



# An Overview of Membrane Distillation Technology: One of the Perfect Fighters for Desalination

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## Abstract

Water scarcity is a major concern all over the world and efforts have been made to stop this crisis by making water drinkable. For water purification, different techniques have been used such as reverse osmosis (RO), ultra-filtration (UF), nano-filtration (NF), microfiltration (MF), multi-effect distillation (MED), multi-stage flash evaporation (MSF), mechanical vapor compression (MVC) and membrane distillation (MD). Among these techniques, MD is one of the most promising technologies that emerged in the last few decades. It is a temperature-driven separation process in which only water vapors can pass through the micro-porous hydrophobic membrane leaving behind the other undesired substances. The main factor in this process is the temperature gradient developed across the membrane. The hydrophobicity of the membrane restricts the mass transfer through the membrane. In this review, the membrane distillation technique has been discussed with all its properties and applications. The main focus is on membrane characteristics finding a way to develop a suitable membrane for water desalination. The battle to acquire 100 % salt rejection in membrane distillation is a continuing effort by researchers. This review article highlights certain point regarding the membrane distillation technology viz.; membrane distillation history, its characteristics, properties, types and applications.

**Keywords:** Membrane distillation; Ultrafiltration; Hydrophobicity; Sweeping; Module; Synthetic membranes; Treatment; Membrane fouling.

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## 1. Introduction

Presently, the percentage of clean drinking water on earth is very small and is the biggest concern of the present generation. To solve this water crisis, two processes viz treatment of wastewater and desalination of seawater are mainly considered. The treatment of industrial wastewater can also be a good option for freshwater.<sup>[1]</sup> However, the treatment of wastewater (industrial or municipal) is not that much easy because of the presence of a large amount of salinity along

with other contaminants. On the other hand, at present desalination is mostly preferred in around 120 countries and approximately 15,000 desalination plants are operating all over the world.<sup>[1]</sup> The largest desalination plants are located in Saudi Arabia, United Arab Emirates. Presently, desalination plants are working on different pressure-driven technologies such as nano-filtration (NF), ultra-filtration (UF), microfiltration (MF), and reverse osmosis (RO). Some of the thermal-based technologies were also used on small scale such as multi-effect distillation (MED), multi-stage flash evaporation (MSF), and mechanical vapour compression (MVC). Moreover, both technologies are used but membrane technologies are leading in the current scenario. The key element in membrane-based technologies is a membrane.<sup>[1]</sup>

Among all the technologies for desalination, membrane distillation (MD) is one of the rising and promising technologies. It is a temperature-driven separation process in which only water vapours can pass through the micro-porous hydrophobic membrane leaving behind the other undesired

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substances. The main factor in this process is the temperature gradient developed across the membrane. The hydrophobicity of the membrane restricts the mass transfer through the membrane. The micro-porous hydrophobic membrane is inserted between the feed side and the permeate side. The solution (such as seawater) on the feed side is heated and the cold solution is filled on the permeate side.<sup>[2]</sup> MD technology is a combination of membrane and distillation as shown in Fig. 1. Vapour pressure is the propeller in membrane distillation. Different types of MD configurations are used in this technology.<sup>[3]</sup> The most common configurations are air gap membrane distillation (AGMD), sweeping gas membrane distillation (SGMD), direct contact membrane distillation (DCMD), and vacuum membrane distillation (VMD).

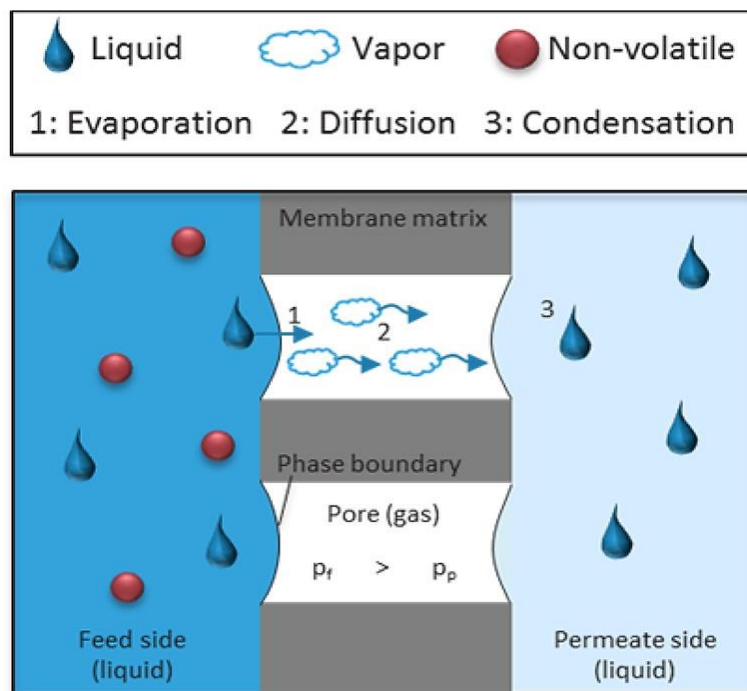
## 2. History of the membrane distillation

The membrane distillation process was first explained by Bodell<sup>[4]</sup> (June 3, 1963) for which he filed a U.S. patent which describes an approach to producing potable water from an importable aqueous mixture. He designed an apparatus with silicone rubber as a membrane that was permeable only to water vapours and not to water. He further stated that hydrophobic polymers such as polysulfone, polyether sulfone, polyvinyl chloride and hydrophilic polymers coated by hydrophobic material could be used for the fabrication of MD membranes.

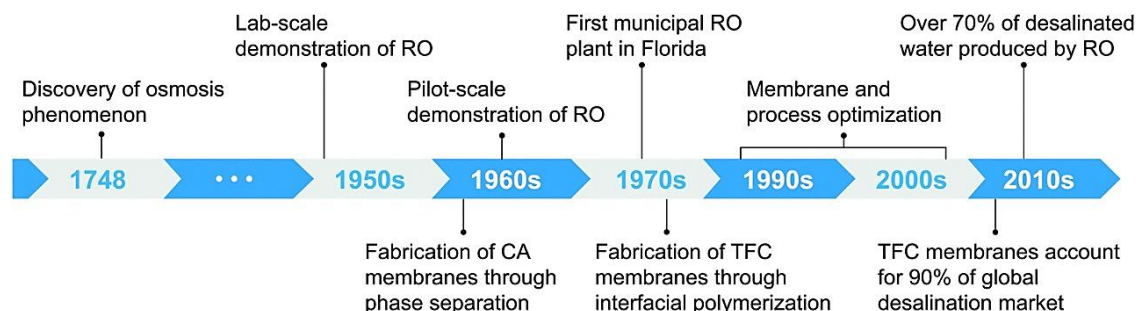
Further, in 1967, Weyl filed a U.S. patent in which he described the assembly with polytetrafluoroethylene [PTFE] membrane for the recovery of water from seawater.<sup>[5]</sup> In the same year, the first paper on membrane distillation was

published by Findley<sup>[6]</sup> in the international journal “Industrial & Engineering Chemistry Process Design and Development”. A second U.S. patent was filed by Bodell in 1968, partly as a continuation of his first U.S. patent. In this, Bodell explained about a system in which importable aqueous solutions were converted to potable water using a parallel array of tubular silicone membranes having 0.3mm and 0.64mm inner and outer diameters, respectively. Membrane characteristics such as pore size and porosity were not discussed. The vapour pressure i.e. 4 kPa was also recommended by Bodell in the airside of the previously cited U.S. patents. Findley<sup>[6]</sup> used gumwood, aluminium foil, cellophane, silicon, teflon, and glass fibers to fabricate MD membranes. Due to the low flux of fluids through the membranes, research interest in this field decreased on MD for a short period of time.

In the early 1980s, MD further gained attention due to improvement in membrane manufacturing techniques. The MD was first commercialized by Enka AG, Gore and co-workers at the Swedish National Development Co.,<sup>[4]</sup> where they used the plate and frame membrane module in air gap membrane distillation. The biologically oxygenator inert membranes were also developed by Esato *et al.*<sup>[6]</sup> and were commercialized under the name Gore-Tex membranes distillation as a spiral wound module. In 1984, in the Europe-Japan joint Congress on membranes and membrane processes, Enka presented the results of his experiments in which he used DCMD configurations applying polypropylene (PP) hollow fiber membranes. A brief view of membrane distillation history is shown in Fig. 2. The interest in MD has been grown in the academic community for the past 25 years.<sup>[4-7]</sup>



**Fig. 1** Schematic representation of the direct contact membrane distillation process. Reproduced with the permission from [2], Copyright 2018 American Chemical Society.



**Fig. 2** Timeline history of membranes distillation process with different phases. Reproduced with the permission from [7], Copyright 2018 Royal Society of Chemistry.

### 3. MD membrane characteristics

To develop high quality membrane for the membrane distillation process, the knowledge of membrane characteristics is very important.<sup>[8-11]</sup> Although, the basic characteristics of high-quality membranes are hydrophobicity and microporosity. The hydrophobicity is required to restrict the passage of liquid; hydrophobicity must be as high as possible to make a well-controlled membrane. On the other hand, microporosity is required to obtain the impressive transit of vapours through the membrane. The layer of the membrane could be one, two, or multiple but the necessary condition is that one layer should be hydrophobic and micro-porous. Additionally, there are various general specialties of the membrane such as prolonged service life, stationary selectivity, and penetrability, good thermal and mechanical stability, resistance towards the chemical agents must be high and low thermal conductivity to control heat losses.

#### 3.1 Pore size and pore size distribution (PSD)

The general range of pore size used in the membrane for MD lies in between 0.1 to 1 $\mu$ m. With the help of pore size and mean path travelled by transferred molecules, the permeate flux can be rated. Generally, the vapour flux can be assessed by mean pore size. To attain high, permeate flux, large pore size is required. However, the size of the pores should be small to avert liquid penetration across the membrane. As a consequence, an optimum pore size should be taken for different MD performance. The feed solution and operating conditions are the two main factors on which the pore size depends. The reason behind two mechanisms (heat and mass transfer) that are taken simultaneously is the absence of uniform pore size. Various studies have been done to examine the importance of PSD in MD flux. Khayet *et al.*<sup>[9-11]</sup> have shown that the vapour transfer coefficient could be found out with the help of mean pore size instead of PSD. On the contrary, Martinez *et al.* got the identical vapour pressure coefficient by utilizing the PSD.<sup>[1,7-11]</sup>

#### 3.2 Thickness

It is also a major property of membrane for distillation. The permeate flux and thickness are inversely proportional to each other, which means permeate flux decreases with increasing thickness. The reason behind low permeate flux is high mass transfer resistance. On the other hand heat losses have also inverse relation with thickness. Lagana *et al.*<sup>[8-11]</sup> have done a theoretical study on thickness and pore size distribution. After their study, they concluded that membrane thickness value should lie between 30-60  $\mu$ m. The thickness does not have much effect on air gap membrane distillation (AGMD) because the air gap also works as a predominant resistance to mass transfer.

In the case of multilayer membranes, the hydrophobic layer should be as thin as possible to avoid the resistance of mass transfer. However, the total thickness of the multilayer membrane should be high so that it can prevent heat loss. Some other studies are also conducted by Martinez and Rodriguez-Morto. They showed that in direct contact membrane distillation configurations (DCMD), the thickness was dependent on the operating conditions, the concentration of feed, and the support system of the membrane. Moreover, Essalhi and Khayet also revealed the same observation.<sup>[3,9]</sup>

#### 3.3 Thermal conductivity

Heat conduction of a material is known as thermal conductivity that is represented by symbol  $k$ . The value of thermal conductivity should be low because it directly influences the flux. High thermal conductivity results in a low value of flux. The amount of flux can be increased by using the membranes of low thermal conductivity as suggested by Khayet *et al.*<sup>[11-15]</sup> The thermal conductivity range of many commercial membranes lies in 0.04 ~ 0.07  $Wm^{-1}K^{-1}$ . The thermal conductivity of different materials are shown in Table 1.

#### 3.4 Liquid entry pressure (Wetting pressure)

The liquid entry pressure [LEP] is defined as the pressure

required for penetrating the membrane. Whereas the liquid should not penetrate the pores of the membrane, if this happens then the membrane becomes wet. To prevent the wetting of the membrane there is a condition that the liquid entry pressure must be high as compared to applied pressure. The value of LEP should be high and this further depends on the pore size and hydrophobicity.

**Table 1.** Thermal conductivity ranges of different materials.<sup>[12]</sup>

Thermal conductivity	Range (Wm <sup>-1</sup> K <sup>-1</sup> )
Water vapor	0.026 at 298 K and 0.03 at 348 K
Air	0.020 at 298 K and 0.022 at 348 K
PVDF (Polyvinylidene fluoride)	0.17~0.19 at 296 K and 0.21 at 348 K
PTFE (Polytetrafluoroethylene)	0.25~0.27 at 296 K and 0.29 at 348 K
PP (Polypropylene)	0.11~0.16 at 296 K and 0.2 at 348 K

There are some conditions to acquire high LEP such as smaller pore size and high hydrophobicity. The list of commercial membranes for distillation with liquid entry pressure values is shown in Table 2. On the contrary, the small value of maximum pore size decreases the permeability. So, to obtain the high value of LEP and permeability, the value of maximum pore size should be targeted properly. To avoid the membrane humidify, the maximum value of pore size should be between 0.1 to 0.6 μm. LEP can be calculated by the classical Young Laplace model using Equation 1:<sup>[1]</sup>

$$LEP = P_F - P_P = \frac{-2\beta\gamma\cos(\theta)}{r_{max}} \quad (1)$$

where,  $P_F$  and  $P_P$  represent the hydraulic pressure of the feed side and permeate side, respectively. The pore geometric ratio is denoted by  $\beta$ . The contact angle is denoted by  $\theta$  and  $\gamma$  is the surface tension. The study by Garcia *et al.*<sup>[9]</sup> indicated that the

LEP was also influenced by the feed concentration and organic materials. In their study, they concluded that the concentration of alcohol and type of alcohol had a massive effect on LEP.<sup>[9]</sup>

### 3.5 Tortuosity

The divergence that occurs in the path of molecules while diffusing through the membrane is known as tortuosity, in other words, it is the measurement of deviation across the membrane. The tortuosity is denoted by the symbol  $\tau$ . Normally, the pore in the membrane is not in a straight manner as a result diffusing molecules have to follow a tortuous path. And the path length becomes longer due to the tortuous path. Hence, an increase in the path length maximizes mass transfer resistance and decreases flux. The tortuosity can be calculated using the following relations given by Equations 2 or 3<sup>[1]</sup>:

$$\tau = 1/\varepsilon \quad (2)$$

or

$$\tau = (2 - \varepsilon)^2/\varepsilon \quad (3)$$

Here membrane tortuosity is represented by  $\tau$  and porosity by  $\varepsilon$ . Recently, Kit *et al.* proposed theoretical models of tortuosity and porosity which were based on Euclidean dimension and Fractal theory.<sup>[1]</sup>

### 3.6 Porosity

Membrane porosity is defined as the volume of void fraction or total membrane volume that divides the volume of the pores. Porosity is represented by the symbol  $\varepsilon$ . To obtain a higher value of permeability and flux, membrane porosity should be high. Although, higher porosity has some other benefits as it helps to decrease heat losses. The reason behind lower heat loss is the presence of air or water vapour in the pores. In MD applications the value of membrane porosity lies in the range of 30 ~ 85%. It can be calculated by the mathematical

**Table 2.** Commercially available membranes, with their manufacturer, polymeric material used and mean pore size for membrane distillation.<sup>[12]</sup>

Trade name	Manufacturer	Polymer material	Supporting polymer material	Mean pore size of membrane (μm)	LEP (kPa)
TF200	Gelman	PTFE	PP	0.20	282
TF450	Gelman	PTFE	PP	0.45	138
TF1000	Gelman	PTFE	PP	1.00	48
Emflon	Pall	PTFE	PET	0.02	1585
Emflon	Pall	PTFE	PET	0.2	551
Emflon	Pall	PTFE	PET	0.45	206
FGLP	Millipore	PTFE	PE	0.20	280
FHLP	Millipore	PTFE	PE	0.50	124
GVHP	Millipore	PVDF	None	0.22	204
HVHP	Millipore	PVDF	None	0.45	105

Abbreviations: PVDF (Polyvinylidene fluoride), PET (Polyethyleneterephthalate), PP (Polypropylene), PTFE (Polytetrafluoroethylene).

expression given below in Equation 4.<sup>[1]</sup>

$$\varepsilon = 1 - \rho_m / \rho_{pol} \quad (4)$$

where  $\rho_m$  is the density of the membrane and  $\rho_{pol}$  represents the polymer density. The membrane can be fully porous, only if the surface is porous or mixed porous.<sup>[1-4,9]</sup>

#### 4. Membrane distillation configurations

MD process has four main configurations: (i) direct contact membrane distillation (DCMD), (ii) air gap membrane distillation (AGMD), (iii) vacuum membrane distillation (VMD) and (iv) sweeping gas membrane distillation (SGMD). All these four configurations representation is shown in Fig. 3.

##### 4.1 Direct contact membrane distillation (DCMD)

DCMD is a famous configuration and the number of studies done on this configuration is the highest. DCMD has a great number of publications whether in review articles or research articles. The configuration of DCMD is the simplest one as depicted in Fig. 4(a). In DCMD, the hot side and the cold sides are indirect contact with the membrane. On the feed side, the temperature is high and this temperature generates the driving force for vapours to transport via the membrane. These vapours diffuse across the membrane and are condensed by the coolant. In addition, the membrane does not get wet because the membrane has hydrophobic properties.<sup>[16-20]</sup>

##### 4.2 Air gap membrane distillation (AGMD)

The layer of air is compulsory in the AGMD configurations as shown in Fig. 4(b). This air layer is set between the hydrophobic membrane and coolant. The vapours cross the air layer before condensing. AGMD configuration overcomes the DCMD configuration in terms of energy efficiency.<sup>[16-18]</sup> AGMD is used on large scale in various industries, especially in desalination. It is also used to obtain volatile compounds from aqueous solutions. Moreover, treatment of highly concentrated solutions can also be done with the help of AGMD.<sup>[19-21]</sup>

##### 4.3 Vacuum membrane distillation (VMD)

VMD configuration is considered as an attractive technology compared to other configurations. In this technique, feed side is in direct contact with the hydrophobic membrane, whereas the permeate side is connected with a vacuum. This vacuum is generated by a mechanical pump. All the vapors are sucked by the vacuum and are transported to the condenser. The pressure on the permeate side is maintained lower than the volatile solvent pressure. The main advantage of this configuration is that on the permeate side, the vapor pressure can be diminished to zero, which results in increased driving force. Moreover, its loss of heat conduction is almost negligible.<sup>[16-20]</sup>

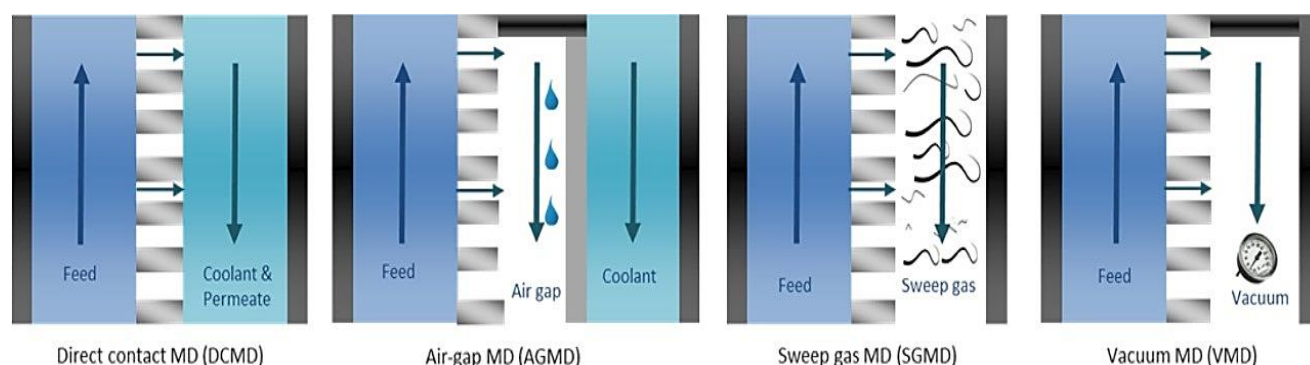
##### 4.4 Sweeping gas membrane distillation (SGMD)

There is a similarity between SGMD AGMD. The vapours on the permeate side are swept by the inert gas, after that these vapours are condensed in a condenser. The mass transfer resistance is reduced. This configuration can also be used to get volatile compounds from an aqueous solution. The gas barrier in SGMD has its advantage as it helps to diminish heat loss. The thermostatic sweep gas membrane distillation module was introduced by Rivier *et al.* to overcome the drawbacks of SGMD. In SGMD, the vapours are diluted by sweep gas and this increases the condenser demand capacity. On the contrary, if low sweep gas is used then the temperature of the sweep gas is increased because of the transfer of heat. Consequently, the driving force is decreased because of similar temperatures.<sup>[17-24]</sup> The below mentioned Table 3 represents the advantages and disadvantages of different membrane configurations.

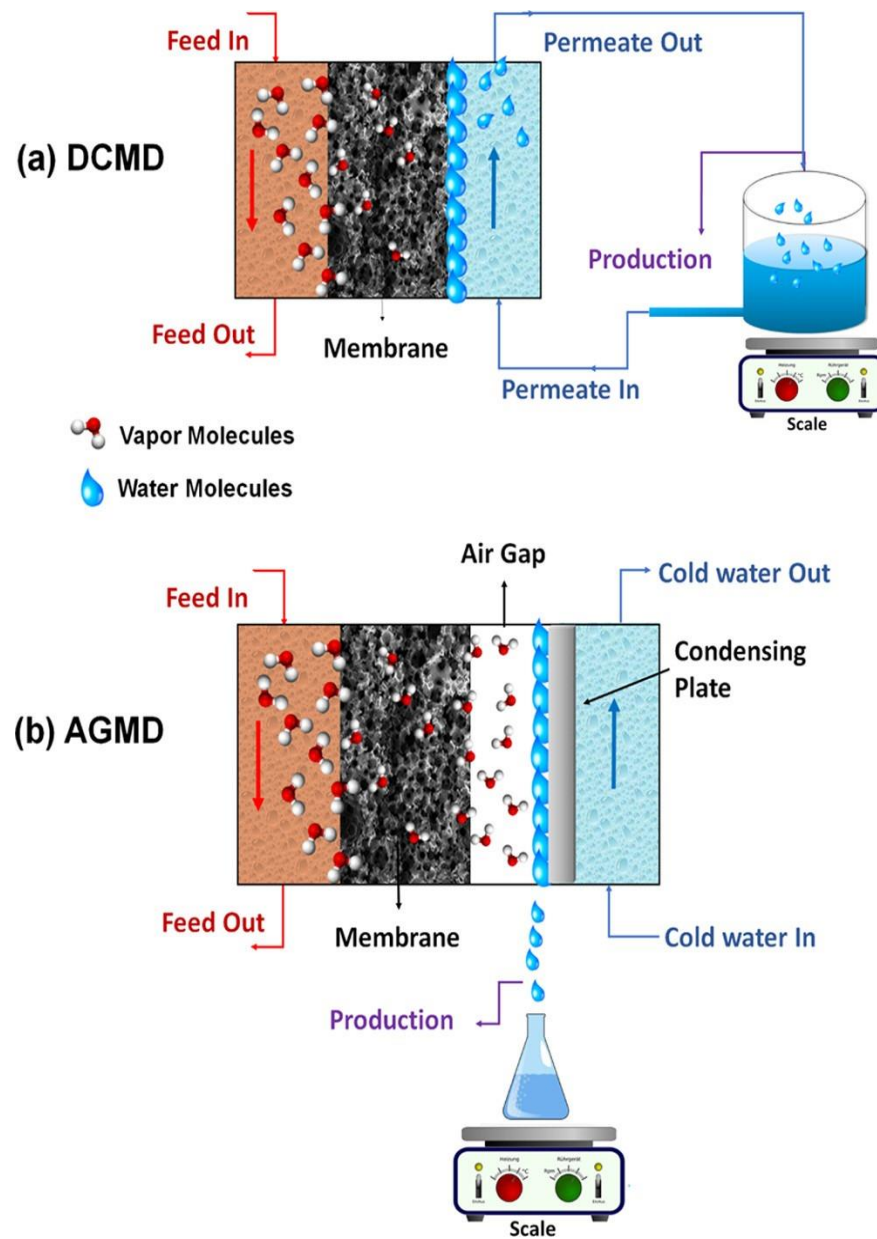
#### 5. MD membrane module designs

##### 5.1 Plate and frame module

Among all the modules, this is one of the simplest modules. It consists of plates, membranes, supporters and spacers, and these are all connected in series as shown in Fig. 5. Plate and frame module has 2 two types: dead-end plate frame system



**Fig. 3** The four basic MD configurations: (a) DCMD (b) VMD (c) AGMD (d) SGMD. Reproduced with the permission from [2], Copyright 2018 American Chemical Society.

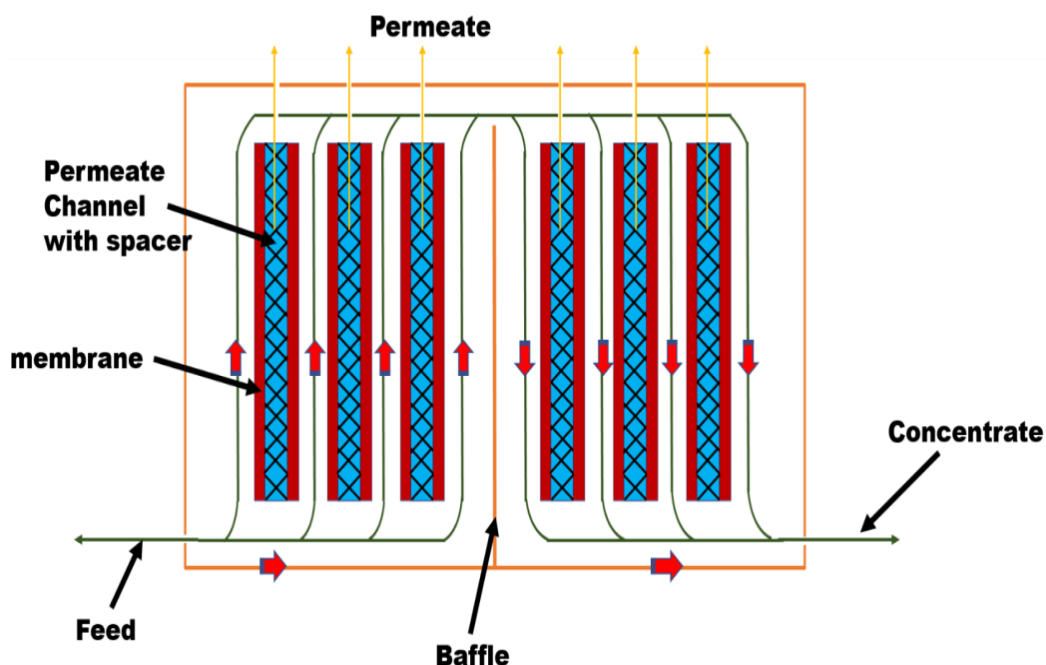


**Fig. 4** Pictorial representation of (a) DCMD (b) AGMD. Reproduced with the permission from [21], Copyright 2018 American Chemical Society.

or cross flow plate frame system. The key difference between them is the flow of the feed solution. The flow is perpendicular in the first one and tangential in the second.<sup>[25-27]</sup>

**Table 3.** Advantages and disadvantages of different MD configurations.<sup>[17]</sup>

Type of MD configuration	Advantages of MD	Disadvantages of MD
DCMD	High value of permeate flux Simple and easy to design	Thermal efficiency value is low. Chances of permeate pollution are high
AGMD	High Value of thermal efficiency Internal heat is recovered	Resistance towards water vapor decreases permeate flux Difficult module designing.
VMD	High value of permeate flux Heat conduction loss is small	Chances of pore wetting are high. Recovery of heat is difficult
SGMD	Rate of mass transfer is high Heat conduction loss is small	Recovery of heat is difficult Huge condenser is needed



**Fig. 5** The diagram represents the plate and frame module configuration. Reproduced with the permission from [27], Copyright 2018 MDPI.

### 5.2 Tubular module

The tubular module is not that much different in concept from a hollow fiber module. They all have a different value of diameter with different packaging capacities. The tube-shaped membrane is placed between the hot and cold fluid chambers. The diameter of the tubular module lies in the range of 5 ~ 25 mm. The tubular module is an attraction for commercial industries because of its easy cleaning and less fouling tendency. But, it is expensive and has low packaging density. The tubular ceramic membrane exhibits excellent results with less than 99% salt rejection with different types of configurations.<sup>[26,27]</sup>

### 5.3 Spiral wound module

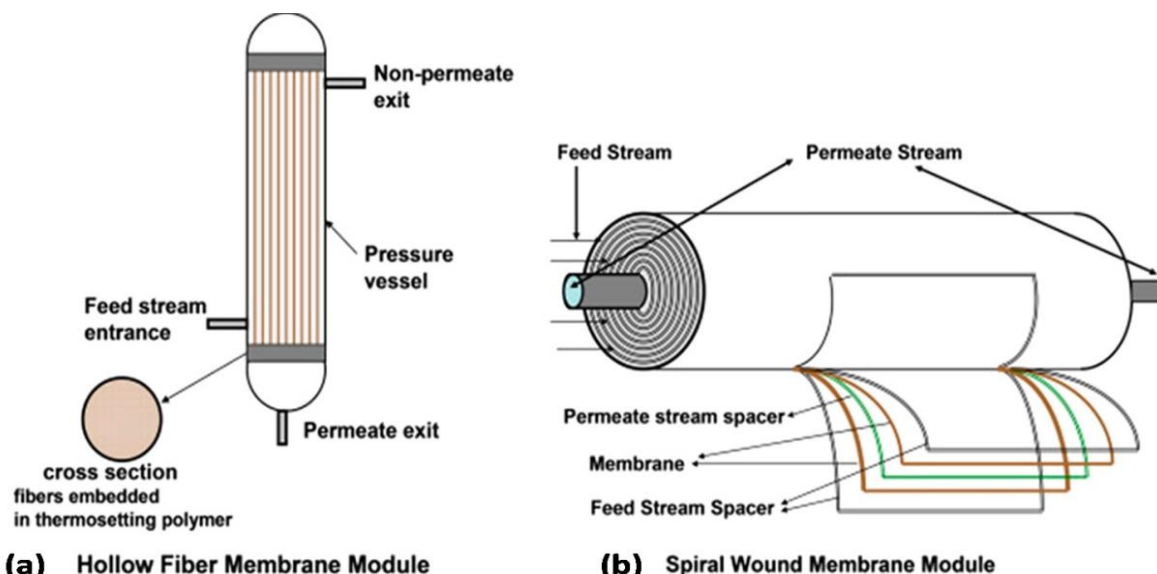
A spiral wound module is the modification of the plate and frame module. There is a collection pipe that is surrounded by the plate and frame system, in other words it looks like a sandwich roll as shown in Fig. 6(a). The membrane is present between the spacers. The feed solution is transported to the membrane via axial direction then the permeate flux reaches center. Finally, the collection pipe exits the permeate flux. Unlike plate and frame modules spiral wound has good packaging. In addition to this, its fouling tendency is average. Recently, Koschikowski *et al.* have employed a PTFE membrane with a spiral wound module for desalination. In this process, around 140-200 kWh/m<sup>3</sup> of energy was consumed. The same concept was also employed by Gore for desalination.<sup>[25-28]</sup>

### 5.4 Hollow fiber module

A hollow fiber module is the collection of many hollow fibers packed in a shell tube or a pressure vessel. The diameter of hollow fiber is less than 1 mm. The feed solution is added through the central pipe which is implemented inside the shell tube as shown in Fig. 6(b). After traveling across the membrane, the feed solution collected outside the membrane. Although, the feed solution can be added from the outside and collected from the inside (outside-inside). The hollow fiber module has a very large packaging tendency. For example, the hollow fiber module with DCMD configuration was implemented by Lgana *et al.* to concentrate apple juice and the same process was used by Fujii *et al.* for concentrating alcohol.<sup>[27-30]</sup> The advantages and disadvantages of different modules are shown in Table 4.

## 6. Types of synthetic membranes in MD

In the 20<sup>th</sup> century, synthetic membranes come into existence and are utilized in many industries on a large as well as small scale. A large synthetic membranes range is known. Various types of materials can be used to prepare artificial membranes such as inorganic material, polymers, and liquids. Commercially, polymeric membranes are utilized in many industrial processes on a wide scale as compared to other synthetic membranes. The four main types of synthetic membranes are liquid membrane, polymeric membrane, polymer electrolyte membrane, and ceramic membrane. Enriched with good performance the polymeric membranes are used in high proportions.<sup>[31]</sup>



**Fig. 6** Schematic of (a) hollow fiber (b) spiral wound membrane modules as part of a membrane separation unit operation. Reproduced with the permission from [29], Copyright 2018 American Chemical Society.

**Table 4.** Different membrane modules with their advantages and disadvantages.<sup>[27]</sup>

Different types of membrane modules	Advantages of membrane modules	Disadvantages of membrane modules
Plate and frame	High flow with control on both permeates and feed sides of the membrane. Solid is being able to be easily separated from the water. The cleaning process is quite easy and membranes can be easily replaced.	Low packing density. Low efficiency. Irreversible damage is also a common problem because of the constant build-up on the membrane surface.
Tubular	Relatively easy cleaning. Easy in handling suspended solids and viscous fluids. Ability to replace or plug a failed tube while the rest of the system runs.	Low packing density. High capital cost and pumping cost. Limited achievable concentrations.
Spiral wound	More packing density compared to flat sheet module. Relatively low cost.	Cannot handle high with Trans membrane pressure. Difficulty in cleaning process of membrane.
Hollow sphere	Low pumping power. Very high packing density. Easy cleaning process using back flushing.	Fragility of the fiber. Inability to handle suspended solid well. The hollow fiber module could be used only when the feed stream is relatively clean

### 6.1 Liquid membranes

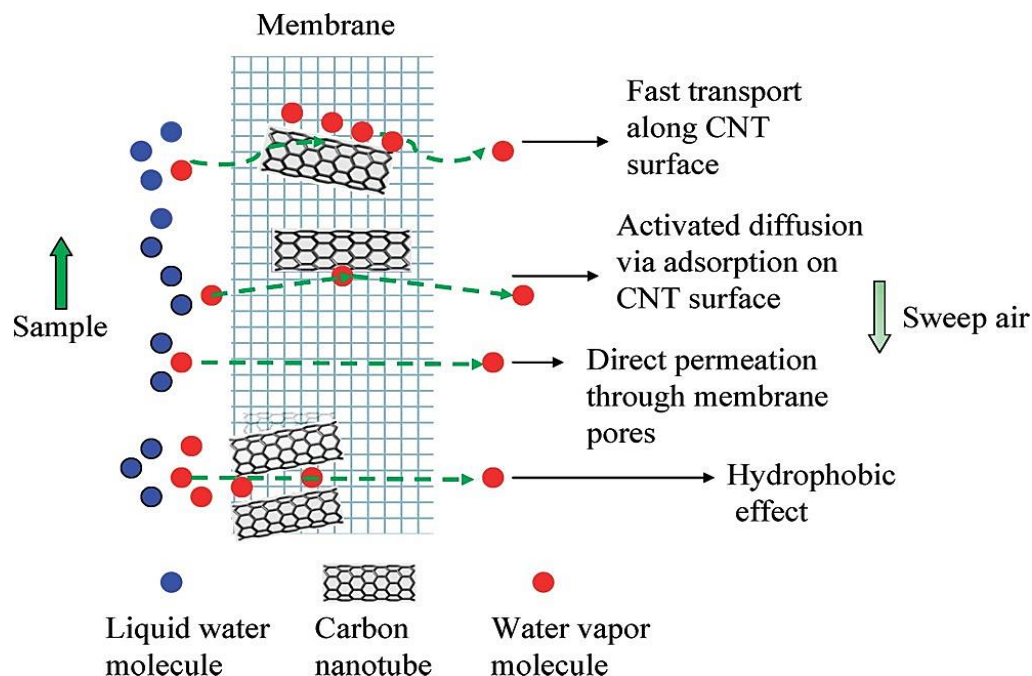
As the name suggests, the liquid membranes are made up of thin film of liquid either supported or unsupported inserted between the two phases of solutions as shown in Fig. 7. One of the great benefits of liquid membranes is its high efficiency and selectivity, making it the first choice of many industries. Along with advantages, it has some disadvantages. The liquid membranes do bursts due to pressure difference reducing their stability which is still a challenge. The two basic types of liquid membranes are the emulsion liquid membrane and immobilized liquid membrane.<sup>[31,32]</sup>

### 6.2 Polymer electrolyte membranes

The polymer electrolyte membranes (PEMs) are also known as proton exchange membranes. The PEMs work as a conductor or separating fence between the cathode and anode section. A polymer electrolyte membrane is used for water treatment, energy storage, and energy generation processes.<sup>[31-33]</sup> The current and famous application is the use of polymer electrolyte membrane in a fuel cell for water management as shown in Fig. 8.

### 6.3 Ceramic membranes

Inorganic material is the base of the ceramic membranes as

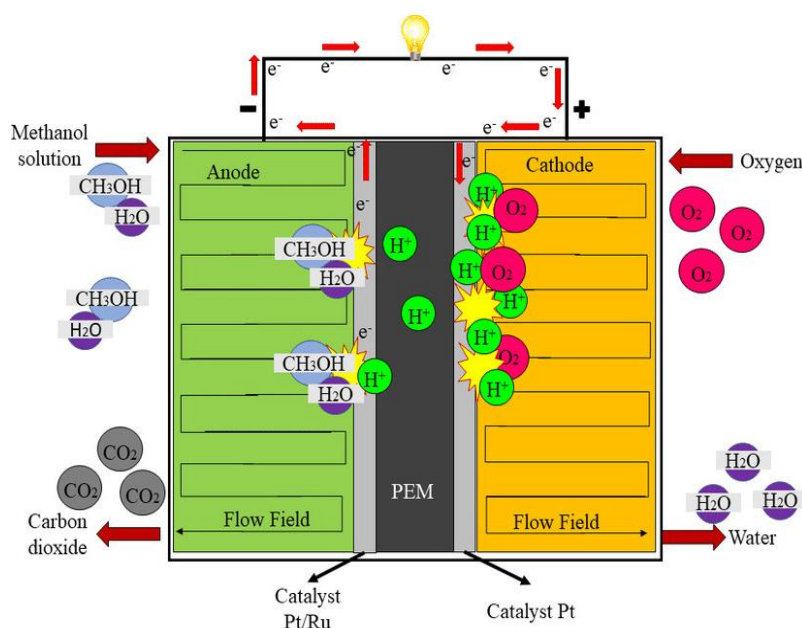


**Fig. 7** Representation of water desalination using liquid membrane. Reproduced with the permission from [32], Copyright 2018 American Chemical Society.

they are made from alumina, silicon carbide, titania, zirconia, and some glassy material. They can be used in separation even in the presence of strong solvents and acids. Unlike liquid membranes, they have excellent stability, which works at high temperatures and makes them more usable in harsh conditions. Ceramic membranes are used widely in industries such as oil separation, recovery of catalysts, and wastewater. Till 2017, in the USA, almost half a dozen installations for potable water have used ceramic membranes<sup>[32,33]</sup> as their first choice for water purification.

### 6.4 Polymeric membrane

Polymeric membranes are membranes that are made from polymers. Polymeric membranes overcome all the othersynthetic membranes in terms of usage in industries. Due to large availability of these polymeric membranes, choosing between them for various purposes is not a difficult job. For applications, the polymeric membrane has perfect characteristics which we already discussed in the membrane characteristics section. The common polymers for membrane distillation are polysulfone, polyether sulfone, fluoride,



**Fig. 8** Representation of polymer electrolyte membranes in fuel cell for water management. Reproduced with the permission from [34], Copyright 2018 MDPI.

polyacrylonitrile, polyamide, polyimide, polyethylene, polypropylene, polytetrafluoroethylene, polyvinylidene and polyvinylchloride.<sup>[31-35]</sup> The common characteristics of polymers used for MD synthesis are shown in Fig. 9 and Table 5.

## 7. Membrane distillation applications

Generally, MD has been used widely in numerous industries *viz* chemical industry, water desalination industry, food industry (juice and dairy), textile industry, pulp and paper industry, pharmaceutical and biomedical industries, nuclear industry, gold mining, and bio-ethanol production plants as depicted in Table 6.

MD has demonstrated as an enhanced technology in several areas, some of them are mentioned below:

### 7.1 Seawater desalination

The international standards have set the quality of potable water and surprisingly 80~90% of the population consumes water that does not meet the quality. Membrane distillation is the perfect technique for the desalination of concentrated salt solutions with great salt rejection as compared to RO, which is driven by osmotic pressure.<sup>[36]</sup> To attain drinkable water

from seawater, brackish, surface, and groundwater, MD is considered as an excellent technique as depicted in Fig. 10.<sup>[37]</sup> The pilot investigations of MD for seawater desalination applications are shown in Table 7.

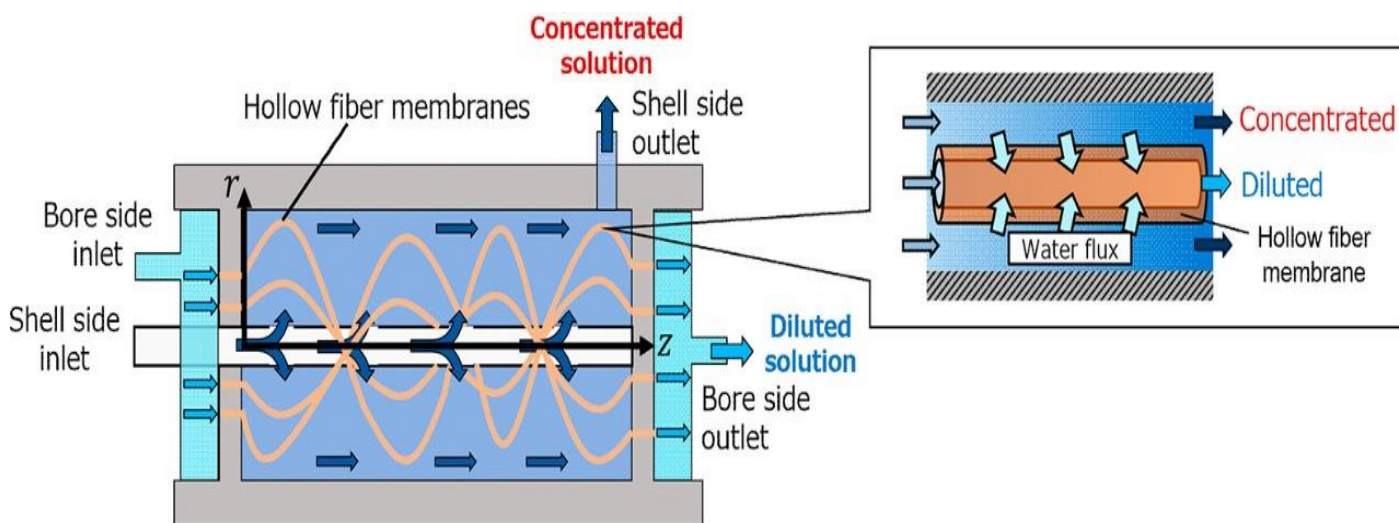
### 7.2 Oily wastewater treatment

In the current scenario, the oily wastewater percentage on earth has been increasing. Many sources are producing this oily wastewater such as fuel production plants, leather industry, petrochemical industry, oil drilling gigs, and many more. The abandoned wastewater treatment is necessary because its direct disposal increases pollution which is very harmful to the environment and indirectly to all living things. Several techniques can be used to separate the oil from water such as skimming, coagulation, de-emulsification, froth-floatation, gravity, aerobic, and fermentation.<sup>[38-40]</sup> These all are traditional methods. The membrane-containing techniques are leading because of many factors for example high efficiency, and purity. On the other hand, membrane processes with pressure as a driving force (Ultrafiltration, nano-filtration, microfiltration and reverse osmosis) are also not suitable for oily wastewater treatment because of fouling by oil, whereas membrane distillation technique can use excessive heat.

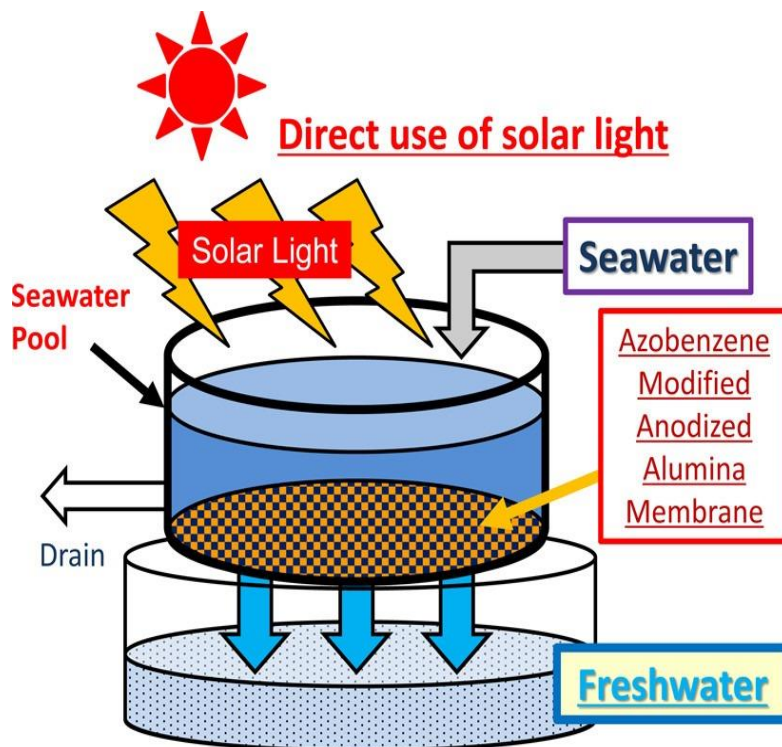
**Table 5.** Common characteristics of polymer used for MD synthesis.<sup>[12]</sup>

Polymer used	Surface energy ( $\times 10^{-3} \text{ Nm}^{-1}$ )	Thermal conductivity ( $\text{Wm}^{-1} \text{ K}^{-1}$ )	Thermal stability	Chemical stability
PVDF	30.3	~0.18	Moderate	Good
PTFE	9-20	~0.26	Good	Good
PP	30	~0.14	Moderate	Good
PE	28-33	~0.40	Poor	Good

Abbreviations: PVDF (Polyvinylidene fluoride), PTFE (Polytetrafluoroethylene), PP (Polypropylene), PET (Polyethyleneterephthalate)



**Fig. 9** A typical representation of hollow fiber polymer membrane for water desalination. Reproduced with the permission from [35], Copyright 2018 American Chemical Society.



**Fig. 10** Representation of a simple process to attain drinkable water from seawater via membrane. Reproduced with the permission from [37], Copyright 2018 American Chemical Society.

**Table 6.** Applications of membrane distillation in various areas with different configurations.<sup>[6]</sup>

Application area	Applications of membranes in various areas	Type of membranes used
Chemical Industry	Removing volatile compounds from water samples.	VMD
	Acid concentrating and crystallization	DCMD
		SGMD
		AGMD
Desalination	Producing pure water from brackish water	VMD
		DCMD
		SGMD
		AGMD
Food Industry (juice and dairy)	Juice concentrating	VMD
	Processing of milk	DCMD
	Temperature-sensitive materials	AGMD
Textile industry	Dye removal	VMD
	Wastewater treatment	DCMD
Pulp and paper industry	Removing sodium sulphate, organic and inorganic compounds, absorbable organic halogens, colour, phenolic compounds, and chemical oxygen demand from wastewater.	DCMD
Pharmaceutical and biomedical industries	Wastewater treatment	DCMD
	Water removing from protein and blood solutions	
Nuclear industry	Producing pure water	DCMD
	Wastewater treatment	VMD
	Radioactive solutions concentrating	
Gold mining	Reusing mining effluents	DCMD
	Removing hazardous metal and ions such as sulphate from mining effluents	
Bio-ethanol production plants	Recovery of ethanol from scrubber water	AGMD

**Table 7.** Pilot investigations of MD for seawater desalination applications.<sup>[36,37]</sup>

Description of membrane distillation	Trade name or technology Developer	Location/Country	Established year
MD for desalination of water	Memstill	Netherland	2010
MD joint with solar energy for desalination of seawater	Fraunhofer	Spain	2012
MD for desalination of brines from thermal desalination plants	Memsys, Xzero	Qatar	2014
Desalinating hypersaline groundwater by MD	Memsys	USA	2016
MD for seawater desalination with air gap configuration at the pilot-scale level	Aquastill	Australia	2016
MD organization with hybrid solar-power operation	Memsys	Saudi Arabia	2016
MD for saline water desalination with vacuum multi-effect configuration	Memsys	Greece	2017
MD methodical operation and design for desalination	Fraunhofer	Germany	2017
The concentration of hypersaline brines by MD	Solarspring	Germany	2018
MD for desalinating seawater with improved heat recovery	Memsys	Spain	2018
Using solar energy testing of MD pilot	Solarspring	Spain	2019
MD for desalination of brines with vacuum-improved air gap configurations	Aquastill	Spain	2020

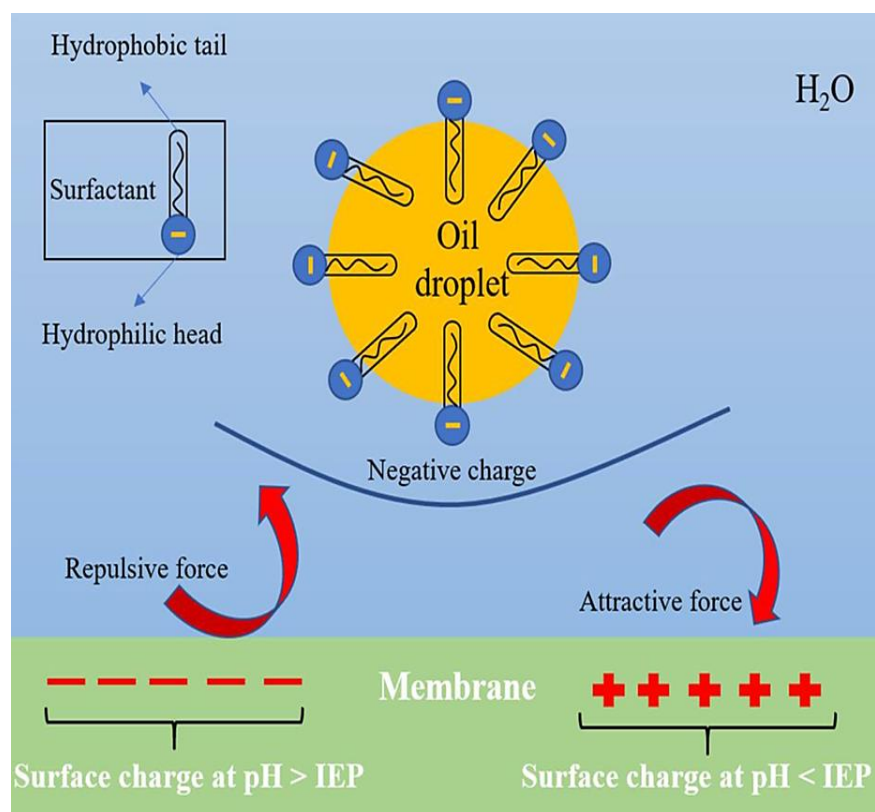
Consequently, MD is considered as a suitable technology for the treatment of oily wastewater. Most of the experiments have already been done by using various MD configurations to treat this type of effluents as shown in Fig. 11. Recently, studies have been conducted by using three types of PTFE membranes (TF200, TF450, and TF1000) with the same configuration with different pore sizes. This process is favored over traditional methods because AGMD can work at low temperatures.<sup>[5]</sup>

### 7.3 Drinking water treatment

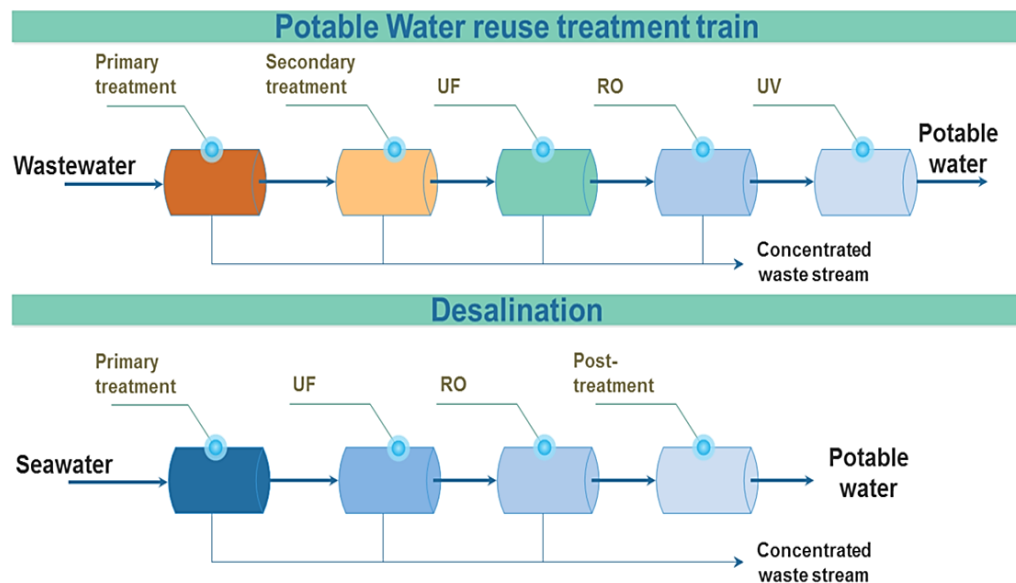
To fulfill the need of freshwater, the wastewater resources

should be used to get drinkable water. There is not any restriction regarding the water sources. The sources can be artificial, groundwater and natural but these are polluted by different pollutants *viz* fluoride, nitrates, heavy metals, colors, dyes and pesticides.<sup>[41-43]</sup> Moreover, the shocking news that the presence of nitrate in the groundwater can lead to a disease called methemoglobinemia.

To remove nitrates, studies were also performed by DCMD with the help of PP and PVDF membranes as shown in Fig. 12.<sup>[43]</sup> The results revealed that 99.9 % rejection was obtained by PP and PVDF membranes. The value of flux was quite different for both membranes. The flux attained by



**Fig. 11** Interaction between the oil droplets and membrane. Reproduced with the permission from [40], Copyright 2018 MDPI.



**Fig. 12** Representation of desalination process by membrane. Reproduced with the permission from [43], Copyright 2018 MDPI.

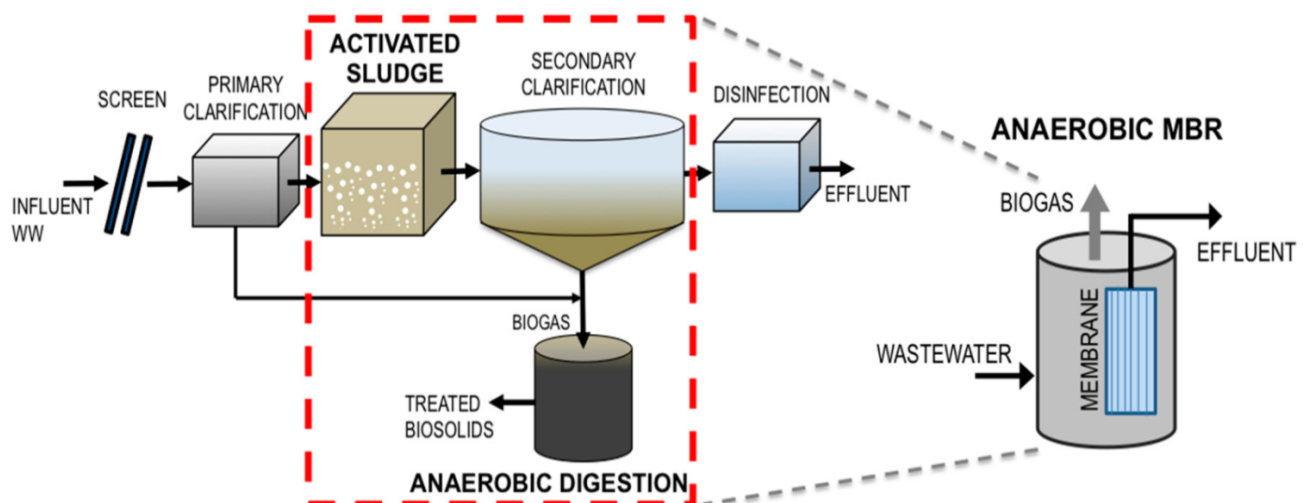
PVDF and PP membrane was 37.21 kg/m<sup>2</sup>hr and 4.21 kg/m<sup>2</sup>, respectively. Moreover, the value of flux gradually increased with increasing temperature on the feed side. Although, water with 5 ~ 15% salt content can also be drunk when needed, but the presence of arsenic in water makes it undrinkable. Some attempts have also been made on the separation of arsenic (III) via hydrophobic PTFE membrane under VMD configuration.

In Vietnam, many studies were conducted and the results showed that the rejection of salt was greater than 99.5% along with high rejection of arsenic around 98.5%, whereas fouling did not occur there. Similarly, different type of PTFE membrane were also used for removing fluoride ions from groundwater.<sup>[5]</sup>

**7. 4 Treatment of textile industrial effluent**

The textile industry is considered as a red alert of the decreasing amount of water. The reason behind this is the use of water on a large scale for the manufacturing of its materials. Almost 50 ~100% of water is absorbed during the process of dyeing of fabrication and after that, the water is decanted as wastewater.

A large percentage of water is contaminated. This can be harmful to the environment as well as to human beings. Most of the studies for the purification of water have been done with different polymeric membranes and with a low value of dye concentration. One more study has been conducted and this study aims to see the conditions for the operation of the DCMMD configuration process by using a PTFE membrane and a high value of dye concentration. To know the circumstances, an experiment has been conducted by using distilled water as the solution on permeate side and artificial dye on the feed side.



**Fig. 13** Schematic diagram of dairy wastewater treatment plant using membrane. Reproduced with the permission from [46], Copyright 2018 MDPI.

The results that come from this give a suitable value of temperature, feed flow, and permeate flow are 607 °C, 1.5 L h<sup>-1</sup>, and 0.5 L h<sup>-1</sup>, respectively. Many of the polymeric membranes are in use but the PTFE membranes have given good permeate flux with 99.9% colour rejection.<sup>[5]</sup>

### 7.5 Food industry applications

Applications of food industries are spread in large areas. Although not all the applications are taken on a large scale some have been done on a laboratory level. There is only one application that is done on a pilot scale and that is the demineralization of water and this is limited to fruit juices and beverages.

### Beverages and fruit juices

The main factor in the fruit and juice industries is concentration. By removing the water, the value of solid material in the juice is increased. The technique used for the concentration of fruit juices is the traditional multistage falling film evaporators. But this technique decreases the colour and flavour of the juice. However, techniques are advancing in food industries to get better concentration without any loss in taste. As we already discussed that the MD technique has overcome the processes driven by pressure. The experiment has also been carried out with orange fruit juice, and the flux has increased with the temperature of the feed side. Many studies have been undertaken which disclosed that there was no wetting observed but the fouling occurred after using a long time. This fouling can be reversed by acid or alkali wash.<sup>[35,36, 44-46]</sup>

### 7.6 Dairy effluent treatment

The membrane distillation process is not fully explored still its applications have been studied. MD is very new to the dairy industry. Membrane distillation is used to separate the various components such as whey and lactose, whole milk, and skim milk. After the experiment of membrane distillation at low pressure with less electrical energy, it is proved that the concentration of dairy products with more than 99.9% rejection is possible. The DCMD configuration is used with PTFE membranes to process the aqueous dairy liquids or solutions. In this process, the permeate is sent back to the feed using a peristaltic pump. The feed concentration, feed temperature, and permeate temperature are analyzed and are separated accordingly.<sup>[6]</sup>

### 8. Conclusion and future perspectives

MD is an excellent and promising technology for separation and purification processes used in numerous industries. Unlike

other membrane processes which operate on temperature difference, MD is vapour pressure-driven separation process in which only water vapours can pass through the microporous hydrophobic membrane leaving behind the other undesired substances. In this review, membrane configuration, membrane characteristics, membrane modules, mass and heat transport mechanisms, thermal efficiency, fouling and operating parameters have been covered. This review reveals that some potential research areas pertinent to MD deserve further exploration. Along with this, the effect of operating parameters require further investigation as the available research data on this research work is quite limited.

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### Conflict of Interest

The authors declare no conflict of interest.

### Supporting Information

Not applicable.

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