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The Pilot-Scale Membrane Distillation Systems for Wastewater Treatment: A Mini-Review

Mohd Ridhwan Adam[a]*, Muhammad Hakimin Shafie[b], Siti Khadijah Hubadillah[c],
Mohd Haiqal Abd Aziz[d], Mohd Riduan Jamalludin[e] & Atikah Mohd Nasir[f]

[a]School of Chemical Sciences, Universiti Sains Malaysia, 11800 Minden, Penang, Malaysia
[b]Analytical Biochemistry Research Centre (ABrC), Universiti Sains Malaysia, University Innovation Incubator Building, SAINS@USM Campus, Lebuh Bukit Jambul, Bayan Lepas, Penang 11900, Malaysia
[c]School of Technology Management and Logistics, Universiti Utara Malaysia, 06010 Sintok, Kedah, Malaysia
[d]Department of Chemical Engineering Technology, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, Pagoh Higher Education Hub, 84600 Panchor, Johor, Malaysia
[e]Faculty of Mechanical Engineering Technology, Universiti Malaysia Perlis (UniMAP), Kampus Alam UniMAP, Pauh Putra, 02600 Arau, Perlis, Malaysia
[f]Centre for Diagnostic, Therapeutic and Investigative Studies (CODTIS), Faculty of Health Sciences, Universiti Kebangsaan Malaysia, 50300 Kuala Lumpur, Malaysia

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ABSTRACT

Industrial wastewater includes large amounts of contaminants thus, the wastewater must be treated prior to disposal. Moreover, since a substantial volume of wastewater is generated, environmental considerations should include the reutilizing of reclaimed water. Since industrial wastewater consists mostly of chemicals and persistent contaminants, it must be adequately treated with eco-friendly technology. Membrane technologies, specifically membrane distillation, are frequently employed in the treatment of industrial wastewater due to their significant benefits over typical wastewater remediation approaches. The substantial investigation completed to date has been undertaken on a lab scale, however, both full and pilot-scale practices have already been implemented progressively. This study presents a concise overview of industrial wastewater treatment and its utilization following proper handling by membrane processes in both full and pilot-scale relevance. In addition, the future prospects and existing obstacles for membrane processes, including cleansing techniques and financial impact, are also studied. In addition, given that there are fewer full-scale trials than pilot-scale studies, process flaws are highlighted to facilitate future research investigations.

Keywords: Membrane distillation, industrial wastewater, pilot-scale, eco-friendly technology

1.0 INTRODUCTION

Water is known as the greatest, most precious and necessary natural source in life. Water covers about two-thirds of the planet's surface, including saline water accounting for 97.5% and the remaining representing freshwater. A significant proportion of the water consumed in daily life comes from freshwater supplies. Nevertheless, with the notable expansion of the population, there has been a significant indication of the high demand for domestic water

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* Corresponding to: Mohd Ridhwan Adam (email: mohd.ridhwan@usm.my)

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consumption as well as commercial and manufacturing purposes [1]. As a consequence of this increment, protecting the water supply has turned critical in order to prevent future water stress. Several preventative measures can be implemented to protect sources of water. Considering the growing pressure for surplus water supplies, one of the more essential precautionary measures is the recycling of processed wastewater [2].

On the other hand, almost one-third of the global population lives in water-stressed areas. As a result, governments throughout the world must implement a variety of water policies in order to combat water scarcity while preserving quality requirements for ecosystem conservation. According to the World Bank report 2020, by the year 2050, over half of the planet's population would face water stress [3]. Global warming and growing urbanization in middle/low-income nations must be taken into account, since these factors may affect the volume, availability, and allocation of water. As the population grows, so will the need for energy and commodities. Considering scarcity is the driving force under the circular economy, prudent resource management is vital for future ventures. Collectively, these variables provide significant problems for stakeholders in ensuring and maintaining adequate funding, health care, and environmental preservation [4]. Notwithstanding the above, wastewater recovery has emerged as an appealing platform. The scientific community's persistent efforts and constant breakthroughs in analytical methods proved that wastewater is a combination of various chemicals. In reality, it is no longer considered dumping for remediation, but rather a rich source for recovering potable water, alternative resources, minerals/salts, as well as other important compounds [5]. Furthermore, the development of novel treatment technologies, as well as the massive change from ordinary to sustainable power for treatment manufacturing, has resulted in a carbon-free environment, owing to huge reductions in carbon output. As a consequence, wastewater restoration not only aids in the fight against water shortages and the reclamation of minerals and renewable resources, merely it may also intensify considerable value to the entire conduct and generate profits in a sustainable way.

In light of the significant presence of human faeces, sewage water comprises a large portion of non-utilized outliers of nutrition components and their decomposition harvests. Carbon (carbohydrates, proteins, lipids, and so on), phosphorus (dispersed ortho-phosphate and biologically combined phosphorus), nitrogen (urea, ammonia, and other organic nitrogen-based compounds), potassium, and sulphur compounds are all possible nutrition sources identified in domestic sewage [6]. Apart from nutrients and heavy metals contaminants, a broad assortment of substances and natural materials can be reclaimed from manufacturing effluent (such as pulp, paper, textile, automotive, chemical, metallurgic, and batteries). For example, recovering hemicellulose, cellulose, and lignin as crude resources for biofuels manufacture from pulp and paper industrial discharge [7], recovering Congo red and methylene blue dyes for reutilization from fabric waste discharge [8], preferential retrieval of crude materials (zinc) from utilized hydrochloric acid-based galvanizing wastewater [9], reclamation of lithium from battery chemical manufacturing discharge [10], and the usage of sludge from industrial effluent physicochemical treatment as a constituent of clinker meals in processing facilities, as well as the reclamation of metal-free fuels from petroleum unwanted sludge [11], has been claimed to preserve the ecosystem, boost production processes, and reduced overall operational expenses.

Physical, chemical, and biological procedures used in the detoxification of industrial effluent have been mentioned in the literature. Physical processes such as ion exchange, adsorption, and membrane approaches have all been used, while chemical practices such as coagulation, oxidation, and electrocoagulation have been employed. On the other hand, aerobic and anaerobic procedures have been utilised as biological approaches. On top of that, physical techniques are uncomplicated and low-cost but produce enormous volumes of thick sludge as a by-product. While chemical techniques of treatment are efficient, they are often expensive and produce excessive sludge containing harmful chemicals [12]. Nevertheless, electrocoagulation is a widely used hybrid technology that is simple to use and generates less sludge. Biological processes on the other hand are difficult to govern, easily influenced by external variables, and need a huge area. However, these solutions are insufficient to fulfil discharge criteria. As a result, every year, legal effluent discharge limitations are enforced, and effluent detoxification has become a major challenge for the industrial sector. After all treatment options are considered, membrane technology is found to be one of the highly sustainable and commonly used methods in industrial wastewater management. Membrane technology, which has small pore diameters, could indeed remove contaminant compounds and release high-quality effluent, making it an excellent alternative for treating industrial wastewater in recent years [13]. Many investigations have been conducted on the removal of contaminants using membrane technology.

Membrane separation is amongst the greatest approaches for getting the targeted quality of the water for reuse in terms of innovation, effectiveness, and safety. The membrane process is a sophisticated treatment method that requires minimal space and is simple to implement in order to extract pollutants and treat wastewater. Microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) membranes are the four different types of wastewater treatment membranes. For example, to eliminate the colloidal colours, MF membranes have been employed in the removal of large pollutants such as pigment dyes [14]. It might also be employed as a preventative measure against membrane fouling. Meanwhile, smaller pores in the UF membranes are commonly used to retain high molecular weight compounds, synthetic products, and other tiny particles. Furthermore, UF effluent might be utilized in the textile industry's rinsing and washing operations. On the other hand, organic chemicals and divalent salts in wastewater are separated by NF membranes, while RO membranes are capable of removing entirely mineral salts and hydrolysed ions. Membrane-coupled biological systems, such as membrane bioreactors (MBRs), generate fewer sludge, are applicable for high intensities of pollutants, and take up a smaller area than conventional biological wastewater treatment systems.

Membrane distillation (MD) is a new thermal-based membrane technique that can treat a broad range of supply waters, involving wastewater and high-salinity brine water. Despite the application of the membrane distillation technique in wastewater treatment having several benefits namely minimal consumption of electrical energy and total removal of non-volatile solutes, and moderate operational pressures, it has received less research attention than other techniques [15]. Membrane distillation is also a viable substitute for conventional separation processes like RO and heating technologies. Membranes are only essential for desalination procedures in RO, whereas thermal approaches require a large quantity of heat to convert water into steam prior desalination process commencing [16]. Membrane distillation is a hybrid technique that combines membrane and thermal processes. As compared to typical thermal distillation methods such as multi-stage flash desalination, mechanical vapor compression, and multiple-effect distillation, it may perform at lower temperatures than the boiling point of the fluid feeding solution and involves considerable pressures than RO. Moreover, MD rejects more undesirable substances, such as colloidal cells, salts, non-volatile organic chemicals, ions, and macromolecules [17]. Consequently, it may create high-purity distillate while emitting less CO_2. Membrane distillation may reclaim thermal energy and use low-cost sources of heat including heat waste from other systems and renewable energy sources (geothermal or solar energy), lowering operational costs and providing ecologically friendly separation processes [18]. Additionally, owing to the hydrophobic nature of MD, fouling on the MD membrane surface is not as severe as it is on hydrophilic membranes. As several industries like textile dyeing mills operate at high temperatures, there is accessible waste heat that may be employed to recover water in a single step via MD. To prevent any unforeseen difference from the real samples, synthetic effluent comprising the major components of industrial effluents, particularly colours, surfactants, and salts, has been used. In addition, there are many commercial membranes available in the market that eventually utilized for the MD applications. Table 1 shows the currently available membranes and their producer used for MD in the bigger scale measures [19]. It is found that these membranes are of various configurations and materials used. The porosities of the membranes are also varies depending on the material employed.

Table 1 The commercial membranes used in MD [19]

Membrane module	**Producer**	**Membrane configuration**	**Membrane material**	**Porosity (%)**	**Reference**
G-4.0-6-7	Gore-Tex Sep GmbH	Flat sheet	Polytetrafluoroethylene (PTFE)	80	[20]
GVHP	Millipore	Flat sheet	Polyvinylidene fluoride (PVDF)	70-75	[21]
3 MA	3 M Corporation	Flat sheet	Polypropylene (PP)	60	[22]
PP 50/200	Accurel Membrana	Hollow fibre	Polypropylene (PP)	0.5	[23]
Celgard X-20	Hoechst Celanese Co.	Tubular	Polypropylene (PP)	35	[24]
MD020TP2N	Enka Microdyn	Tubular	Polypropylene (PP)	75	[25]

The major aims of this study are to review the pilot-scale studies on the wastewater treatment process using membrane technology, specifically on the membrane distillation process, and to forecast future studies and challenges using the available evidence. Primarily, only pilot-scale membrane technologies for wastewater treatment were examined in this review, including the treatment and filtration performance. Physical and biological research are studied and reported in depth in the application section. The clogging and cleaning procedures utilized in the analyses were also investigated. Furthermore, it was intended to emphasize the need for future research based on present results.

2.0 MEMBRANE DISTILLATION PROGRESS

In recognition of the benefits of these processes, investigations on wastewater treatment with membrane separation processes have gained prominence. The primary benefits are outstanding permeate quality, the ability to reuse treated water within that industrial manufacturing process, a compact footprint, and the reusing of materials. According to the study performed using the SCOPUS Database, there are about 1690 research publications, including 224 review papers, that have been undertaken on "wastewater treatment employing membrane distillation" over the last 22 years, from 2000 to 2022. For the same period, another 160 research articles with 20 review papers were published by inserting the "pilot-scale membrane distillation" search into the study subject. Furthermore, as seen in Figure 1, the number of papers published in the research is steadily growing. It is also noted that the dominated countries for the membrane distillation for water treatment were China, United states and Australia. Meanwhile for the pilot-scale membrane distillation, United States was leading and followed by China and Spain. These findings could be led by the advancement of the countries as well as the number of experts coming from the listed regions.

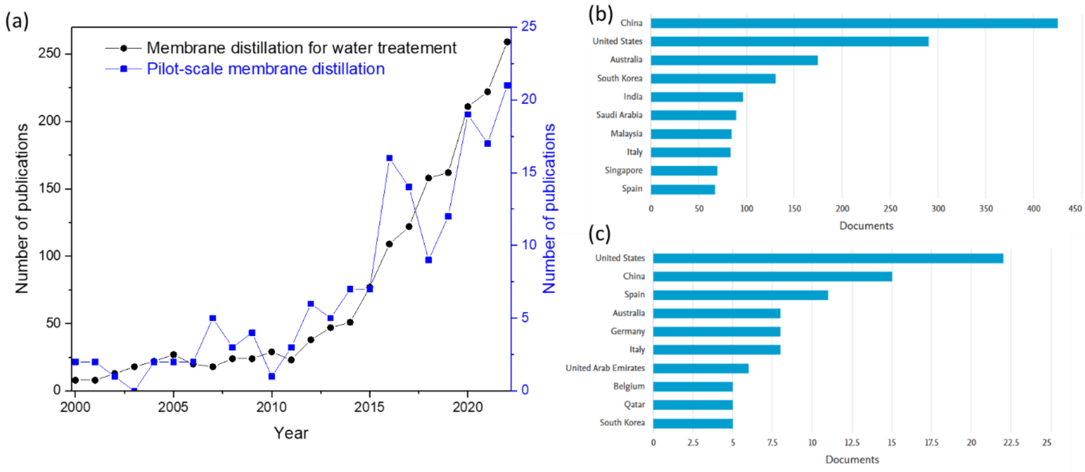

Figure 1 The publication trends of the membrane distillation process for water treatment from 2000 to 2022 of (a) total number of publications; (b) dominate countries of publications in membrane distillation for water treatment; and (c) leading countries of publications on pilot-scale membrane distillation (SCOPUS)

In the early research, the effects of numerous variables on the effectiveness and appearance of membrane processes available to treat wastewater were explored at the laboratory scale. Pilot-scale systems were then explored once sufficient information was obtained from lab-scale applications. According to the literature research, there were fewer investigations conducted at the pilot scale in contrast to the lab-scale implementations [26]. By reviewing pilot scale research, it is possible to determine if full-size systems will function properly as well as whether effectiveness setbacks will occur. Engineering measures should be put in place to certify that full-scale systems may be used at a reasonable charge while yet providing an environmentally pleasant process with great effectiveness. Membrane operations might be efficaciously scaled up from lab-scale to pilot- and/or full-scale, and membrane performances were also shown to be increased at bigger-size deployments.

The restricted number of pilot/full-scale membrane distillation technologies available, on the other hand, is owing to a multitude of factors. These issues include changes in system performance caused by clogging of the media filter (pre-treatment procedure prior to the membrane) induced by the use of various chemicals for coagulation and pH correction [27]. Moreover, biofouling has lowered membrane efficiency by accumulating on the membrane surface and thus, lowering membrane fluxes. The presence of microorganisms in the feed saline water has caused biofouling to occur [28]. The scaling phenomena, which finally adhered to the membranes or the system, is another contributor to the downsides. This is caused by excessive salt concentrations that exceed solubility limitations and hence crystallize on the membrane surfaces. At all since, due to the dismal performance of conventional pre-treatment systems, several research on immediate solution pre-treatment approaches, particularly the viability of membrane and consolidated membrane systems to be employed as a pre-treatment, have been recorded.

3.0 PILOT-SCALE MEMBRANE DISTILLATION APPLICATIONS

In real industries, extracting treated water from effluent utilizing membrane technologies is a difficult operation. To do this, wastewater characteristics should be investigated, optimal technology and performance parameters must be identified, and a development plan should be conducted. Pilot-scale experiments on membrane treatment devices in the previous research were thoroughly examined. This section presents the processing and separation performance of pilot-scale membrane technologies applied in the treatment of several forms of industrial effluents. For instance, Table 2 presents the usage of membrane technology in textile effluent. From the listed works, it can be seen that all membrane treatment processes were capable of removing more than 90% of colour from the treated colour-contained effluent. This also indicated that the membranes were efficient in terms of size exclusion and distillation processes.

Table 2 The usage of membrane technologies for textile industrial effluent

Wastewater	Membrane specifications	Feed condition	Process condition	Process performance	Reference
Synthetic and natural fibre dyeing effluent	Spiral wound ultrafiltration and reverse osmosis	N/A	Flux: 9.26 L/m^2·h Pressure: 8 bar	99% conductivity, 95% colour and 76% chemical oxygen demand (COD) removal	[29]
Chemical and dye substances effluent	Spiral wound nanofiltration	COD: 1530-2750 mg/L Conductivity: 1850-6400 µS/cm Turbidity: 51-176.5 NTU	Flux: 88 L/m^2·h Pressure: 10 bar	98% turbidity, 50% conductivity, 98% colour and 98% COD removal	[30]
Textile and non-textile dye effluent	Flat sheet ultrafiltration and nanofiltration	COD: 708 mg/L Conductivity: 3840 µS/cm Turbidity: 4.02 NTU	Flux: 145 L/m^2·h Pressure: 15 bar	80% conductivity, 90% colour and 90% COD removal	[31]
Polyester and cotton dye effluent	Flat sheet nanofiltration	COD: 2690 mg/L Conductivity: 14.95 mS/cm Turbidity: 1500 NTU	Flux: 50 L/m^2·h Pressure: 10 bar	99% turbidity, 87% colour and 74% COD removal	[32]
Denim dye effluent	Submerged hollow fibre (membrane bioreactor)	COD: 1411 mg/L Conductivity: 5125 µS/cm Turbidity: 294 NTU	Flux: 20 L/m^2·h	41% conductivity, 99.8% turbidity, 97.8% colour and 97.4% COD removal	[33]
Wool dye effluent	Spiral wound nanofiltration and reverse osmosis	COD: 918 mg/L Conductivity: 3463 µS/cm Turbidity: 148 NTU	Flux: 13 L/m^2·h Pressure: 8-12 bar	97% conductivity, 99% turbidity, 85% colour and 99% COD removal	[34]
Textile dye effluent	Hydrophilic and hydrophobic-coated polytetrafluoroethylene (PTFE) (membrane distillation)	COD: 2830 mg/L Conductivity: 976 µS/cm Turbidity: 148 NTU	Flux: 30 L/m^2·h	99.5% conductivity, 99.5% salt and pigment and 93.4% COD removal	[35]

Apart from the superior elimination accomplishment, membrane treatment can be suffered from deterioration in the permeation. Although, the UF process significantly reduced the COD level in effluents discharged from printing, colouring, and washing units and prevented the succeeding NF measures from fouling. The fouling was caused by dissolved organic and inorganic chemicals. The NF membrane was capable of removing up to 90% of the COD value, 90% of the colour, and 80% of the conductivity and the flow of the membrane remained constant in the investigation at 145 L/m2·h at 15 bars. In virtue of this research, collecting excellent permeate and reusing recovered wastewater in textile industry production processes were deemed suitable. To eliminate big particles and prevent fouling of the NF membrane, a spiral wound configure UF membrane module was employed for pre-treatment process [36]. The UF process possessed the turbidity, COD, and colour removal efficiency of 95-99%, 64-76%, and more than 75%, respectively. The transmembrane pressure (TMP) ranged from 8 to 10 bar was measured throughout this investigation, while the membrane flow was kept constant at 88 to 104 L/m2·h. While the membrane fouling assessments in the research were analysed, it happened that the NF membrane had 23% irreversible fouling and the RO membrane had 25% throughout the testing days. On the other hand, a ceramic membrane with a functional layer of zirconium dioxide titanium dioxide (ZrO_2-TiO_2) and a support layer of TiO_2 was studied for the recovery process of textile mill wastewaters [37]. Cartridge filters were employed as pre-treatment step to eliminate large particles in order to avoid membrane fouling, which is reversible in this method. According to the findings of this study, pH and pressure are critical factors that influence membrane performance in the treatment of textile industrial wastewater. Figure 2 depicts the vacuum MD pilot plant reported for the decontamination of low-level radioactive wastewater from nuclear power plant [38]. The major components of the pilot-scale VMD system were the feed water tank, the main frame, and the membrane module stack. The connection of each equipment and the water and vapour flow direction in the VMD system. Particularly, all of the containers, pipelines, valves, and pumps were constructed from stainless steel to boost their corrosion and radiation resistance. For heat preservation, the pipes on the hot side were insulated and double-layer containers were utilised on the hot side. To regulate the functioning of the VMD and collect all sensor data, a self-designed automated system was created.

Figure 2 The VMD pilot plant for low-level radioactive wastewater decontamination [38]

On the other example, Memsys Water Technologies is a German water technology company that manufactures commercial water treatment techniques based on membrane distillation technologies [39]. Memsys employs vacuum multi effect membrane distillation (V-MEMD) innovation in the MSF brine region of high concentration to thicken the brine output from desalination works without any pre-treatment. The inclusion of scale inhibitors in the discarding brine increases membrane efficacy and consequently the whole system not including having a significant surface impact on the MD membrane. Similarly, when discard brine from thermally filtration systems is 25% hotter than feed saltwater, the temperature effectiveness of the Memsys system was observed to be rather high. For instance, in Qatar, the conductivity of the input brine was roughly a thousand times that of the distillate, that could be utilized to subsidize industrial water production [40]. The overall water output of the sustainable and renewable energy saltwater desalination process in Abu Dhabi, UAE, was 1060 m^3 daily, combining different membrane technologies (MF, UF, RO, and MD). The operation consumed about 3.6 kWh/m^3 and recovered water about 41 to 85% from the RO and 40 to 50% from the MD processes. The Memsys MD procedure was claimed to produce 60 to 70 m^3 of freshwater in a day exclusive of any input pre-treatment, including a 47% regaining rate. The distillate's conductivity value was measured at less than 20 µm/cm, while the resulting brine's total dissolved solids (TDS) was 150,000 ppm. Moreover, the Memsys MD system's specific thermal and electrical amount of usage were 160 and 3 kWh/m^3, respectively.

MD technique was also used to treat produced water from the oil and gas companies [41, 42]. The pilot scale system, with a manufacture capacity of 1 m^3/day, recovered about half of the total volume of water in the influent (thermal brine) with a TDS value of 70,000 ppm [43]. With TDS less than 10 ppm, a consistent permeate flow of 5 $L/m^2{\cdot}h$ was obtained. The implementation of MD technology in industry was also accomplished by employing the Aquastill system to produce a distillate that may be utilised in the practice [44]. The air gap MD system treated 2 m^3/day of textile industrial effluent from a textile mill in Surat, India with an overall unit surface area of 26 m^2. The dyeing manufacturing plant's input stream possessed a TDS value of roughly 4000 ppm. Additionally, the waste heat produced in the textile mill (which must be released) was used to power the MD system. The MD system was claimed to eliminate about 93% of the salt contained in the input effluent streams. Furthermore, the MD system recovered about 88% of the water in the effluents with conductivity values of less than 500 µS/cm.

4.0 FUTURE OUTLOOKS AND CHALLENGES OF PILOT-SCALE MEMBRANE DISTILLATION

Notwithstanding substantial innovations in membrane separation for the past decades, the ubiquitous use of membranes in MD is still hampered by inevitable membrane fouling and wetting issues, which lead to poor permeate quality and high maintenance and operating costs. There are complicated issues that are impeding membrane commercialization in MD applications. There are no research studies available that explain the principle of fouling and wetting on hydrophobic membranes in MD implementations for long-term operation. Nevertheless, only a few research have been conducted to investigate the behaviour of fouling and wetting on polymeric membranes [45]. All of the research is focused on converting hydrophilic membrane surfaces to hydrophobic characteristics. Additional research is required to fully comprehend these two complicated issues in order to enhance hydrophobic membranes in MD applications in the time ahead.

Desalination technologies, on the other hand, such as membrane distillation, consume a significant amount of energy and are usually fuelled by fossil fuels, which are costlier and exacerbate climate change [46]. As a result, renewable energy has received more attention as an alternative to desalination methods. Solar energy appeared to be an interesting alternative for distillation operations among all available renewable energies due to its great accessibility and minimal maintenance and operating expenses [47]. Notwithstanding these benefits, solar desalination systems are not frequently employed in the distillation industries, owing to their high cost and limited water extraction when compared to large-scale typical desalination processes. Solar-powered desalination, on the other hand, has the capacity to be an appealing option for modest systems, especially in isolated and dry places [48]. Solar energy can be gathered as electrical power via photovoltaic (PV) modules or directly as heat using solar thermal collectors. Additionally, more intensive research efforts, including experimental and simulations, are required to investigate membrane fouling, wetting, and scaling in the solar-powered MD process, especially in the water recovery process of natural effluents with complex components, such as produced and brine water. Scaling and fouling on the surface of MD membrane, in general, own the potential to significantly reduce light-to-heat power density. The membrane with outstanding surface omniphobicity might significantly improve anti-wetting, for both low and high-surface tension compounds, as well as anti-fouling qualities [49]. Furthermore, a Janus membrane with a super/hydrophilic layer towards the influent stream and an omniphobic permeable substrate may improve wetting and fouling resilience.

The incorporation of nanoparticles to membranes, as is established and has enhanced both physicochemical qualities and operations for both selectivity and permeability. Carbon, silver, titanium dioxide, and halloysite nanoparticles were employed to alter membranes used for industrial wastewater treatment process [50]. By taking into account the adsorption capabilities of nanomaterial additives, an improvement in degradation efficacy and permeability has been discovered with each inclusion of nanoparticles. Previous studies have shown that the utilization of nanocomposites in membranes is frequent in the laboratory and pilot-scale researches, however, the quantity of treatments in full-scale setups is rather limited attributable to problems in the nanocomposite membrane fabrication process [51]. Surface changes, the creation of novel nanomaterials with structural features, and optimization studies to boost endurance are necessary to overcome this barrier.

The other consideration of effective MD process is the influence of membrane configurations. In the case of flat sheet membranes, both plate-and-frame and spiral wrapped modules were discovered to be appropriate for MD application. Meanwhile, shell-and-tube module units are compatible with hollow fibre membranes, which have considerably smaller inner diameters than tubular and capillary membranes. Flat sheet membranes are favoured due to their easy production process and adaptability, whilst hollow fibre membranes are favourable due to their increased packing density (surface area to volume ratio). In MD, hollow fibre membranes have demonstrated poorer performance than flat sheet membranes

[52]. This may be due to the decreased surface porosity of the hollow fibre membrane's external surface. Moreover, the direction of the feed flow has an impact on the efficiency of hollow fibre membranes. When the temperature difference between the feed and permeate sides was exceedingly high while the feed stream was in the shell side, in counter-current flow mode to the permeate inside the fibres, hollow fibre modules produced an exceptionally high flux. Additionally, the rate of permeate produced from the flat sheet and hollow fibre modules may not be same under identical operating conditions. Under the comparable DCMD process parameters, the computational fluid dynamics (CFD) models reveal that the flat sheet membrane module outperforms the hollow fibre membrane module in terms of permeate flow production [53].

5.0 CONCLUSION

In comparison to other water reuse technologies, membrane processes are among the most efficient. Numerous research in the literature focuses on the industrial wastewater treatment utilizing lab-scale membrane systems. However, study on the use of full and pilot-scale systems for the industrial wastewater treatment is currently insufficient. The available research on pilot-scale treatments treating industrial wastewater demonstrated that membrane technologies are effective at treating industrial wastewater, allowing for water reuse within the sector. Few large-scale research on industrial wastewater treatment have been done, and significant information is still inadequate. Hence, pilot-scale research should give both information and experience for the full-scale implementation of these technologies. On the basis of the properties of the wastewater to be processed and the discharge regulations, it has been determined that membrane procedures, particularly membrane distillation systems, are feasible. Both system effectiveness and water reuse possibilities require more exploration. In fact, maintenance methods for fouling management, which is crucial for membranes, should also be evolved. It is necessary to do viability studies in order to determine the most effective membrane method from a cost and performance viewpoint.

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