

New Membrane Technologies and Their Applications in Reusing and Desalination Processes of Water

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Abstract

There has been an increase in the development of desalination technologies and alternate water sources as a result of the growing scarcity of freshwater. This paper provides an analysis of the aspects that have an impact on costs and emphasises areas that require further investigation. These topics include the characterisation of feed water, the optimisation of systems, and the management of concentrates. It places an emphasis on the necessity of mathematical, computational, and analytical methods in order to enhance water treatment procedures for use in practical applications. Although membrane technologies have shown promise in tackling global water shortages, there are still challenges that need to be addressed before they can be used in a sustainable manner. These challenges include high energy consumption and fouling. Recent technological advances are aimed at enhancing water reuse and desalination processes. Non-conventional water resources, such as desalination and reuse, are increasingly being incorporated into hydrological planning by nations as a result of climate change, population growth, and rising needs, notably in the agricultural sector. Reusing water helps to promote conservation and sustainability, and it aids in the development of a circular economy.

Keywords: Sustainability , desalination, Membranes

1. Introduction

Renewable energy sources like solar energy have been traditionally used for several life-sustaining activities like solar heating, hot water supply, desalination of water, etc. [1-10]. In several arid and semi-arid regions, the problem of water required for drinking and other day-to-day requirements has been critical. Several researchers have studied the impact of water shortage and demand dynamics, alongside cost reduction through Research and Development (R&D) initiatives, on the optimal advancement of desalination technology and the temporal patterns of fresh and desalinated water supply. The growing population of people and businesses has accelerated worldwide water demand. Desalination of seawater and water reclamation are vital strategies to address the significant water demand and ensure our continued prosperity. Nevertheless, the prevailing membranes used for water reclamation and saltwater desalination exhibit limitations, including fouling, elevated energy usage, and inadequate resistance to chlorine. The present study demonstrates the policy characterized by a non-standard most rapid approach path (NSMRAP), wherein the state of desalination technology—represents the cumulative knowledge gained from the R&D initiative covering a predetermined goal process as swiftly as feasible and then progressing along that trajectory of water desalination and reuse. The NSMRAP feature facilitates a comprehensive characterization of the optimal water strategy. Advancements in membrane materials and system design are critically required to enhance their performance.

The regeneration capacity of freshwater allows its stock to follow a non-linear pattern, meaning it can be depleted and later refilled. This review highlights recent advancements in membrane science and materials that enhance sustainability, focusing on the development of next-generation membranes for water reuse and seawater desalination. Thin-film composite (TFC) and thin-film nanocomposite (TFN) membranes, widely used in reverse osmosis (RO), forward osmosis (FO), and nanofiltration (NF) over the last two decades, are the central focus. As TFC membrane manufacturing processes are well-established, any material improvements can be easily scaled up for commercial use. The review also explores innovative membrane technologies like membrane distillation (MD) and hybrid systems, aiming for sustainable water reclamation and seawater desalination [11-12].

2. Optimizing the Design and Functionality of TFC and TFN Membranes

Since Cadotte and Petersen's initial discovery, there has been a substantial amount of progress made in the creation of thin-film composite (TFC) membranes for reverse osmosis and other osmotic processes. Surface changes, tweaks to the interfacial polymerization process, solvent treatments, and the incorporation of aquaporin (AQP) and porous nanoparticles are some of the advancements that have been made. Researchers have been concentrating their efforts on the selective polyamide layer, which is responsible for determining water permeability, salt rejection, and energy consumption. In contrast to porous nanoparticles, which are manufactured from inorganic or organic-inorganic hybrid materials, AQP is a water-channel protein that is generated from living creatures. As a result of denaturation under harsh conditions, AQP-based membranes may have a restricted operational range and a lower capacity for maintaining their sustainability. The performance of hydrophilic porous nanoparticles may be comparable to that of aquaporins, while also providing an increased level of sustainability [12-20]

Researchers have included a variety of porous nanoparticles into the polyamide layer to improve thin-film composite (TFC) membranes for seawater desalination and water reclamation. Nanoparticles, including zeolites, carbon nanotubes, and metal-organic frameworks (MOFs), have significantly enhanced membrane performance. For example, these advanced TFC membranes exhibit a water permeability of 48.5 $L \cdot m^{-2} \cdot h^{-1} \cdot MPa^{-1}$, a salt permeability of 0.913 $L \cdot m^{-2} \cdot h^{-1}$, and a remarkable NaCl rejection rate of 98.8%, illustrating their effectiveness in desalination applications.

Alongside porous nanoparticles, non-porous nanoparticles such as silica, titanium dioxide, nanosilver, and graphene oxide have been included into the polyamide layer of TFC membranes. These non-porous materials have synergistic effects that augment membrane performance. The functional groups on these nanoparticles, exhibiting a strong attraction for water molecules, are thought to significantly enhance water permeability and facilitate interactions with monomers to create an efficient polyamide layer. These operational interactions enhance the overall efficacy of the desalination process [21-29].

The incorporation of porous or non-porous nanoparticles into the polyamide layer ought to be the primary focus of study in the future concerning TFC and TFN membranes. The most desirable nanoparticles are those that are water-stable, porous, and have a particle size, pore size, and chemical functionality that can be adjusted. There is a possibility that UiO-66 could be a porous nanoparticle because of its resistance to both chemicals and heat. In order to promote water transport while simultaneously preventing hydrated cations such as Na+, K+, Ca2+, and Mg2+, pores around 0.6 nm in size may function as water channels. Because of its hydrophilicity and water stability, it can be incorporated into the polyamide layer of reverse osmosis membranes for the purpose of desalinating saltwater [23-24].

Non-porous nanoparticles include carbon quantum dots (CQDs) [30-31]. Li et al. showed that integrating hydrophilic nanocarbon dots, measuring 6.8 nm in quantum size, into the polyamide layer produced reverse osmosis membranes with 56 LMH.MPa-1 pure water permeability, 1.05 LMH salt permeability, and 98.8% NaCl rejection [30]. The surprising results may be due to CQDs' high affinity for water molecules, robust interactions with monomers during interfacial polymerisation, and decreased polymer chain packing [29]. CQD-modified TFC membranes were chlorine-resistant because the hydrogen bonds between CQDs and the polyamide layer tightened polymer chains and prevented amidic hydrogen substitution. The charge repulsion between ACOO- from electron-rich CQDs and active chlorine (OCl-) prevented OCl- from interacting with the membrane surface and reducing its diffusion rate in the polyamide matrix. Ma et al. found that ultrasound-assisted thin-film polymerisation with bicarbonate improves water permeability and salt rejection in interfacial polymerisation [32]. Next-generation reverse osmosis membranes may have better permeability-selectivity.

3. Advanced Hybrid Systems for Sustainable Desalination

Modern seawater reverse osmosis (SWRO) facilities require between 2 and 3.5 kilowatt hours (kWh) to produce 1 cubic metre of freshwater [12]. This is even though substantial developments have been made in the production of RO membranes, high-pressure pumps, and energy recovery devices. As a result of the requirement to make use of high hydraulic pressure to offset the osmotic pressure of seawater, a sizeable amount of the operational expenditure (OpEx) is incurred as a result of increased energy consumption [105-110]. In addition to the ongoing improvement of energy recovery devices, there are primarily two methods that can be utilised to further reduce the amount of energy that is consumed by SWRO [105-110]. These methods are as follows: (a) dilute the seawater feed to increase recovery or decrease RO operating pressure, and (b) recycle and/or reutilise energy from the brine [33-34].

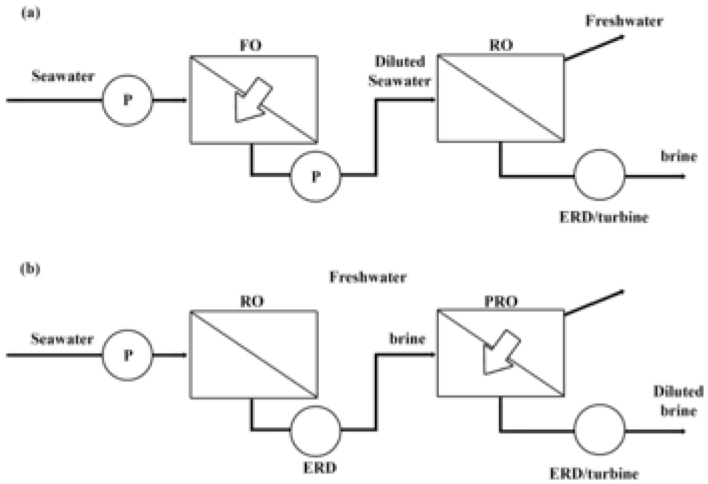


Fig. 1. (a) Forward Osmosis–RO and (b) Reverse Osmosis–PRO combined processes for energy-efficient desalination

Forward osmosis (FO) can be integrated with seawater reverse osmosis (RO) by employing saltwater as the draw solution and wastewater as the feed solution, respectively [35]. FO use the osmotic gradient to enable water movement through semi-permeable membranes, thereby obviating the necessity for high-pressure hydraulic pumping and demonstrating enhanced reversibility in fouling [36].

The osmotic pressure of seawater is decreased as a result of the osmotic dilution of saltwater by wastewater through the process of forward osmosis (FO). This enables reverse osmosis (RO) to function at lower pressures or achieve higher recovery rates while maintaining the same pressure. Furthermore, FO decreases the salinity of saltwater as well as the amounts of contaminants, hence minimizing the fouling and scaling of the RO membrane. Additionally, the pre-treatment costs of seawater reverse osmosis (SWRO) are decreased as a result of this integration, which serves as a pre-treatment stage for wastewater. However, to prevent membrane fouling in FO, the selection of wastewater feed is of the utmost importance. The use of biologically treated wastewater and primary effluent resulted in a reduction of water flux by 25% and 50%, respectively. On the other hand, the fouling caused by secondary effluent was negligible. Techno-economic studies indicate that the energy savings from FO–RO integration outweigh the additional capital expenditure, which results in a 16% reduction in the overall cost of saltwater desalination. This is even though these challenges exist. These findings shed insight into the technological and economic potential of the FO–RO hybrid strategy, which provides a solution for desalination processes that is both more energy-efficient and more cost-effective [37-39].

The brine that is produced by reverse osmosis after saltwater has been subjected to reverse osmosis has a temperature of around 30 degrees Celsius, a high concentration of salts, and a raised pressure. In addition to this, the SWRO pre-treatment provides it with a relatively clean appearance. Pressure exchangers and other conventional energy recovery devices (ERDs) are the only equipment that are capable of recovering energy from high pressure. The warm brine produced by reverse osmosis does not make use of the higher osmotic energy that it can produce. Pressure-retarded osmosis (PRO) was the method that was initially utilised by Loeb and colleagues in order to obtain osmotic energy from concentrated brine [40-41]. One of the first pilot-scale osmotic power facilities was developed by Statkraft, which is located in Norway [42]. In spite of this, both attempts were unsuccessful since there were no membranes that were highly effective [43]. As a result of recent advancements in PRO membranes, transport capacities have been improved, mechanical characteristics have been strengthened, and structural parameters have been lowered [43-44]. When Zhang and Chung synthesised TFC membranes on polyethersulfone (PES) hollow fibre supports, they found that a reduction in salt permeability, which helps to mitigate internal concentration polarisation (ICP), was essential for achieving a maximum power density of 24.3 W.m-2. This was accomplished by using 1 mol. L-1 NaCl and deionised (DI) water as feed solutions [44].

Effectively harvesting osmotic energy from RO brine could reduce SWRO energy consumption by 40%-50%, resulting in 1.1 kWh/m³ [45-46]. Pressure Retarded Osmosis (PRO) fouling is more severe and complex than in FO and RO because wastewater enters Thin-Film Composite (TFC) membranes' porous support. Foulants deposit in the porous, convoluted substrate underlying the polyamide layer [47-50]. It reduces power density and hinders cleaning.

Due to calcium phosphate fouling in the porous membrane substrate, the power density of the TFC-PES membrane decreased from 21.6 $W \cdot m^{-2}$ to 5.7 $W \cdot m^{-2}$. This occurred when the feed solution consisted of municipal wastewater retentate, and the draw solution consisted of 0.8 $mol \cdot L^{-1}$ of sodium chloride at a pressure of 2 MPa [47-48]. The power density was restored to 9–13 $W \cdot m^{-2}$ with the application of coagulation pre-treatment and the acidification of the municipal wastewater retentate. This was accomplished by minimising scaling. In the future, research should concentrate on determining the mechanisms that cause fouling, establishing efficient pretreatment procedures, constructing innovative membrane cleaning systems, and producing anti-fouling membranes in order to keep the power density of PRO membranes stable [51-53]. In spite of these obstacles, the RO-PRO trials conducted at the National University of Singapore and the Japan Megaton Water Project have exceeded the breakeven power density of 5 $W \cdot m^{-2}$ that is necessary for the commercial feasibility of PRO, as forecasted by Statkraft. The incorporation of RO-PRO has the potential to improve the energy efficiency of seawater reverse osmosis (SWRO) as well as its economic competitiveness [54-57]. MD-PRO and SWRO-MD-PRO are suggested due to MD generating a more saline and warmer brine compared to SWRO in Korean GMVP project. The hybrid system can quadruple the maximum power density when the draw solution for PRO is elevated. However, the cost of seawater desalination may be further lowered if an inexpensive heating source is obtained [58-60].

Because FO having a lower propensity to foul, a hybrid system consisting of FO and PRO has been suggested [61]. The draw solution in forward osmosis (FO) and the feed solution in pressure retarded osmosis (PRO) are both functions that are performed by the inter-loop solution. It is possible to achieve a power density that is greater than 5 W.m-2 by taking the inter-loop solution and choosing a NaCl concentration of 0.1 mol. L-1. At the same time, the concentrated brine that is used in PRO as the draw solution can be diluted to the level of saltwater in order to facilitate disposal. Under these circumstances, FO demonstrated a water flux that was comparable to that of existing pretreatment technologies that make use of pressure-driven membrane processes, possibly at a lower cost of operation.

4. Emerging Innovations in Membrane Distillation Technology

It was formerly thought that membrane distillation (MD) was an inefficient method for desalinating saltwater since it required a significant amount of energy. This made it less desirable in comparison to other desalination technologies. MD, on the other hand, has had a rebirth and is presently a fast developing topic of interest as a result of substantial breakthroughs in solar panel efficiency, nanotechnology, and membrane design. Researchers from academic institutions and stakeholders from industry are beginning to acknowledge its promise for desalination that is both more environmentally friendly and more energy efficient. Recent innovations have led to the development of integrated processes such as forward osmosis-membrane distillation (FO-MD), freeze distillation-membrane distillation (FD-MD), freeze distillation-vacuum membrane distillation (FD-VDM), freeze distillation-membrane distillation-crystallization (FD-MD-C), submerged vacuum membrane distillation crystallisation (VMDC) and membrane distillation-solid hollow fibre cooling crystallisation (MD-SHFCC) systems. Crystallisation, wastewater treatment, and resource recovery are just some of the applications that are being investigated for these cutting-edge hybrid systems. Desalination is only one of the many applications that are being investigated. By incorporating MD with other technologies that complement it, the process has become more adaptable, more efficient in terms of energy use, and more financially feasible. As a consequence of this, MD is gaining traction as a potentially useful approach for finding solutions to problems related to water shortage on a worldwide scale and for other industrial uses [66-68].

These processes are in addition to the traditional MD-crystallizer (MD-C) systems [62-66] and the previously mentioned MD- Except in cases where the regeneration of the draw solution is not required, forward osmosis is not an energy-efficient procedure [33,69]. Furthermore, a draw solution that has a higher osmotic pressure may have extra challenges when it comes to regeneration using the conventional pressure-driven procedures. An approach that is conceivable for the economic revitalisation of the draw solution is presented by the incorporation of FO-MD [70-71]. When compared to RO or NF, FO-MD may display more economic viability for the recycling of the draw solution [71]. This is because FO-MD incorporates solar energy and waste heat into its process. In addition, the revitalisation can be attributed to MD's inclusion of distinctive qualities derived from the membrane and distillation processes. It functions at a moderate temperature (50–90 degrees Celsius) and pressure (atmospheric or vacuum), and it potentially achieves complete salt rejection (100 percent). Additionally, it is modular and maximises the use of space. Its separation efficiency is less impacted by feed concentration than other pressure-driven membrane processes, and its energy source may be solar energy or waste heat rather than electricity. In addition, its separation efficiency is less affected by feed concentration. Consequently, MD is a crucial component of the process that must be utilised in order to accomplish the objective of zero liquid discharge desalination (ZLDD), which is characterised by high water recovery, zero waste generation, a variety of energy sources, and cost-effective salt production [72-73].

A hybrid Zero Liquid Discharge (ZLDD) system is seen in Figure 2. This system incorporates Forward Osmosis (FD), Membrane Distillation (MD), and crystallisation, and it makes use of solar energy and liquefied natural gas (LNG) as its sources of power [74]. In a nutshell, the process of acquiring pure ice begins with the freezing of seawater using the cold energy that is generated during the process of LNG regasification. After that, the concentrated brine from the FD process is put through MD treatment, which is supplemented with solar energy, in order to maximise the amount of water that is recovered overall [67,75]. At the end of the process, salt crystals are extracted from the residual brine by use of a crystalliser. The brine that is left over is then recycled and further concentrated in the MD unit [62-65,68].

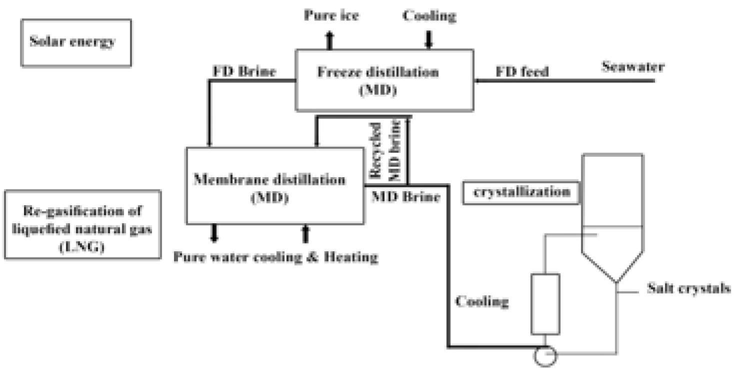


Fig. 2. An integrated hybrid ZLDD system utilizing FD, MD, and crystallization with solar and LNG energy sources, © 2019 Elsevier

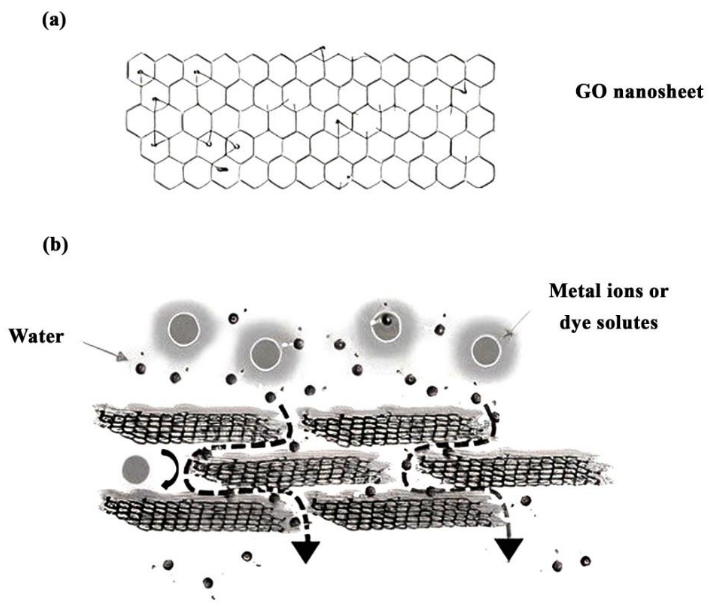
The application of membrane-driven distillation (ZLDD) is essential for attaining zero liquid discharge and converting seawater into drinkable water and valuable salts. The integration of membrane-driven distillation (MD) in zero liquid discharge (ZLD) processes improves its viability by producing pure water and increasing brine concentration for effective crystallisation. High salinity concentrations can induce scaling, obstructing the vapour transport channel, reducing surface energy, and leading to membrane wetness. To establish sustainable ZLDD systems, it is imperative to develop creative designs for MD membranes and modules, as well as distinctive restoration methodologies for regenerating MD membranes, to mitigate scaling challenges and attain a sustainable solution [64,76].

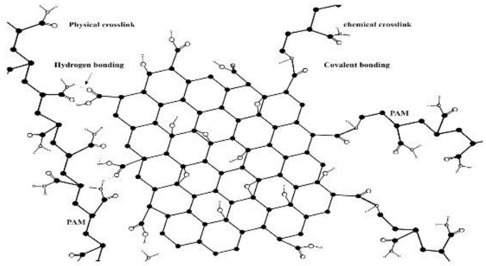
Microporous membranes made of PP, PVDF, and PTFE, together with their modified variants, are frequently utilized as MD membranes [62-66,68]. The short-term efficacy of membranes in seawater and wastewater is noteworthy; nevertheless, long-term performance issues emerge due to scaling, moisture, and the complexity of the input stream. Future membranes must have omniphobic features to reject both high and low-surface tension molecules. Two essential factors for attaining surface omniphobicity are the re-entrant architecture and minimal surface energy. These are accomplished via the deposition or coating of nano/microparticles, mixing, or plasma treatment utilizing fluorinated materials. Future studies should optimize the production process, investigate 3D printing technology for omniphobic re-entrant structures, and examine eco-friendly solvents to mitigate environmental impact [77-79].

Future studies should prioritize the exploration of AGMD and VMD over DCMD in system configuration [79-81]. Despite AGMD exhibiting a lesser flux than DCMD, it demonstrates superior sustainability due to reduced fouling propensity, diminished conductive heat loss, and enhanced energy recovery [82-83]. Conversely, VMD may exhibit superior flux and energy efficiency compared to DCMD, as the vacuum enhances water vapor movement and reduces thermal conduction through the membrane [81,84]. MD membranes engineered with a sandwich cross-sectional structure, including two sponge-like porous layers—inner and outer—and a thin central layer filled with small microvoids, have been developed for VMD to endure vacuum pressure and demonstrate enhanced wetting resistance [85]. Furthermore, to reduce energy consumption, MD membranes including solar heating or photothermal components may represent a promising future approach since this could decrease the necessity for costly solar panels [86].

5. Nanofiltration Membranes: The Role of Graphene Oxide and Carbon Quantum Dots

Nanofiltration (NF) is recognised as an excellent approach for removing contaminants from wastewater, particularly heavy metal ions and dye solutes because it acts through both size exclusion and charge repulsion mechanisms, [87–88]. This is because nanofiltration operates through both of these mechanisms together. It is possible that nanofiltration membranes made of graphene oxide have a substantial potential for use in separation applications. This is because of their ability to improve separation efficiency, mechanical robustness, and chemical durability. The hydration activity that occurs on GO laminates that are submerged in water will result in the incorporation of water layers into the laminates, which will result in an increase in the d-spacing of the virgin GO membranes to about (1.3 ± 0.1) nanometres. Because graphene has an effective thickness of 0.34 nanometres, the dimensions of the nanochannels that exist between graphene sheets are approximately 0.9 to 1 nanometres. This allows for the quick passage of molecules that are smaller than 0.9 nanometres, while simultaneously inhibiting ions or molecules that are larger than that size [89–91]. Because of the presence of carboxyl and hydroxyl groups, graphene oxide (GO) normally displays a negative charge across a wide range of pH levels. As a consequence, pure GO laminates demonstrate improved rejection of negatively charged molecules and divalent anions [90]. Additionally, it contains impressive antibacterial properties, which have the potential to greatly minimise the fouling tendency of the membranes that are produced as a result [89–91]. As a consequence of this, GO has been utilised in the production of NF membranes that are extremely efficient for use in water treatment applications. Figure 3 illustrates a potential chemical structure of a graphene oxide nanosheet, together with the water transport pathways and size exclusion mechanism in graphene oxide membranes [87-91].





(c)

Fig. 3. (a) Proposed chemical structure of a GO nanosheet and (b) mechanisms of water transport and size exclusion in a GO membrane (c) The general arrangement of chemical structure

Many studies have used graphene oxide to remove metal ions and dye solutes from wastewater. Han and colleagues coated commercial microfiltration membranes with base-refluxing reduced graphene oxide (brGO). Reducing the brGO layer thickness to 22 nm led to a 99.2% rejection rate for methyl blue (MW 800) and 218.7 LMH.MPa^{-1} pure water permeability (PWP) in the ultrathin graphene nanofiltration membrane [92]. Layer-by-layer deposition of a graphene oxide selective layer on Torlon hollow fibre substrates by Zhang et al. rejected over 95% of heavy metal cations such Pb2+, Ni2+, and Zn2+ with a permeate water permeability of 47 LMH_MPa_1 [93]. The GO films, produced by vacuum-assisted deposition and cross-linked with boron compounds, rejected 98.74% of methylene blue (MW: 320) and had a PWP above 70 LMH.MPa-1 [94]. Thus, GO is promise for selective molecule capture and transport in water treatment. However, pure GO laminates may swell in water, increasing their d-spacing and nanochannels, making interlayer spacing manipulation difficult [95–97]. Isolating small ions from oedema requires effective methods [98-99]. Thus, future research may adjust and improve the interstitial area between GO layers to remove small ions.

However, CQDs may be suitable for water treatment NF membranes. It is hydrophilic and anti-fouling and antibiofouling like GO. No fully integrated CQD asymmetric membranes for nanofiltration have been shown; only thin-film nanocomposite membranes have been studied [100-101]. Zero-dimensional CQDs in TFN layers are usually evenly distributed due to their small size and versatility. CQDs may lower membrane pore size and increase hydrophilicity, increasing water permeability without reducing rejection efficiency. They are more anti-fouling than membranes without CQDs [100–104]. Thus, CQD-based NF membranes may be promising nanofiltration membranes.

6. Conclusion

The conclusion is that in order to address the worldwide dilemma of fresh water scarcity through desalination, major breakthroughs in both technology and cost reduction are required. The purpose of this study is to emphasise important areas of research and development, specifically in the areas of feedwater and system characterisation, process optimisation, and concentrate recovery. All of these concepts are essential for reducing the costs associated with desalination. There is a significant role played by membrane desalination, which has exceeded thermal methods in terms of popularity. However, the efficiency of membrane desalination is strongly dependent on the quality of the water that is being absorbed and the dependability of modern characterisation techniques. Both the integration of hybrid systems such as FO, MD, and SWRO, as well as innovations in membrane materials such as TFN membranes with MOFs and CQDs, offer viable solutions for reducing energy consumption and operational costs while simultaneously attaining zero liquid discharge desalination (ZLDD) targets. It will be possible to significantly improve the sustainability and affordability of future desalination processes by simplifying the production of omniphobic membranes and making use of low-cost materials such as GO and CQDs. It is anticipated that as renewable energy technologies continue to progress, they will complement these advancements, so facilitating the development of desalination facilities that are both environmentally benign and cost-effective, and this will be the case in both large urban centres and smaller coastal towns. The research that is currently being conducted provides hope for tackling both the current and future concerns of water scarcity.

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