internal heat-recovery loops; (3) integrating phase-change materials (PCMs) for solar-thermal energy storage and nighttime operation; and (4) improving membrane thermal insulation and modifying pore structures to reduce conductive heat loss.

3.2.2 VMD

VMD is an important operational configuration within the broader family of MD technologies. In VMD, a vacuum is applied on the permeate side of a hydrophobic microporous membrane, typically maintaining an absolute pressure between 10 and 50 kPa, which significantly reduces the partial pressure of water vapor in the permeate channel. This creates a strong transmembrane vapor pressure gradient, enabling water vapor to be efficiently transported from the heated saline feed, through the membrane pores, and into the low-pressure permeate chamber. The extracted vapor is subsequently condensed, producing high-quality freshwater without the need for high hydraulic pressures or elevated feed temperatures[154-156].

Compared with other MD processes such as DCMD and AGMD, VMD offers several inherent advantages. The direct removal of vapor by vacuum extraction mitigates conductive and convective heat losses, resulting in reduced temperature polarization, lower overall mass-transfer resistance, and significantly enhanced permeate flux. For example, under typical operating conditions, such as a feed temperature of approximately 70 °C and a permeate-side vacuum of 10 kPa, PTFE hollow-fiber VMD modules have demonstrated water fluxes in the range of 30–50 $kg \cdot m^{-2} \cdot h^{-1}$, which is roughly two to three times higher than fluxes achievable under comparable DCMD operation. These elevated fluxes are attributed to the more efficient removal of vapor and improved thermal-driving-force utilization[157].

A notable advantage of VMD is its compatibility with low-grade thermal energy sources, including solar-thermal heating, geothermal heat, and various forms of industrial waste heat. When coupled with optimized system engineering, VMD systems can achieve high thermal efficiencies, commonly evaluated using the gained output ratio (GOR). With appropriate heat recovery and module configuration, GOR values exceeding 3.0 have been reported, highlighting the technology's potential for costeffective and energy-efficient desalination. VMD's high tolerance for hypersaline feeds and suitability for decentralized or offgrid conditions further enhance its appeal for brine management, zero-liquid-discharge systems, and renewable-powered desalination infrastructures[157].

Despite its advantages, VMD also presents challenges, including ensuring effective vacuum sealing, minimizing membrane wetting under low-pressure conditions, and optimizing permeate-side condensation efficiency. Future progress will depend on advances in membrane material design (e.g., higher LEP, superhydrophobicity, and thermal stability), module optimization, and integration with renewable thermal sources.

3.2.3 PLASMA-ASSISTED TECHNIQUES

Plasma-assisted technologies, particularly non-thermal atmospheric-pressure plasma, have recently emerged as innovative and environmentally sustainable approaches for water purification and desalination. Traditional desalination technologies such as RO and MSF distillation remain limited by high energy consumption, membrane fouling, and the environmental impacts associated with brine discharge[158-159]. By contrast, plasma-based techniques offer dual functionality that directly addresses these bottlenecks: (1) plasma-enabled surface modification of membrane materials and (2) direct plasma-driven desalination and resource recovery[160]. This versatility positions plasma technology as a promising complement, or potentially a disruptive alternative, to conventional desalination processes.

In membrane engineering, plasma treatment enables precise modification of surface chemistry and microstructure without altering the bulk properties of the underlying material. Exposure to O_2, NH_3, Ar, N_2, or mixed-gas plasmas can introduce hydrophilic functional groups (e.g., –OH, –COOH, $–NH_2$), thereby improving membrane wettability, antifouling performance, and interfacial adhesion for TFC fabrication[161-163].

Beyond membrane modification, direct plasma desalination represents a transformative development. Non-thermal plasma, distinguished by high electron temperatures and low gas temperatures (<500 K), generates energetic electrons, reactive oxygen/nitrogen species (RONS), and intense localized electric fields upon contact with saline water. These reactive species can induce oxidation–reduction reactions that destabilize dissolved ions such as Na^+ and Cl^-, promoting salt nucleation, crystallization, and subsequent precipitation[164-165]. Ekanayake et al.[166] demonstrated efficient NaCl removal using an APP system, producing plasma-activated desalinated water with a conductivity as low as 5.6 mS/cm. The process required only 2,140 kWh/m^3, substantially lower than conventional thermal desalination (~29,000 kWh/m^3), with energy consumption reducible by 52.8% when integrated with thermal distillation[167]. Beyond meeting drinking-water standards, PADW has shown enhanced biological activity, improving seed germination, and can function as an efficient electrolyte for hydrogen production via water splitting[167]. Meanwhile, precipitated salts can be upcycled into functional 2D nanomaterials such as $Mg(OH)_2$ nanosheets through simple thermal treatment, enabling simultaneous water purification, energy generation, and resource valorization[168].

Despite its promise, plasma-based desalination remains an emerging technology with several challenges that must be addressed before large-scale deployment. Key research needs include the development of scalable and energy-efficient APP reactors, improved understanding of plasma–liquid interfacial chemistry, integration of plasma processes with existing membrane systems, and long-term durability studies.

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4. FUNCTIONALIZATION OF NONWOVEN MEMBRANES FOR ENHANCED SEAWATER DESALINATION PERFORMANCE

Membrane-based desalination technologies, particularly RO and FO, have become leading solutions for large-scale freshwater production due to their relatively low energy consumption, modularity, and reduced environmental footprint compared with traditional thermal processes. Despite their widespread adoption, conventional polymeric membranes still face several fundamental challenges that restrict their long-term performance and operational efficiency. These include the well-known permeability, selectivity trade-off, high vulnerability to organic, inorganic, and biological fouling, limited mechanical robustness under hydraulic or osmotic stress, and concerns regarding environmental sustainability related to polymer production, membrane disposal, and chemical cleaning. Addressing these limitations requires transformational improvements in membrane materials, structure, and functionality. To enhance desalination efficiency, fouling resistance, stability, and sustainability, researchers have developed four major categories of functionalization strategies for nonwoven-based composite membranes: (1) surface modification, (2) integration of nanoparticles and 2D materials, (3) polymer blending and copolymer design, and (4) incorporation of sustainable or bio-based materials.

4.1 SURFACE MODIFICATION

Surface modification has become one of the most powerful and versatile strategies for enhancing the performance of membranebased seawater desalination systems. By tailoring key interfacial parameters, such as hydrophilicity or hydrophobicity, surface energy, roughness, charge, and chemical functionality, surface modification can significantly influence water–membrane interactions, foulant adhesion, vapor–liquid stability, and mass-transfer characteristics[169]. Consequently, these techniques have proven essential for improving water permeability, salt rejection, antifouling performance, and long-term operational durability across various desalination platforms. Recent advances in materials engineering now enable precise and controllable surface functionalization on diverse nonwoven and polymeric substrates, allowing the systematic optimization of membrane interfacial properties without compromising bulk mechanical integrity[170].

One illustrative example is the work by Purwanto et al.[171], who engineered a gradient-structured hollow-fiber PVDF membrane by incorporating a hydrophilic surface-modifying macromolecule and polyethylene glycol (PEG) into the dope formulation, followed by dip-coating with a hydrophobic macromolecule. This dual-modification approach created hydrophilic internal pathways to facilitate water transport and a hydrophobic outer layer to prevent pore wetting, an essential requirement for MD. The resulting membrane exhibited a 57% increase in water contact angle, achieved a permeate flux of 81.32 $kg \cdot m^{-2} \cdot h^{-1}$, and maintained a salt rejection of 99.9%, demonstrating excellent thermal, structural, and operational stability under MD conditions.

In RO applications, controlling surface energy is critical for fouling mitigation. Lee et al.[172] modified commercial PA membranes with fluorinated compounds, thereby reducing surface energy without significantly altering surface roughness or charge. This modification markedly suppressed the adsorption of marine organic foulants such as humic acid and sodium alginate, underscoring the effectiveness of the “low surface energy antifouling” mechanism in minimizing organic fouling on RO membranes. Such approaches demonstrate that even subtle chemical modifications can yield substantial improvements in resistance to foulant deposition.

In FO, reducing ICP is central to enhancing water flux. Gonzales et al.[173] addressed this challenge by grafting PAA onto an electrospun PVDF nanofibrous substrate, followed by constructing a polyelectrolyte network via layer-by-layer (LbL) assembly of polyethylenimine (PEI) and PAA. This modification significantly improved support-layer hydrophilicity, pore interconnectivity, and water transport pathways. The resulting TFC FO membrane achieved an ultralow structural parameter of 221 μm and a pure water permeability (A value) of 4.12 $L \cdot m^{-2} \cdot h^{-1} \cdot bar^{-1}$, far surpassing conventional commercial FO membranes. This work highlights how surface modification can address both interfacial and internal transport limitations in advanced osmotically driven processes.

These studies demonstrate that surface modification can be strategically implemented through 1) Macromolecular additives for bulk–surface synergistic tuning of hydrophilicity and hydrophobicity; 2) Polyelectrolyte LbL self-assembly to engineer interfacial microstructures and reduce ICP; and 3) Low-surface-energy coatings to create robust antifouling barriers.

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4.2 INTEGRATION OF NANOPARTICLES AND 2D MATERIALS

The incorporation of nanoparticles and 2D materials into nonwoven-based membranes has emerged as one of the most impactful strategies for overcoming the intrinsic permeability–selectivity trade-off that limits conventional polymeric membranes in seawater desalination[168]. While traditional nonwoven substrates, such as poly(vinylidene fluoride) (PVDF), PP, or PET, provide high porosity, mechanical strength, and low transport resistance, they lack inherent selectivity and must rely on additional functional layers or fillers to impart ion rejection capability. Recent advances in nanomaterials have enabled the integration of selective, highly permeable nanoarchitectures directly onto or within nonwoven composites, dramatically enhancing desalination performance[174, 175].

Among these nanostructured materials, 2D nanosheets, including graphene oxide (GO), metal–organic framework (MOF)derived nanosheets, covalent organic framework (COF) nanosheets, covalent aromatic polymers (CAPs), and graphitic carbon nitride (g-C_3N_4), have attracted intense interest due to their atomic thickness, tunable interlayer spacing, and robust chemical and thermal stability. These materials naturally form ultrathin, laminar channels that facilitate rapid water permeation while offering precise size- and charge-based ion sieving. When incorporated into nonwoven composite architectures, the 2D nanosheets complement the mechanical robustness and hierarchical porosity of the nonwoven substrate, enabling the creation of ultrathin selective layers with dramatically reduced mass-transfer resistance[168].

Of particular significance are 2D polymer nanosheets, such as COFs and CAPs, which contain intrinsically ordered subnanometer pores within their crystalline frameworks. Molecular dynamics simulations have shown that a bilayer CAP membrane can achieve nearly 100% salt rejection while delivering an extraordinary water permeability of 1172 $L \cdot m^{-2} \cdot h^{-1} \cdot bar^{-1}$, approximately three orders of magnitude higher than commercial RO membranes[176]. These findings underscore the potential of 2D polymer membranes to serve as ideal ion-selective barriers. When these nanosheets are integrated with nonwoven supports via interfacial polymerization, LbL assembly, vacuum filtration, or in situ growth, it is possible to fabricate defect-free, conformal selective layers that maintain structural integrity and resist delamination, one of the primary challenges in freestanding 2D membranes.

Beyond COFs and CAPs, porous g-C_3N_4 nanosheets have further expanded the functional versatility of 2D materials in desalination. By engineering the interlayer spacing, for example, via the intercalation of sulfonated aromatic molecules to enlarge nanochannel dimensions, researchers have achieved remarkable water permeabilities of up to 8867 $L \cdot m^{-2} \cdot h^{-1} \cdot bar^{-1}$ while maintaining complete rejection of dyes and ionic contaminants[168]. Such interlayer-spacing engineering enhances water transport without compromising sieving precision. When these nanosheets are deposited onto hydrophilically modified nonwoven substrates, the resulting composite membranes exhibit a synergistic performance profile: 1) High water flux, due to the low-resistance porous structure of the nonwoven base; 2) Precise molecular sieving, provided by the 2D nanosheet selective layer; 3) Reduced CP, due to improved surface hydrophilicity and interfacial transport; and 4) Enhanced antifouling properties, stemming from the smooth, chemically tunable 2D surfaces.

4.3 POLYMER BLENDS AND COPOLYMERS

Polymer blending and copolymer design have emerged as two complementary and versatile strategies for enhancing the performance of nonwoven-supported membranes in seawater desalination. Although nonwoven substrates provide excellent mechanical strength, high porosity, and low hydraulic resistance, they often exhibit intrinsic drawbacks, including high surface roughness, limited hydrophilicity, and insufficient chemical functionality. These deficiencies hinder the formation of uniform, ultrathin selective layers during interfacial polymerization, thereby constraining the permeability, selectivity, and long-term stability of TFC membranes used in RO and NF. To overcome these challenges, polymer blending and copolymer incorporation have become critical for improving interfacial compatibility, tuning surface energy, enhancing hydrophilicity, and ultimately advancing desalination performance[177].

Polymer blending involves physically incorporating hydrophilic polymers, such as poly(vinyl alcohol), PEG, poly(acrylic acid) (PAA), zwitterionic polymers, or other hydrophilic additives, into traditional hydrophobic matrices like PSf, polyethersulfone (PES), or PVDF. This approach modifies the physicochemical properties of the support layer without requiring significant changes to established fabrication processes. For example, blending PVDF with hydrophilic block copolymers such as PEO–PPO–PEO (Pluronic surfactants) can substantially reduce interfacial tension during interfacial polymerization. This promotes the development of a smoother, more uniform, and defect-free PA selective layer, thereby enhancing salt rejection and reducing fouling propensity. Furthermore, polymer blending can tailor pore-size distribution, surface charge, and overall substrate

morphology, indirectly influencing the permeability–selectivity balance of the resulting TFC membrane. Improved hydrophilicity also mitigates ICP, a critical limitation in FO[177].

While blending improves bulk and surface properties, copolymer-based strategies offer molecular-level precision in membrane functionalization. By designing block or graft copolymers containing targeted functional groups, such as sulfonic acid, carboxyl, quaternary ammonium, or zwitterionic moieties, membrane surfaces can be endowed with durable hydrophilicity, strong hydration layers, and enhanced fouling resistance. These copolymers may be incorporated into the substrate, applied as surface coatings, or introduced during phase inversion to create tailored interfacial architectures. For instance, copolymers containing poly(2-methyl-2-oxazoline) or sulfonated poly(ether ether ketone) have been used to form negatively charged, highly hydrated surfaces that provide strong electrostatic repulsion against multivalent ions such as Mg^{2+} and SO_4^{2-}, a key advantage for seawater desalination where divalent ions contribute significantly to membrane fouling and scaling. Some amphiphilic block copolymers can even undergo self-assembly during phase inversion, forming ordered nanochannels within the support layer that improve water transport pathways and reduce mass-transfer resistance[178].

4.4 SUSTAINABLE MATERIALS

With the rapid development of seawater desalination technologies, the pursuit of environmentally sustainable, high-performance membrane materials has gained substantial momentum. Thin-film nanofibrous composite (TFN) membranes, widely applied in NF and RO, have emerged as a central research focus due to their high permeability, excellent salt rejection, and structurally customizable architectures. In these membranes, the nonwoven fabric serves as a mechanically robust support layer, and its surface morphology, chemical functionality, and pore structure critically govern the formation, adhesion, and long-term stability of the overlying PA selective layer. Consequently, recent efforts have increasingly targeted the functionalization and greening of nonwoven substrates to simultaneously enhance membrane performance and environmental sustainability[179].

A major thrust in sustainable membrane design involves the substitution of petroleum-derived polymers, such as PSf, PP, or PES, with bio-based or biodegradable alternatives, including polylactic acid (PLA), chitosan, cellulose nanofibers, and lignin derivatives. These renewable materials not only reduce the environmental burden associated with conventional polymer production and disposal but also inherently exhibit advantageous properties such as hydrophilicity, biocompatibility, and reduced foulant adhesion. Their hydrophilic nature helps suppress organic and biological fouling, improving long-term operational stability. Additionally, bio-based nonwovens can be chemically tailored to achieve mechanical strengths comparable to synthetic substrates, making them suitable for supporting high-pressure RO operations[180-183].

Electrospinning has further expanded the design space for sustainable nonwoven supports by enabling the creation of nanofibrous intermediate layers with high porosity, uniform pore distribution, and interconnected 3D networks. Compared with traditional phase-inversion supports that often suffer from macrovoid collapse, heterogeneous pore alignment, and interfacial stress concentration, nanofibrous layers provide a smoother, more open, and mechanically resilient platform for interfacial polymerization. This promotes the deposition of ultrathin, defect-minimized PA selective layers, thereby enhancing both permeability and selectivity. Moreover, electrospun nanofibers derived from renewable polymers such as PLA or cellulose offer a scalable route toward producing fully or partially bio-based TFN membranes[184-186].

In parallel, surface chemical modification of nonwoven supports has proven highly effective for improving interfacial polymerization kinetics and selective-layer integrity. Functional groups such as hydroxyl, carboxyl, sulfonic acid, and zwitterionic moieties can be introduced through plasma treatment, graft copolymerization, or wet-chemical modification. These modifications increase surface hydrophilicity, optimize surface energy, and enhance monomer adsorption during PA formation. As a result, the resulting TFC or TFN membranes exhibit improved monomer diffusion uniformity, reduced defect formation, and stronger bonding between the selective layer and the substrate. Such synergistic improvements allow membranes to achieve high water flux and salt rejection values exceeding 98%, while also exhibiting enhanced antifouling and anti-swelling properties[187, 188]. Performance evaluations under real seawater conditions have further confirmed that TFN membranes supported on functionalized, sustainable nonwovens exhibit exceptional operational stability, fouling resistance, and mechanical resilience[179].

5. MULTIPLE-CYCLE AND LONG-TERM SEAWATER DESALINATION PERFORMANCE

Achieving reliable, long-term seawater desalination performance is essential for maintaining a stable freshwater supply, particularly in regions facing chronic water scarcity. Although fossil-fuel-driven thermal desalination technologies have reached

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technological maturity, their high operational costs and substantial carbon emissions limit their scalability and environmental sustainability. Conversely, RO has emerged as the dominant desalination technology due to its relatively low SEC, high water recovery rate, and steadily decreasing operating costs, making it the cornerstone of modern desalination infrastructure[189]. Yet, ensuring stable performance under extended operation and repeated cycling remains a complex challenge.

In brackish water desalination systems that operate under repeated or batch cycles, recent studies have revealed the advantages of batch and hybrid RO configurations. Hosseinipour et al.[190] and Beni et al.[191] demonstrated that these configurations outperform conventional semi-batch systems, particularly at high water-recovery ratios, by achieving improved energy efficiency and operational stability. However, real-world long-term operation introduces additional stressors. RO membranes are highly susceptible to biofouling, inorganic scaling, chemical degradation, and mechanical fatigue, especially under frequent start–stop cycling, fluctuating transmembrane pressures, or operation at high recovery. These degradation pathways accumulate over time, leading to flux decline, deterioration in salt rejection, increased energy demand, and reduced overall system reliability and economic viability.

To mitigate these issues, Massons-Gassol et al.[192] proposed a pollution-source–oriented fouling management approach that prioritizes targeted pretreatment measures. When biofouling is dominant, strategies such as nutrient limitation, optimized chlorination–dechlorination cycles, or biocide dosing are recommended. In contrast, when organic or colloidal fouling is prevalent, enhanced coagulation, adsorption, or advanced filtration should be incorporated into pretreatment. These targeted approaches must be paired with tailored chemical cleaning protocols. For instance, disinfectants or protease- based enzymatic cleaners can be used to remove biofilm biomass, thereby improving cleaning efficiency and extending membrane lifespan.

Renewable energy–driven desalination systems present promising pathways toward sustainable operation but introduce new long-term performance challenges. Brodersen et al.[193] investigated a wave-powered batch RO (WPBRO) system that eliminates the traditional multi-stage energy conversion chain ("wave-to-electricity-to-high-pressure pump") by directly coupling wave motion to the RO process via a hydraulic energy converter. Using seawater as the working fluid, the WPBRO system achieved a freshwater production capacity of 1,700–2,400 m^3/day and a specific energy consumption (SEC) as low as 2.30–2.39 kWh/m^3, demonstrating remarkable energy efficiency. However, renewable-driven desalination systems inherently experience intermittent and variable power supply, which can induce rapid pressure fluctuations, abrupt shutdown– restart cycles,and increased mechanical stress on membrane modules. These dynamic operating conditions accelerate membrane fatigue and may exacerbate fouling due to unstable hydrodynamic conditions. **Figure 3** is a schematic diagram of a direct-drive ocean wave energy-driven batch reverse osmosis operation.

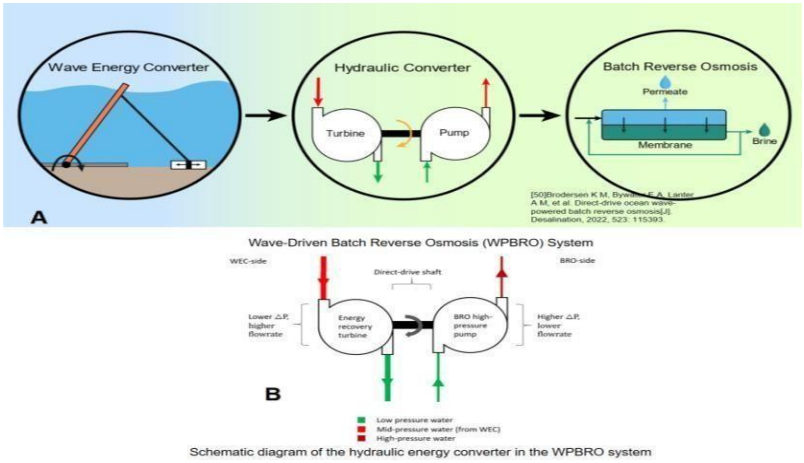

Figure 3. Schematic diagram of ocean wave energy driving batch reverse osmosis with direct drive[193]. (**A**) Wave-Driven Batch Reverse Osmosis (WPBRO) System. (**B**) Schematic diagram of the hydraulic energy converter in the WPBRO system.

6. MODELING AND SIMULATION

As seawater desalination advances toward higher efficiency, lower carbon intensity, and greater integration with renewable energy systems, modeling and simulation have become indispensable tools linking membrane material design, module engineering, process optimization, and system-level deployment. Modern computational frameworks, ranging from

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molecularscale simulations to full-plant dynamic models, provide critical insights into heat and mass transfer, CP, fouling evolution, energy consumption, and techno-economic trade-offs. Such models not only enhance fundamental understanding but also substantially accelerate the translation of laboratory innovations into commercially viable desalination technologies.

In hybrid membrane systems, numerical modeling plays a central role in optimizing multi-stage and multi-process configurations. Yalamanchili et al.[194] developed a MATLAB®-based simulation platform for a FO–RO hybrid system, incorporating detailed material and energy balances along with integration of the LewaPlus® process design software. Their comprehensive simulation framework enabled evaluation of system adaptability to varying wastewater salinity (0.5–3 g/L) and feed-to-draw solution volume ratios (50:50 to 90:10). The study identified an optimal operational condition, 0.5 g/L wastewater salinity and an 80:20 feed/draw ratio, yielding a 90% wastewater recovery rate with an exceptionally low RO SEC of 0.96 kWh/m³. This work underscores the power of simulation in identifying feasible operating windows for integrated wastewater reuse and seawater desalination, guiding the scale-up of hybrid systems.

Modeling also plays a pivotal role in advancing renewable-energy-driven desalination, where intermittency and dynamic operating conditions require robust predictive tools. Mi et al.[195] established a dynamic time-domain model for a wavepowered RO system integrating an oscillating surge wave energy converter (OSWEC), a self-rectifying piston pump, and an onshore RO module. Simulations performed using realistic irregular wave spectra demonstrated excellent agreement with wave tank experiments, validating the feasibility of direct mechanical coupling between wave energy and RO desalination, a critical milestone for off-grid, ocean-based freshwater production. Complementarily, Aldei et al.[196] conducted a technoenvironmental co-simulation of solar photovoltaic (PV)–coupled RO systems in hyper-arid coastal zones using PVsyst software. Their results showed that thin-film PV modules produced 8.3% and 5.9% higher annual energy output than monocrystalline and polycrystalline silicon modules, respectively, but required greater land area (15.9% and 5.7% more). For a large-scale 30 MIGD plant, a 120 MWp PV array with 60 inverters and a 30° tilt angle was necessary—cutting fossil-fuel consumption by ~80% and reducing the carbon footprint from 7.3×10^{-5} to 1.8×10^{-5} kg CO_2-eq per unit of freshwater, albeit at the expense of increased land use and material consumption. These findings highlight the need for multi-objective optimization in renewable-powered desalination design. **Figure 4** is a schematic diagram of the structure, modeling, and multi-objective optimization process of the wave energy and photovoltaic-driven seawater desalination system.

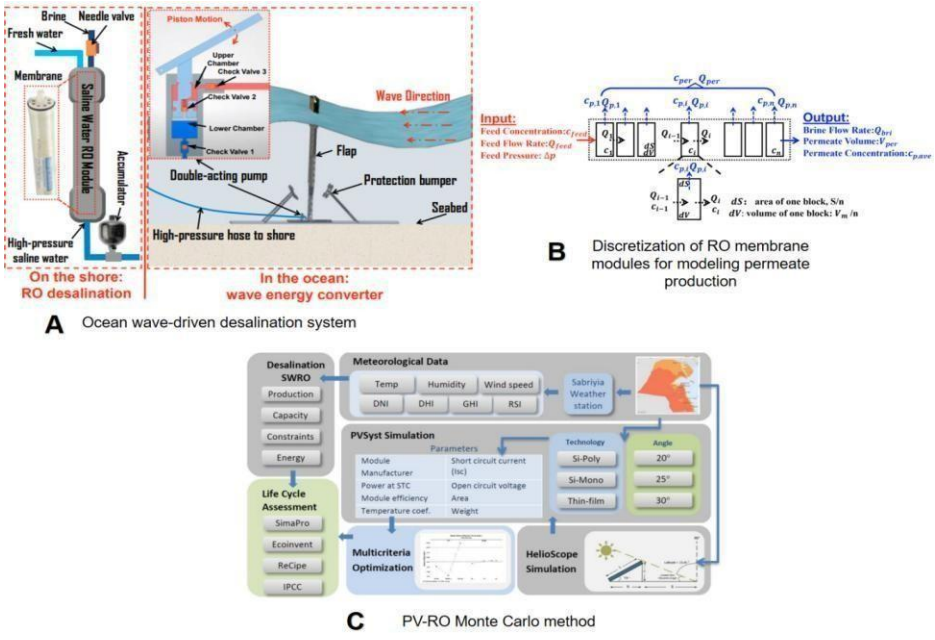

Figure 4. Structure, modeling and multi-objective optimization process of wave energy and photovoltaic-driven seawater desalination system. (**A**) Ocean wave-driven desalination system[195]. (**B**) Discretization of RO membrane modules for modeling permeate production[195]. (**C**) PV-RO Monte Carlo method[196].

In thermally driven desalination processes such as MD, modeling efforts focus on capturing the complex interplay of heat transfer, mass transfer, and polarization effects. El Mokhtar et al.[197] proposed a predictive mass transfer model for AGMD accounting

for feed temperature, air-gap width, flow rate, and membrane pore size. Their model demonstrated high predictive accuracy with an average deviation of 6.9%, confirming that 0.45 μm membranes significantly enhance flux, up to 9.06 $kg \cdot m^{-2} \cdot h^{-1}$ at 77°C, though at a slight expense to permeate quality. Meanwhile, Triki et al.[198] developed a comprehensive numerical model for VMD, examining both single- and multi-stage configurations. Simulations showed that under 35 g/L feed salinity, 65°C feed temperature, 50 L/h flow rate, and 3 kPa vacuum, VMD achieves fluxes of 18.42 $kg \cdot m^{-2} \cdot h^{-1}$, with feed temperature identified as the dominant factor governing performance. Importantly, the study emphasized that the permeability and structural composition of the membrane support layer strongly influence VMD efficiency, offering critical guidance for material selection and membrane architecture design.

7. CHALLENGES AND FUTURE PERSPECTIVES

Despite the substantial progress achieved in developing nonwoven membranes for seawater desalination, translating laboratoryscale innovations into industrially deployable technologies remains a multifaceted challenge. While nonwoven-supported and nanofibrous composite membranes have demonstrated excellent permeability, tunable structural design, and compatibility with diverse desalination configurations, their long-term stability, large-scale manufacturability, and integration into variable energy environments continue to limit full-scale implementation. At the same time, emerging material innovations, system-level optimization strategies, and digital intelligence frameworks present unprecedented opportunities for future advancement.

7.1 CURRENT CHALLENGES

(1) LONG-TERM OPERATIONAL STABILITY REMAINS INSUFFICIENT.

In real-world seawater desalination systems, membranes are continuously exposed to harsh environmental and operational conditions, including high salinity, organic and inorganic contaminants, fluctuating hydraulic pressures, thermal cycling, and microbial activity. These stressors lead to fouling accumulation, oxidative degradation, chemical hydrolysis, pore wetting (in MD), and mechanical fatigue. Nanofibrous membranes, despite offering high specific surface area and superior permeability, exhibit strong foulant affinity and are prone to pore constriction or structural collapse under long-term operation. Likewise, micrometer-scale nonwoven support layers used in RO may densify under high transmembrane pressure, reducing porosity and increasing ICP, ultimately causing irreversible flux decline and diminished salt rejection

(2) INTERMITTENCY OF RENEWABLE ENERGY SYSTEMS INTRODUCES NEW RELIABILITY CONSTRAINTS.

Solar, wave, and wind energy present promising low-carbon pathways for powering desalination. However, their intrinsic intermittency leads to dynamic variations in feed pressure, temperature, and flow rate. These fluctuations induce pressure surges, cyclic stress, and thermal shock within membrane modules, accelerating material fatigue and increasing the risk of wetting failure (in MD), membrane compaction (in RO), or aggravated ICP/CEP (in FO). Designing membranes and modules that can tolerate highly transient operating conditions remains an unresolved engineering challenge.

(3) SCALABLE AND COST-EFFECTIVE MANUFACTURING OF MULTILAYER NONWOVEN MEMBRANES IS STILL LIMITED.

Electrospinning enables precise control over fiber diameter, surface chemistry, and hierarchical pore structures, yet its production rate remains orders of magnitude lower than industrial requirements. Meltblown and spunbond technologies offer scalable manufacturing, but they lack fine control over pore-size uniformity, fiber orientation, and surface functionality, which are crucial for high-performance desalination membranes. Achieving simultaneously high throughput, high precision, and low cost remains a key bottleneck in commercializing advanced multilayer nonwoven composites.

7.2 FUTURE OPPORTUNITIES

Despite these challenges, nonwoven membranes hold substantial potential to shape the next generation of sustainable desalination technologies. Several promising pathways for future development are outlined below:

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(1) INTELLIGENT AND ADAPTIVE MEMBRANE MATERIALS.

Emerging research on stimuli-responsive polymers, dynamic nanoarchitectures, and self-cleaning surfaces offers avenues to develop membranes capable of adjusting wettability, porosity, or charge in response to operational conditions. Gradient-pore structures, biomimetic anti-fouling coatings, and catalytic surfaces could dramatically reduce fouling and extend membrane lifespan.

(2) HYBRID RENEWABLE-ENERGY DESALINATION SYSTEMS.

Integrating desalination modules with hybrid renewable sources, such as combined solar–wind–wave energy systems, and incorporating thermal or electrochemical energy storage can buffer intermittency and improve system stability. Decentralized renewable-powered desalination networks could become especially valuable for remote, off-grid coastal regions.

(3) DIGITAL TWIN TECHNOLOGY AND OPTIMIZED INTELLIGENT CONTROL.

The convergence of IoT-enabled sensing, big data analytics, and machine learning enables the creation of digital twins, virtual replicas of membrane systems capable of real-time monitoring, fault diagnosis, and predictive optimization. Such frameworks can establish a closed-loop “experiment–simulation–control” cycle, minimizing energy consumption, reducing fouling events, and extending operational lifespan.

(4) LIFE-CYCLE ANALYSIS AND CIRCULAR-ECONOMY MEMBRANE DESIGN.

Sustainable deployment requires full LCA of membrane materials and processes, including carbon footprint, water footprint, resource use, and end-of-life disposal. Strategies such as recyclable polymer systems, solvent-free fabrication, modular repairability, and upcycling of end-of-life membranes can help transition desalination technologies toward circular economy principles.

(5) SMALL-SCALE, MODULAR, AND DECENTRALIZED DESALINATION SYSTEMS.

Developing low-cost, energy-efficient small-scale desalination units for rural, island, and emergency applications represents a major future direction. Modular systems allow flexible capacity expansion, simplify maintenance, and reduce infrastructure requirements, accelerating global access to clean water.

Nonwoven membrane–based desalination technologies are at a pivotal transition point, from achieving performance breakthroughs in materials to achieving system-level integration and durable field deployment. Addressing long-term stability, manufacturing scalability, and renewable-energy adaptability is essential for transforming nonwoven membranes into practical, reliable components of global desalination infrastructure. At the same time, integrating innovations across materials design, process engineering, renewable energy utilization, intelligent operation, and sustainability science will accelerate the emergence of next-generation desalination systems that are efficient, stable, low-carbon, and environmentally responsible.

8. CONCLUSIONS

Nonwoven materials have rapidly evolved into indispensable components within modern seawater desalination technologies due to their unique 3D architecture, high porosity, tunable physicochemical properties, and exceptional mechanical robustness. As global freshwater scarcity intensifies, driven by population growth, industrial expansion, and climate-induced variability in natural water resources, the demand for desalination systems that are efficient, low-energy, and environmentally sustainable has never been greater. In this context, nonwoven membranes are uniquely positioned to address emerging challenges by offering structural versatility, multifunctionality, and compatibility with advanced material-processing techniques.

Across diverse desalination platforms, nonwoven membranes fulfill critical functional roles. In RO, PET and PP nonwoven substrates provide the mechanical strength necessary to withstand high operating pressures while promoting uniform PA formation, reducing ICP, and enabling high water flux and salt rejection. In MD, nonwovens must maintain stable hydrophobic and microporous structures to preserve the vapor–liquid interface and prevent pore wetting. Electrospun nanofiber membranes composed of fluorinated PVDF or PTFE have demonstrated exceptional salt rejection (>99.99%) and water fluxes exceeding 50 $L \cdot m^{-2} \cdot h^{-1}$ due to their finely tuned surface roughness and Cassie–Baxter wetting characteristics. In SIE, nonwoven substrates facilitate continuous water supply through interconnected hydrophilic channels and simultaneously support photothermal materials, such as carbon nanostructures or MXenes, that convert solar radiation into highly localized heat. Furthermore, in FO

and ED, controlling pore-size distribution, surface charge, and ion-transport pathways in nonwoven architecture enhances water permeability and reduces energy consumption through minimized mass-transfer resistance.

Importantly, the performance of nonwoven membranes arises not from a single structural parameter but from the synergistic interplay of multiscale features, including fiber diameter, spatial orientation, porosity, membrane thickness, and hierarchical multilayer configurations. Randomly oriented structures, with their inherently high porosity and tortuous pathways, excel in MD and SIE systems where vapor transport or interfacial evaporation dominates. Partially aligned or gradient-oriented structures, though lower in porosity, may enable directional water transport, improved mechanical stability, or integrated sensing functionalities. Fabrication techniques fundamentally shape these architectures: meltblowing supports high-throughput production of micrometer-scale hydrophobic membranes, while electrospinning yields ultrathin nanofibrous layers with high surface area and tunable surface chemistry. Advances in surface functionalization, including plasma activation, PDA and zwitterionic coatings, nanoparticle embedding, and Janus wetting design, further enhance antifouling properties, mechanical durability, wetting resistance, and environmental adaptability.

Despite these advances, several key challenges remain before nonwoven membranes can achieve full-scale commercial deployment. First, membranes that demonstrate excellent short-term performance often experience flux decline, pore wetting, or structural degradation during long-term operation due to thermo-mechanical stress, chemical corrosion, or microbial fouling. Second, nanofibrous membranes tend to lack the intrinsic mechanical strength required for standalone use in high-pressure RO environments, necessitating hybrid reinforcement or post-processing stabilization. Third, many high-performance membranes depend on fluorinated polymers or nanomaterials containing noble metals, which raise concerns regarding cost, recyclability, and environmental impact. Finally, most current research focuses on isolated desalination processes, leaving a need for systematic cross-platform evaluations of nonwoven membrane universality, scalability, and compatibility with renewableenergy-powered desalination systems.

In conclusion, nonwoven membranes represent a highly promising and rapidly advancing frontier in desalination research. Realizing their full potential requires coordinated progress in materials innovation, scalable manufacturing, renewable-energy integration, long-term durability enhancement, and system-level optimization. By bridging these domains, nonwoven architectures can form the foundation of next-generation desalination systems that are not only high-performance and costeffective but also deeply aligned with global sustainability and carbon-reduction goals.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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