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Engineering Advance

# The Latest Developments and Future Directions in Membrane Distillation

Mohammad Mahdi A. Shirazi *

*Membrane Industry Development Institute, Tehran, Iran*

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## Keywords

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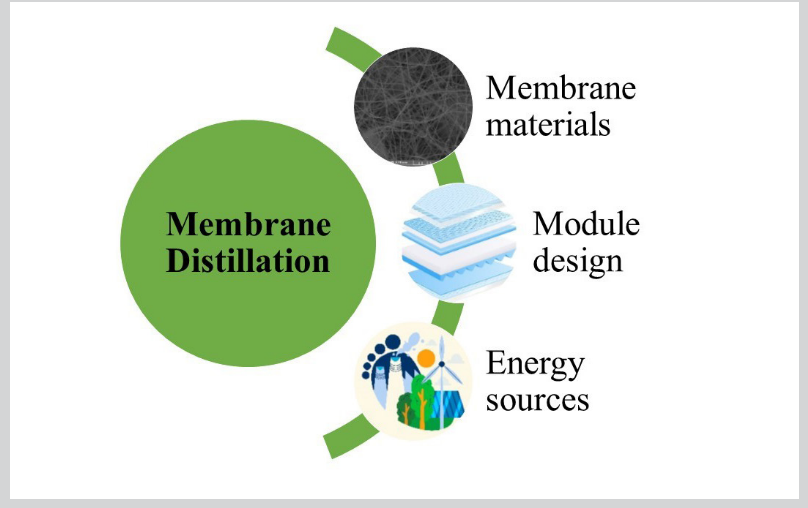
## Highlights

- Membrane distillation (MD) has attracted growing interest in recent years
- Concise and brief discussion of some of the recent developments and future directions for MD
- Future research is focused on new membrane materials, module design, energy efficiency, and scaling up

## Graphical abstract



## Abstract

Membrane distillation (MD) is a thermal separation process that has attracted growing interest in recent years due to its advantages for water and wastewater treatment, and other applications. This “Engineering Advance” provides a concise and brief discussion of some of the most recent developments and future directions for MD for a wide range of applications. According to available data and information on MD in the open literature, the development of new membrane materials and module designs, improving energy efficiency, scaling up, coupling with other technologies, and exploring new applications are some of the key directions for the future of MD technology. This paper highlights these issues with an emphasis on the latest developments.

## 1. Introduction

Membrane distillation (MD) is a non-isothermal separation technique that uses a membrane with high hydrophobicity to selectively allow the passage of water vapor while preventing the liquid feed from intrusion into the pores. The driving force for this process is the vapor pressure difference across the applied microporous membrane. The vapor pressure difference is the driving force for MD, which is provided by imposing a temperature difference across the membrane, where a hot feed stream and a cold permeate stream are separated by the membrane [1]. The temperature difference then creates a vapor pressure gradient across the membrane, resulting in the transport of water vapor through the membrane pores [2]. This process offers several advantages over other separation technologies, including low energy consumption, high efficiency, and the ability to operate at very low pressures. As a result, MD is a promising technology for a wide range of applications, such as desalination, wastewater treatment, and concentration of liquid streams such as fruit juices [3].

Membrane distillation is a relatively new process compared to other separation technologies such as reverse osmosis (RO) and nanofiltration (NF) and has been the subject of extensive research in recent years [4]. The technology has undergone significant developments, resulting in improved membrane materials and module designs, as well as advancements in system integration and control. MD can be operated in a variety of configurations, including direct contact MD (DCMD), air gap MD (AGMD), and sweep gas MD (SGMD), each with its unique advantages and challenges [5]–[8]. The general scheme of these configurations is presented in the supplementary file.

One of the key benefits of MD is its ability to remove a wide range of contaminants with high rejection from a variety of feed streams. This includes the removal of dissolved solids and salts, organic compounds, and other impurities from water, as well as the concentration of liquids such as fruit juices and milk. The process can also be used for the recovery of valuable compounds, such as in the production of biofuels or pharmaceuticals, by separating and purifying specific components of a complex feed stream [9]–[11].

While MD has several advantages, there are also some challenges associated with the technology, such as the lack of specific membranes,

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* Corresponding author: che.shirazi@gmail.com (M.M.A. Shirazi)

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sustainable energy resources, membrane pore wetting, membrane fouling, and scaling, as well as low flux rates in comparison with RO [12]–[16]. However, ongoing research efforts are aimed at addressing these challenges to further improve the efficiency and scalability of membrane distillation.

This paper is an Engineering Advance paper highlighting the latest developments in membrane distillation technology. This includes in recent developments membranes and the MD process. Moreover, future directions are also highlighted.

## 2. New developments for membrane distillation

### 2.1. MD membranes

The membrane is a key component in MD, as it provides the selective barrier that allows the transport of water vapor while preventing the passage of liquid water. Thus, the success of MD relies on the ability of the membrane to maintain a high value of liquid entry pressure (LEP), which is necessary to prevent the wetting of the membrane surface and maintain the vapor-liquid separation [17]. LEP is an important membrane characteristic for MD. It can be defined by the minimum pressure that is required for the feed solution to penetrate the large pores. It is indicated in the literature that an LEP value of >2.5 bar is required for the durable performance of MD [15]. The membrane used in MD must be highly porous to allow for the efficient transport of water vapor, while at the same time being highly hydrophobic to prevent the passage of liquid water and other impurities through the pores [16]. Table 1 presents the recommended values for MD membrane for providing a proper long-term performance.

The widely used membranes in MD are microfiltration (MF) membranes which are made of hydrophobic polymers such as polypropylene (PP), polytetrafluoroethylene (PTFE), and polyvinylidene fluoride (PVDF). These materials have excellent chemical and thermal stability and can withstand the high temperatures and harsh chemical environments encountered in MD [22]. It is reported in the literature that among them, PTFE membranes have already shown better performance [23], [24]. However, these MF membranes have not been specifically fabricated for MD, as a result, have shown limited performance for various applications [1]. Therefore, a part of recent research has been focused on fabricating new and specific membranes for MD [25]. Table 2 explains the concept for some of these developments.

Pore structure and morphology of the membrane are important factors in MD. Membranes with a high porosity and a narrow pore size distribution are preferred, as they allow for the efficient transport of water vapor while minimizing heat loss through the thermal conduction of the membrane. Nanofiber membranes are a good example of such alternatives for providing a promising MD application [26]. Nanofiber membranes have been investigated for desalination and wastewater treatment, and the obtained results were promising [27]–[31]. For example, Kim and co-workers [32] fabricated crosshatched nanofiber membranes for DCMD using PVDF-HFP polymer. The proposed crosshatched pattern involved laminating alternating layers of aligned nanofibers. According to the authors, the performance of the membrane could be greatly improved by the novel structure for stable performance over 100 h (permeate flux: 65 kg/m$^2$h; and salt rejection: 99.99%). In contrast to electrospun materials with a random fiber orientation, this was accomplished by decreasing the membrane's tortuosity and increasing mechanical strength. In another work, Afsari and co-workers [33] developed a new nanofiber membrane with a composite structure. The proposed membrane was used for treating the geothermal brine toward lithium enrichment. The membrane sample was tested using feedwater containing different concentrations of NaCl (0–100 g/L). The optimum membrane sample with heat-pressed treatment could provide the permeate flux of 14–19 L/m$^2$.h and 99% salt rejection. The authors also performed the economic analysis and concluded that the 2.9 USD/m$^3$ of leveled cost could be achieved for lithium brine concentration when the heat source is within the feed.

However, the nanofiber membranes suffer from a lack of mechanical strength, which should be improved in future research [34], [35]. Membranes with a composite structure, consisting of a thin, hydrophobic top layer and a hydrophilic support layer, have also shown remarkable performance in MD applications. In this membrane configuration, each layer possesses a specific role. While the hydrophobic top layer prevents liquid intrusion into the pores, the hydrophobic bottom layer can enhance the permeate flux and reduce heat loss via thermal conduction [36]–[40].

Recent advancements in material science and fabrication techniques have also led to the development of new membrane materials and designs for MD, including composite membranes, nanocomposite membranes, and ceramic membranes. These advancements could provide improvements in membrane performance, including increased flux, selectivity, and durability, and have further expanded the potential applications of MD [25], [41]–[44]. There have been several other advancements in the development of new membranes for MD, aimed at improving the performance and efficiency of the process. Superhydrophobic membranes are designed to have a high degree of hydrophobicity, which helps to prevent the wetting of the membrane surface and maintain the vapor-liquid separation. These membranes have a highly textured surface that allows for efficient vapor transport while minimizing the surface area available for liquid water to form. This could provide higher permeate fluxes in comparison with hydrophobic membranes and can lead to improved performance and reduced fouling [30]. For example, Zhou and coworkers [45] developed a superhydrophobic nanofiber membrane with a hierarchical structure design (surface contact angle: 158º). The membrane samples were made of PVDF-HFP polymer, and the optimum membrane sample possessed a large pore size of 3.35 µm, porosity of 81.3%, and thickness of 140 µm. The obtained results revealed that the best membrane sample could provide the permeate flux of 33.45 kg/m$^2$.h and 99% rejection.

Hybrid or mixed matrix membranes are made from a combination of different materials, such as inorganic and polymer materials, to create a membrane with improved selectivity and durability. The properties of each material can be tailored to optimize the membrane for a specific application, resulting in higher fluxes and better separation performance compared to conventional MD membranes. For example, the inorganic additive can provide excellent selectivity, while polymer materials (matrix) can provide good flexibility and resistance to fouling. Hybrid membranes can be designed with a variety of morphologies, including asymmetric or composite structures, to optimize their performance for a given application [46], [47]. Sanaeepur and co-workers [47] comprehensively reviewed mixed matrix nanofiber membranes for water and wastewater treatment using MD. Carbon-based membranes, such as graphene and graphene oxide membranes, are a type of nanocomposite membrane that have been shown to have high selectivity and enhanced permeate flux rates for MD applications. These membranes can have a highly uniform pore size distribution, which can lead to improved separation performance and reduced fouling. Graphene oxide membranes are typically made from a thin layer of graphene oxide sheets, which can be tailored to optimize the properties of the membrane. Carbon-based membranes are also attractive for their excellent thermal and chemical stability, making them suitable for use in harsh environments [48]. For example, Chen and co-workers [49] developed a novel omniphobic membrane to address the issue of wetting caused by low surface energy contaminants in MD. A graphene oxide (GO) membrane, which was fabricated using plasma treatment and fluoroalkyl grafting of stacked GO laminates, was considered for the new design. When a feed sample containing 35 g/L NaCl solution and 0.2–0.4 mM sodium dodecyl sulfate was used at 60 °C, the resulting membrane could provide excellent permeate flux (35 kg/m$^2$.h) and solute rejection (99.9%) during over 450 hours of DCMD process. In another work, Hui Ting and co-workers [50] investigated the development of mixed matrix membranes for MD using PVDF and rGO, using the phase inversion technique. The membrane samples were used for desalination experiments, and the obtained results revealed that mixed matrix membranes with low rGO-PVDF concentration exhibited better permeate flux with a 31.79% increase compared to the pristine membrane, delivering a permeate flux of 31.92 ± 2.85 kg/m$^2$h. Moreover, when the DCND process was run for 40 h, the new membranes could display 99.99% salt rejection.

**Table 1**
Recommended characteristics for MD membranes.

| Parameter | Recommended value | Description | Ref. |
|---|---|---|---|
| Pore size | 0.1-0.45 µ | Smaller pore size is recommended to ensure higher LEP | [1] |
| LEP | 2.5 bar | As high as possible to ensure the pore-wetting prevention | [18] |
| Contact angle | >120º | As hydrophobic as possible | [19] |
| Porosity | 75-85% | As high as possible unless it affects the mechanical strength | [20] |
| Thickness | 30-60 µm<br>or<br>>200 µm | Thin membranes are recommended for low salinity, while thicker membranes can show better performance for higher salinity | [21] |

**Table 2**
New concepts in membrane development for MD technology.

| Concept | Description | Opportunities | Challenges |
|---|---|---|---|
| Superhydrophobic membranes | These membranes have highly textured surfaces that allow for efficient vapor transport while maintaining a high degree of hydrophobicity | • Higher permeate flux than conventional hydrophobic membranes<br>• Higher pore wetting resistance (in case of high LEP value) | • Fouling and scaling are important issues<br>• The durability of the superhydrophobic state after long work life |
| Hybrid or mixed matrix membranes | These membranes combine the properties of multiple materials, such as inorganic and polymer materials, to create a membrane with improved selectivity and durability | • Improved permeate flux<br>• Improved durability<br>• Capable to work with higher feed temperature<br>• Functionability of the membrane surface for wastewater treatment | • Expensive to scale up<br>• Potential release and stability of micro/nanoparticles |
| Carbon-based membranes | Carbon-based membranes, such as graphene and graphene oxide membranes, have been shown to have high selectivity and high flux rates for MD applications | • Unique pore structure<br>• Highly uniform pore size distribution<br>• Reduced fouling tendency | • Challenging in large-scale production and expensive production |
| Smart membranes | These membranes can respond to changes in the feed solution, such as changes in temperature or pH, and adjust their performance accordingly | • Adjusting their properties in response to changing conditions<br>• Promising wastewater treatment | • Challenging in large-scale production and expensive production |
| Self-cleaning membranes | These membranes have a surface coating that can prevent fouling and scaling | • Durable performance for long-term operation on a large scale<br>• Promising wastewater treatment<br>• | • Challenging in large-scale production and expensive production |

Smart membranes are capable to respond to changes in the feed solution, such as changes in temperature or pH, and adjusting their performance accordingly. These membranes are typically made from responsive polymers, which can change their properties and structure in response to external stimuli. For example, a smart membrane could become more hydrophobic in response to changes in pH, which can help to prevent pore wetting and improve separation performance. Smart membranes have the potential to improve the performance of MD by adjusting their properties in response to changing conditions [53], [54]. Self-cleaning membranes have a surface coating that can prevent fouling and scaling, which can lead to reduced performance and increased maintenance requirements [55]. These membranes, also known as Omniphobic and Janus membranes, are typically made from materials such as polyvinylidene fluoride (PVDF) or other polymers, which have excellent chemical and thermal stability. The surface coating can be fabricated using specific materials, depending on the application requirements. For example, a hydrophilic coating can help to prevent fouling by promoting the formation of a thin water layer on the membrane surface, while a hydrophobic coating can help to prevent pore wetting and scaling by repelling mineral deposits. Self-cleaning membranes can have improved durability and reduced maintenance costs, making them more attractive for large-scale MD applications, such as oily wastewater treatment [56]–[58].

According to the observed trend, the future of membranes for MD is promising, as ongoing research efforts continue to explore new materials and designs that can further improve the performance and efficiency of the process [59]. Some of the key areas of focus for future membrane development in MD can be explained as follow.

New research has been exploring the use of advanced materials such as nanomaterials, covalent organic frameworks (COFs), and metal-organic frameworks (MOFs) for MD applications [60]. These materials offer unique properties such as high selectivity, high flux, and improved durability. Moreover, they can provide the chance to significantly improve the performance of MD-based water treatment systems. However, the high production cost and potential release of nanomaterials to the environment are among the major concerns [61]–[63]. 3D printing technology is recently being used to create customized stuff such as spacers with complex geometries and structures that can reduce fouling and enhance separation performance, as well. 3D printing can also reduce manufacturing costs and improve the scalability of membrane production, making MD more accessible for a wider range of applications. For example, Tian and co-workers [64] investigated the use of 3D printing technology for fabricating specific membranes in MD. The authors printed polyamide (PA) membranes using the laser sintering technique and coated them with thin layers of PVDF to reduce the pore size. The results showed that the membrane pore size could be reduced from ~16 μm to 1.0–2.5 μm by imposing the PVDF layers. Moreover, the 3DP membranes had a granular and rough surface, resulting in greater surface hydrophobicity (100°–130°) compared to the control membrane (i.e., the sample which was fabricated on flat substrates with surface hydrophobicity of ~70°). The authors also concluded that imposing higher porosity to the 3D-printed membranes could make the fabrication step faster and reduce the solvent discharge. In another recent study, Thomas and co-workers suggested that modifying the surface of feed spacers rather than the membranes themselves may be a better approach to preventing scaling in MD. The authors developed an anti-scaling 3D-printed spacer made of polyamide. The membrane samples were fabricated via a sol-gel process along with a coating of fluorinated silica (FS) nanoparticles. According to the author's conclusion, the proposed fabrication strategy could enhance hydrophobicity through the increment of the spacer's microscale roughness. DCMD was fed by calcium sulfate solution to test the anti-scaling properties of the FS-coated printed surface. The results showed that the FS-coated spacer significantly reduced scaling compared to the uncoated spacer, with a 74% decrease in scalant attachment and a 60% reduction in scaling on the membrane surface. The authors concluded that the microscale roughness-induced hydrophobicity and reduced surface-free energy of the FS coating were the main factors that contributed to its anti-scaling properties. However, reaching a high resolution for a desired range of membrane pore size and mechanical strength are among the major challenges in the way for 3D-fabricated membranes [65]–[69].

The use of biomimetic designs for membranes, inspired by natural systems such as plant leaves or animal membranes, has recently been explored [70]. These designs can provide improved selectivity and flux rates and can be more resistant to fouling and scaling than conventional membranes. According to the literature, the bio-inspired membrane could perform remarkably in different MD applications [71]. Furthermore, as MD is an energy-intensive process, there is a growing interest in developing low-energy membranes that can enhance the energy efficiency of the process. This includes the use of materials with low thermal conductivity for high-temperature MD as well as the development of membranes that can operate at lower temperatures [25]. Another promising alternative for MD membranes is a photothermal membrane. The photothermal membrane is designed to use light to heat the membrane surface and enhance the rate of water vapor transport, leading to an increase in the permeate flux and energy efficiency [72]. The photothermal membrane is typically composed of a thin layer of a photoactive material that is coated onto a conventional membrane substrate, such as a polymer or ceramic. The photoactive material is typically a semiconductor, such as titanium dioxide or zinc oxide, which can absorb light and convert it into heat. This localized heating at the membrane surface can enhance the rate of water vapor transport through the membrane pores, resulting in increased permeate production and reduced energy consumption. In addition to its enhanced separation efficiency, the photothermal membrane has several other advantages over conventional membranes used in MD. The use of light to heat the membrane surface can provide greater control over the heating process, which can lead to improved selectivity and reduced fouling of the membrane. The use of photoactive material on the membrane surface can also provide additional benefits, such as self-cleaning and antibacterial properties. For example, Chen and co-workers [73] investigated a new photothermal Janus membrane with asymmetric wettability. In the new proposed membrane structure, the high light absorption was provided by a polypyrrole (PPy) coating, the skeleton was provided by PAN nanofibers incorporated with hydrophilic $SiO_2$, and the channels for vapor scape were provided by PVDF-HFP nanofiber layer incorporated with superhydrophobic

F-$SiO_2$. The results revealed that the new membrane could provide 99.9% salt rejection and 44.4 $kg/m^2.h$ permeate flux. Moreover, the efficiency of solar energy utilization could reach ~92%. The authors concluded that this study could open a new way for efficient MD-based water treatment in terms of energy efficiency and permeate flux. Despite these advantages, the development and commercialization of photothermal membranes for MD are still in their early stages. Further research is needed to optimize the design and performance of these membranes, as well as to develop cost-effective methods for large-scale production. However, the potential benefits of photothermal membranes make them a promising technology for improving the efficiency and sustainability of MD processes [74].

According to the above discussion, it can be expected that the future of membranes for MD is focused on developing new materials and designs that can improve the energy efficiency, permeate flux, and sustainability of the process, while also reducing the costs and carbon footprint for production. Ongoing research and development in this area are expected to lead to significant improvements in the performance and scalability of MD, making it a more viable option not only for desalination but also for a wider range of applications such as nutrients and resource recovery.

## 2.2. MD process

The module design is a critical aspect of MD systems, as it determines the efficiency and performance of the process. The design of the module should take into account factors such as the properties of the feed solution, the desired permeate quality, and the flow rates of the system. In MD, the module typically consists of several membrane sheets, tubes, or hollow fibers, which are assembled into a compact module. To perform on an industrial scale, the module should be designed to provide a large membrane surface area, which maximizes the flux rate of the process. The module can be arranged in a parallel or series configuration, depending on the operating conditions and system requirements. In a parallel configuration, the feed solution flows in parallel to the membrane surface, while in a series configuration, the feed solution flows in series along the membrane surface. In addition to the membrane sheets or tubes, the module may also include several additional components, such as spacers, gaskets, and support structures [75]. The spacers help to maintain a consistent flow of the feed solution along the membrane surface, while the gaskets provide a tight seal between the membrane sheets or tubes to prevent leaks. The support structures provide mechanical support to the module and help to distribute the flow of the feed solution evenly across the membrane surface. The module design can also include several additional features to improve the performance and efficiency of the process. For example, some modules may include heating elements to maintain a consistent temperature across the membrane surface, or cooling elements to prevent overheating of the system. Other modules may include a cleaning system to remove fouling or scaling on the membrane surface, which can reduce the performance of the process over time [76]. One important factor in module design is the choice of configuration. In addition to the co-current and counter-current configurations, there are other options, such as a crossflow configuration, in which the feed solution flows perpendicular to the membrane surface. The choice of configuration will depend on factors such as the properties of the feed solution and the desired permeate quality. For example, Shirazi and co-workers [23] investigated the crossflow arrangement for DCMD and its effect on the permeate flux. The authors concluded that this flow arrangement for the MD module along with a PTFE membrane with 0.22 µm pore size could provide the best performance in terms of the permeate flux and solute rejection. Another example is the multi-pass MD module with hollow fiber membranes. Tsai and co-workers [77] investigated novel module designs with multi-pass configurations for MD. The authors examined three module designs including the traditional design with one shell and one tube pass, a design with one shell and multiple tube passes, and a design with equal numbers of shell and tube passes. According to the obtained results, up to 92% higher permeate flux could be achieved by the traditional design compared to the multi-pass design (with equal numbers of shell and tube passes). However, the multi-pass design (with equal numbers of shell and tube passes) was more energy efficient with up to 35% less thermal energy consumption than the traditional single-pass design. Moreover, the pressure drop in the multi-pass modules was only 1.5% higher than in the conventional module with the single pass.

The future of module design for MD is a rapidly evolving field, with ongoing research and development aimed at improving the performance, efficiency, sustainability, and scalability of the process, while reducing costs and increasing accessibility for a wider range of applications. Some of the key areas of focus for future module design in MD are presented in Table 3.

## 2.3. Energy sources for MD

As a non-isothermal separation, MD required an external energy source to drive the process of the separation of water and solutes. The energy sources used to power the process can have a significant impact on the efficiency, cost, and sustainability of the process [78].

The most common energy source for MD is thermal energy. This can be provided by a variety of sources, such as electricity, natural gas, or waste heat from industrial processes. The thermal energy is used to heat the feed solution and create the temperature gradient that drives the separation of water vapor from the feed solution [79]. For example, the waste thermal energy in fuel cell technology can be used for running MD systems [80], [81]. Bazargan Harandi and co-workers [81] investigated two hybrid systems to increase energy efficiency in MD. The first system integrated flat-plate collectors (FPC) and DCMD, while in the second system, DCMD was integrated with a proton exchange membrane fuel cell (PEMFC). These systems could enjoy the utilization of renewable energy and waste heat from PEMFCs to enhance overall efficiency. The performance of the proposed systems was evaluated through a simulation of representative days in Wuhan, China. The obtained permeate flux of the integrated FPC-DCMD system was measured at about 77.4 $kg/m^2h$. The authors claimed that the FPC-DCMD system could provide ~70% of the total energy which is required at maximum mode during the summer solstice. Moreover, the second scenario, i.e., harvesting waste thermal energy from the PEMFC system, could provide ~73% of the total required energy for DCMD-based water treatment.

**Table 3**
Guideline for new concepts in module development for MD technology.

| Concept | Description |
|---|---|
| Integration with renewable energy sources | One of the main challenges of membrane distillation is the energy required to drive the process. Future module designs may incorporate renewable energy sources, such as solar or wind power, to reduce the carbon footprint of the process and increase its sustainability. |
| Advanced materials | The choice of module material is important to the performance of the process, and ongoing research is focused on developing new techniques for module fabrication, such as 3D printing, and new materials with improved properties, such as lower heat loss and better durability in harsh environments. In some cases, such as MD for wastewater treatment, the spacer or the membrane can be impregnated with catalytic materials for efficient and *in-situ* wastewater treatment. |
| Advanced monitoring and control systems | Advanced monitoring and control systems can improve the efficiency and performance of the process by optimizing key parameters, such as flow rate and temperature (specifically the local temperature on the membrane surface), in real-time. |
| Reduced temperature and concentration polarizations | Temperature and concentration polarizations can significantly reduce the permeate flux and energy efficiency, specifically on large scale. Thus, novel strategies, such as spacer design with desired shape using 3D printing, can be investigated. |
| Modular design | Modular designs can provide greater flexibility and scalability in membrane distillation systems, allowing for easy expansion or contraction of the system as needed. |
| Cost reduction | The high cost of MD systems is still a significant barrier to their widespread adoption, and ongoing research is focused on reducing costs through the optimization of materials, manufacturing processes, and module design. |

Solar energy is an attractive option for running MD processes, particularly in remote or off-grid locations where access to electricity or natural gas is limited. For example, solar energy is widely available in Africa, the Middle East, and many other regions. Solar collectors can therefore be used to heat the feed solution in MD, providing the thermal energy needed to drive the process, and make it much more sustainable [82]. Alquraish and co-workers [83] investigated water desalination using a new solar MD plant prototype. The experiment was conducted in Kairouan City, Tunisia, where the plant relied solely upon the sun as its energy source. The process involved using solar energy collectors to heat brackish water through photovoltaic panels. The membrane used in the study was a spiral wound design that allowed for effective internal heat recovery and a compact arrangement. The experiment was successfully carried out, and production averaged approximately 15.92 kg/m$^2$.day in August 2020, with the distillate's electrical conductivity at 1865 µS/cm. Moreover, the authors calculated the specific thermal energy consumption for the system in the range of 90 to 310 kWh/m$^3$. Miladi and co-workers [84] investigated the energy performance of a solar-powered VMD system coupled with a liquid ring vacuum pump, using various energy evaluation criteria for twelve months of the year. The authors discussed that average daily production could vary in the range of 598-217 kg/day across the months. The average gained output ratio, average specific energy consumption, and average energy efficiency were measured in the ranges of 0.93-1.01%, 671-699 kWh/m$^3$, and 56.2-59.3%, respectively. The best energy performance was observed in June due to the highest solar radiation, and the vacuum liquid ring pump was found to have lower electrical energy consumption, ranging from 4.2 to 7.47 kWh/m3 throughout the year. The authors also examined the effect of vacuum level and liquid ring temperature on energy performance, showing that increasing the vacuum led to lower specific energy consumption, and using an operating liquid at reduced temperatures reduced flow rate and energy loss. In other investigations, both life cycle assessment and economic evaluations revealed the great potential in integrating solar energy with MD for different applications [85], [86]. However, further investigations should be carried out in this field and integration of MD with solar energy, in particles in pilot and large scales for water production and wastewater treatment [87].

Geothermal energy is another potential energy source for MD. In areas with high geothermal activity (e.g., Iceland, El Salvador, New Zealand, Kenya, the Philippines, Turkey, Iran, Pakistan, etc.) [89], [90], the natural heat of the earth can be used to heat the feed solution and create the temperature gradient needed for the process [91].

Wind energy can be used to power the generation of electricity, which can then be used to provide the thermal energy needed for MD. For example, there is a great potential for utilizing wind power to run MD systems in some countries such as Denmark, Spain, and Germany, where a considerable amount of the required energy is produced using wind turbines [93]–[95]. Bio-sourced energy, such as biomass and biogas, can be used to generate heat and provide the thermal energy needed for the MD process. This can be particularly useful in areas with abundant biomass resources (e.g., Canada) and/or limited access to other energy sources (e.g., Bangladesh) [96]. Hydroelectric power, which is generated by water flowing through turbines, is another example of a renewable energy source for MD systems. It can be used to power the electricity needed to provide thermal energy for MD. This energy source is renewable and has low greenhouse gas emissions. Another renewable energy source for MD is ocean energy. Ocean energy can be used in various forms. For example, tidal energy, which is generated by the rise and fall of ocean tides, can also be used to power electricity for MD. This energy source is predictable and reliable, with low environmental impact. Wave energy, which is generated by the motion of ocean waves, can also be used to power electricity for MD. This energy source is abundant and has a low environmental impact, but it can be less predictable than other sources [97].

Moreover, a combination of different energy sources may be used to power MD. For example, a solar collector may provide the thermal energy needed during the day, while an electric heater powered by wind energy may be used at night. The choice of energy source will depend on a variety of factors, such as the availability and cost of different energy sources in the area, the desired level of sustainability and environmental impact, and the performance requirements of the MD systems [98]. Ongoing research and development in this field are aimed at improving the efficiency and sustainability of MD by optimizing the energy sources used to power the process.

## 3. Perspectives and conclusions

The future of MD is bright, as it has the potential to provide a sustainable and cost-effective solution for desalination and wastewater treatment. Therefore, some potential areas of development could shape the future of MD technology (Fig. 1), including:

- The development of new membrane materials with improved selectivity, stability, and permeability could lead to better performance and longer membrane lifetimes.
- The integration of MD with renewable energy sources, such as solar, wind, or geothermal energy, could make the process more sustainable and reduce its environmental impact. These alternative energy sources could also help to reduce the overall cost of the process.
- Hybrid systems combining MD with other separation and purification processes, such as RO, FO, crystallization, or electro-dialysis, could lead to more efficient and cost-effective processes. These systems could also make use of waste heat or other alternative energy sources to reduce energy consumption.
- The use of artificial intelligence, machine learning, and advanced process control algorithms, could optimize the operating parameters of the process, reduce energy consumption, and improve the reliability and consistency of MD.
- The modular design and portability of MD systems can provide greater flexibility in system configuration, making it easier to adapt to different feed water qualities, and to scale up or down depending on demand. This can be beneficial for small water production systems, such as emergency water supply.
- The commercialization and market adoption of MD systems could be driven by improvements in the technology's efficiency, cost-effectiveness, and reliability, as well as by increasing demand for sustainable water treatment solutions.

Overall, the future of MD technology is likely to be shaped by advances in membrane materials, integration with renewable energy sources, digitization and automation, modular design and portability, and increased market adoption. These developments could help to make MD a more sustainable, cost-effective, and widely adopted technology for water desalination and purification.

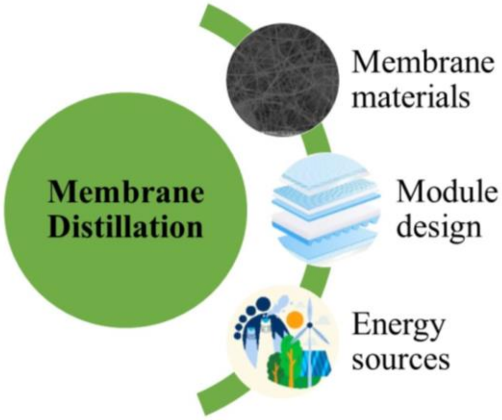

**Fig. 1**. Three main potential areas for developing and industrialization of MD.

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## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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