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Performance Analysis of Membrane Distillation in Desalinating and Concentrating Brine on a Pilot Scale

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ABSTRACT

Investigating desalination and brine concentration using advanced membrane and thermal processes is crucial for reducing energy consumption and costs in the desalination industry. Emerging technologies such as forward osmosis (FO), osmotically assisted forward osmosis (OAFO), pressure-assisted forward osmosis (PAFO), electrodialysis (ED), membrane distillation (MD), and solvent extraction desalination (SED) have shown promise at the lab and pilot scales but are not yet commercially viable due to operational and economic challenges. In our study, we focused on MD to evaluate desalination performance using various saline feeds, including fresh, brackish, seawater, and desalination brine from Kuwait, applying both electrical and solar heating methods. Results revealed higher water flux for brackish water compared to seawater and brine, with salt rejection unaffected by increased salinity. Energy consumption was more influenced by feed quantity than by salinity. The water flux ranged from 1.5 to 2 L per square metre per hour ($L.m^2h^{-1}$), with a water recovery of 3.3 to 4% in electrical heating mode of operation. Solar mode operation of the MD system showed a water flux of 0.95 to 1 $L.m^2h^{-1}$, with an average recovery of 2.75%. Our findings highlight the practical potential of MD for solar desalination and brine concentration in remote areas and small-scale industrial waste treatment.

INTRODUCTION

Membrane distillation (MD) has been utilised in various applications over the past decade and is acknowledged as an effective method for wastewater treatment, desalination, and brine concentration (Reddy et al. 2021, Hegde & Ribeiro 2022, Ali et al. 2011, Gourai et al. 2015, AlMallahi et al. 2024). MD technology has a history of more than three decades. However, MD technology is not available on a commercial scale due to unsolved challenges and its lower efficiency. Several laboratory and pilot-scale studies have been conducted to evaluate the viability of the MD process for different applications in the literature (Gourai et al. 2015, Tiwari et al. 2022, Adewole et al. 2022, Yan et al. 2021, Conidi et al. 2020, Bhattacharjee et al. 2017, Yadav et al. 2021, Zhong et al. 2021, Choi et al. 2019, Shalaby et al. 2022, Drioli et al. 2014, Essalhi 2014, Camacho et al. 2013). All the literature indicates that MD technology is more suitable for small-scale applications due to challenges and limitations in the process. The challenges in MD technology include the unavailability of highly efficient hydrophobic membranes, low thermal energy loss during treatment, low fouling for high-salinity water, and module design. Despite these challenges, MD technology has gained more interest among the research community for treating desalination brine (Bhattacharjee et al. 2017, Yadav et al. 2021, Zhong et al. 2021, Choi et al. 2019). In recent years, applied research on MD technology for desalination and brine concentration applications has gained more interest due to the possibility of using renewable energy and waste heat for the process. The MD process requires low-grade heat to increase the temperature of the feed solution to a range of 50–80 ºC. Therefore, the energy needed for the

MD process can easily be provided by renewable energy sources (Hegde & Ribeiro 2022, Ali et al. 2011, Tiwari et al. 2022). Additionally, MD membranes are hydrophobic and low fouling, requiring minimal pre-treatment, which will reduce chemical costs and minimise the discharge of harmful chemicals into the environment.

On the other hand, literature reviews show that solar MD technology offers a simple and promising solution for effectively producing distilled water on a small scale (Elbar & Hassan 2020, Moossa et al. 2022, Hamwi et al. 2020). This is especially beneficial for remote areas, emergencies, and situations with limited resources. Additionally, the application of MD technology to treat small-scale rejects from industries and desalination brine from farms leads to reduced environmental impact from these rejects. However, MD technology is in the developmental stage; therefore, it requires thorough investigation of its performance in specific geographical locations. Kuwait is blessed with abundant solar energy due to its geographical location, receiving an estimated annual solar irradiation of 2,100-2,200 kilowatt-hours per square metre ($kWh.m^{2-}$) per year, with an average of 7 to 12 hours of sunshine per day (Hadi et al. 2013, Briney 2020, Geography of Kuwait 2020). Consequently, there is great potential for implementing a solar MD system in Kuwait for decentralised freshwater production and brine concentration applications. This would also help reduce greenhouse gas emissions, lessen the carbon footprint in the environment, and reduce the brine discharge problem in remote areas. There are several similar studies conducted worldwide at the laboratory and pilot-scale level (Shatat et al. 2013, Jawed et al. 2024, Kumar & Martin 2017, Al-Sairfi et al. 2023). However, conducting a study in the State of Kuwait is very important due to the higher salinity and turbidity levels in Kuwait's saline water. Additionally, the high solar radiation intensity, along with dust and wind effects, significantly impacts the quantity and quality of distilled water production. As a result, a study was carried out to evaluate the feasibility of implementing an integrated solar-powered MD technology for desalinating seawater and brine concentration by considering the current environmental conditions in Kuwait.

MATERIALS AND METHODS

Materials

The Air-Gap Membrane Distillation (AGMD) membrane module was purchased from Aquastill BV, the Netherlands. The AGMD module, with a membrane area of 5.6 m^2, features a spiral-wound design, and the active material is a super-hydrophobic polypropylene (PP) polymer membrane. The solar thermal unit was purchased from Sanvi Solar Pvt. Ltd., India. The solar thermal unit has both electrical coil heating connections and solar heating. Automated temperature (A GSP-6) and humidity (Elitech RC-5+TE) sensors were purchased through Amazon, and a solar power meter was purchased from Munro Instruments MRC Group Company, United Kingdom. Feed water samples were collected from different locations in Kuwait and analysed at the International Organization for Standardization (ISO)-certified laboratories of the Water Research Center (WRC) at the Kuwait Institute for Scientific Research (KISR), Kuwait. The instruments were calibrated and examined using international standards and techniques.

Methods

The solar MD system was fabricated in the WRC workshop by combining a solar thermal unit with an AGMD module. The required electrical heater, sensors, flow meters, and a heat exchanger were incorporated into the fabricated solar MD system to measure the required parameters. The schematic diagram is shown in Fig. 1, and the actual image of the fabricated system is presented in Fig. 2. The electrical heater in the solar thermal unit was used as a heating source to optimise the feed flow rate and temperature using second-stage reverse osmosis (RO) permeate as feed. The optimisation process was conducted inside the laboratory to avoid the solar thermal heating effect from the evacuation tubes. Optimisation experiments were conducted over a period of 2 hours, and each result was recorded at 30 min intervals. The heat exchanger was used to exchange heat from the thermal storage tank to the feed. The required feed temperature was set by adjusting the heating rate of the coil in the thermal storage tank. After the optimisation of the process was complete, optimised parameters were set to assess the desalination performance of different saline waters. Once the initial trials were completed, the solar MD system was fixed on the rooftop of the building and connected to the RO brine line as feed. Experiments were conducted over a period of six hours during the daytime, and each result was recorded at 30 min intervals for five days. During the experiments, the feed solution was supplied to the bottom of the AGMD module using a feed pump. This initial feed solution passed through the membrane module and heat exchanger and returned to the AGMD module from the top side. During this process, the AGMD module acted as a heat exchanger and increased the temperature of the incoming feed solution. Any additional temperature required for the feed solution was supplied through an electrical heater, as shown in Fig. 1. Due to the temperature difference between the feed side and the hot side of the membrane, water vapour passed through the membrane and emerged in the permeate spacer channel. By measuring the quantity and quality of the distillate, the water flux and

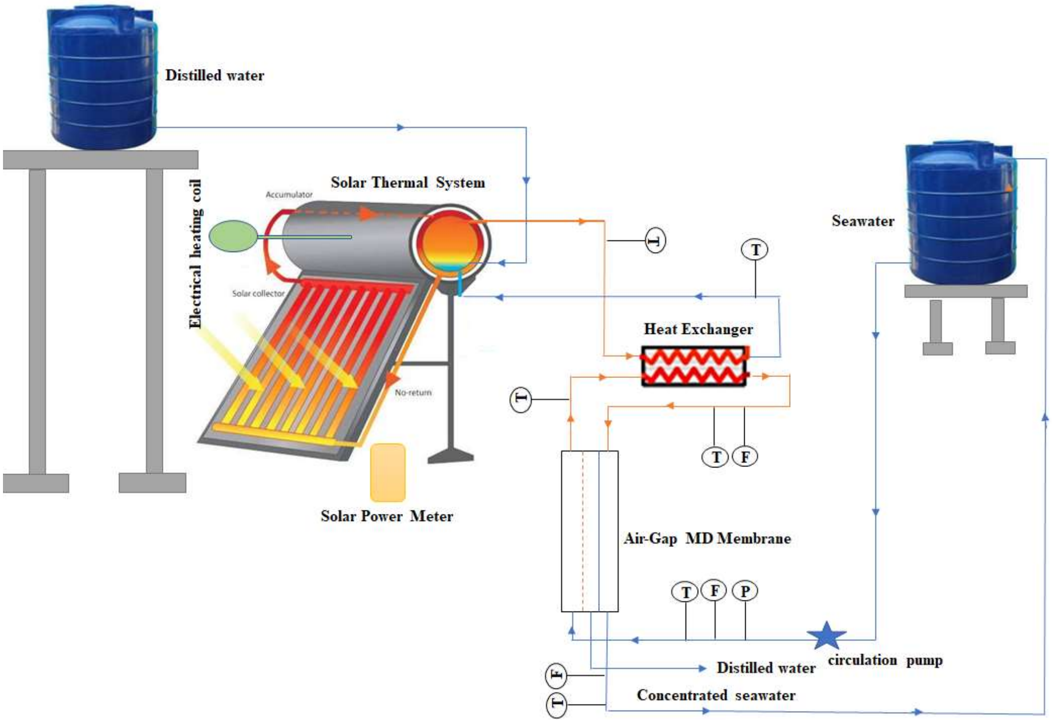


Fig. 1: Schematic process flow diagram of the membrane distillation system.

salt rejection were calculated using Equations 1 and 2. In the brine concentration experiments, MD brine was recirculated back to the feed tank. After completing the electrical heating experiments, the heater was disconnected, and solar energy was used as the heat source to heat the incoming feed. The solar MD brine concentration experiments were conducted for five days, using RO brine feed operating six hours per day. During the solar MD test, solar radiation intensity, weather temperature, humidity levels, feed-in temperature, and brine-out temperature were measured at each 30 min interval using a pre-programmed measuring instrument to record mean values. The changes in the measurement values were correlated with water production values in the Results and Discussion. The experiments conducted using the electrical heating mode of operation were triplicated, and the mean value of the results was reported.

$$J_v = \frac{\Delta V}{A_m \cdot \Delta t} \quad ...(1)$$

Where Jv is the water flux (kg.m^{2}h^{-1}), ΔV is the quantity of distillate (kg), Am is the effective distillation area (m^2), and Δt is the sampling time (h).

The rejection coefficient R will be calculated according to the following equation:

$$J_v = \frac{\Delta V}{A_m \cdot \Delta t}$$

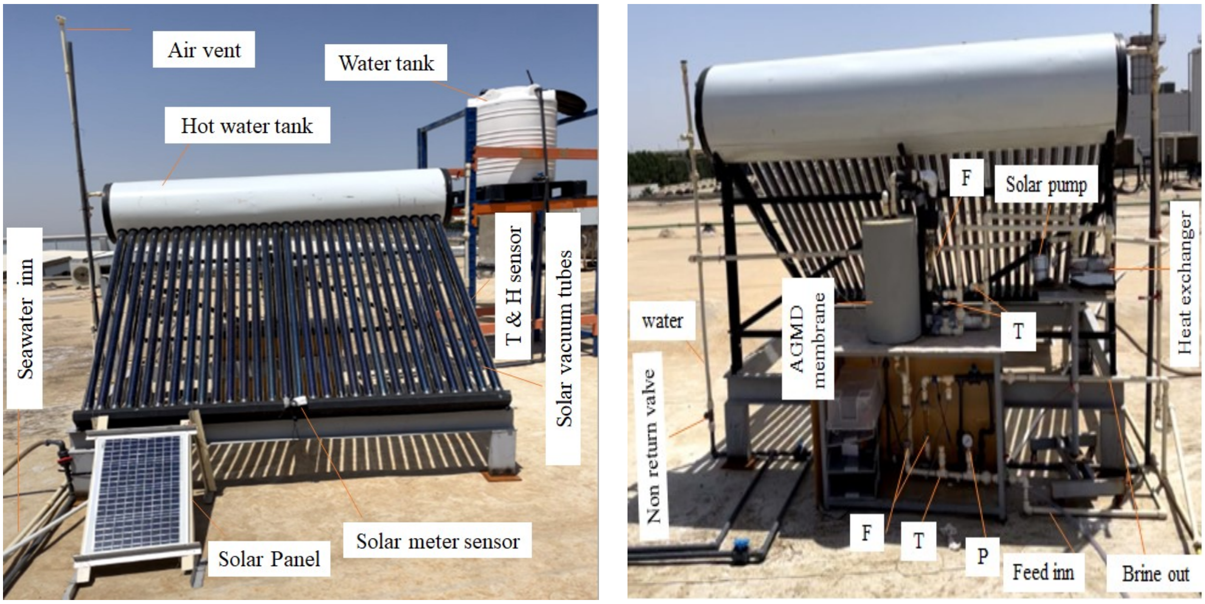
$$R = \frac{C_f - C_p}{C_f} \quad ...(2)$$

Where, C_f and C_p are the concentrations of the feed and distillate, respectively.

RESULTS AND DISCUSSION

Desalination and Brine Concentration Performance Study

The MD system was constructed as shown in Fig. 1. A leakage test and calibration of the sensors were conducted. After the system underwent preliminary testing, the operating parameters of the MD system were optimised using second-stage RO permeate as feed by varying the feed flow rate (120-240 L.h^{-1}) and temperature (50-80°C). The highest water flux (1.64 L.m^{2}h^{-1}) was observed at a feed temperature of 80°C and a feed flow rate of 240 L.h^{-1}. Therefore, an optimised feed flow rate of 120 L.h^{-1} and a temperature of 80°C were considered for desalination and brine concentration applications using different saline waters.



a: Front side view b: Back side view

T: Temperature, H: Humidity

Fig. 2. a) Front side view of integrated solar membrane distillation system, and b) back side view of integrated solar membrane distillation system.

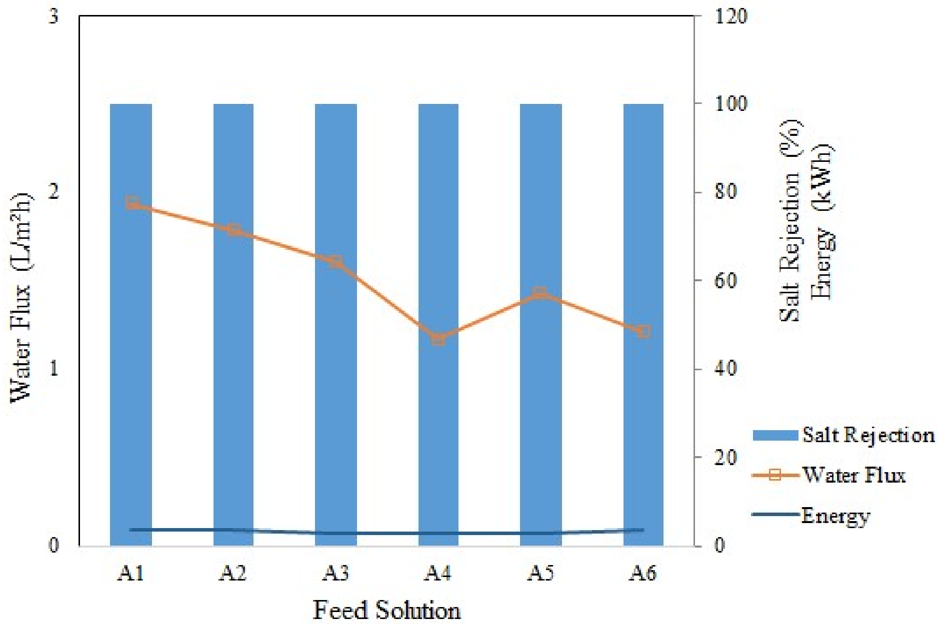
Table 1: Physicochemical Analysis of Investigated Feed Solution.

Sample Name	Parameters/Unit								
	TDS [ppm]	pH	Conductivity [ms.cm^{-1}]	Mg [mg.L^{-1}]	Ca [mg.L^{-1}]	SO_4 [mg.L^{-1}]	Na [mg.L^{-1}]	Cl [mg.L^{-1}]	K [mg.L^{-1}]
A1	4,692	7.94	7.45	123.4	590	1,400.3	910	1,957.7	35
A2	8,358	8.14	13.21	299	916	2,454.7	1,146	4,081	113
A3	43,504	7.93	61.7	1,288	825	4,901.7	11,688	22,938	393
A4	66,784	7.86	94.84	1,663.2	1,240	4,241	18,240	38,908.7	611
A5	43,560	7.96	61.7	1,350	1,288	6,190.7	12,288	25,452.4	422
A6	56,336	8.03	80	1,536	1,306	7,824.7	15,360	31,831.6	520

TDS: Total dissolved solids, ppm: parts per million, ms.cm^{-1}: milli siemens/centimeter, Mg: magnesium, Ca: calcium, SO_4: Sulfate, Na: Sodium, Cl: Chloride, K: Potassium, mg.L^{-1}: mg.L^{-1}
A1: Wafra groundwater, A2: Wafra groundwater RO brine, A3: Doha beach well seawater, A4: Doha beach well seawater RO brine, A5: Shuwaikh surface seawater, A6: Shuwaikh seawater MSF brine.

The desalination and brine concentration study was conducted using different saline feed solutions collected from Kuwait. The collected samples included different salinities ranging from 4,692 parts per million (ppm) to 66,784 ppm, including brackish groundwater and its RO brine, beach well seawater, surface seawater, RO brine, and multistage flash distillation (MSF) brine. The names of the locations and the physicochemical analysis results of the feed solutions are presented in Table 1.

The desalination study conducted using electrical heating mode showed that the water flux was higher for the low-salinity groundwater feed source than for the brine sample, as shown in Fig. 3 and Table 2. The water flux values clearly indicate that an increase in feed concentration results in a decrease in water flux (Schwantes et al. 2018, Duong et al. 2021). All the tested feed solutions showed more than 99% rejection efficiency, and the energy requirement ranged from 3 to 3.5 kilowatt-hours (kWh). Freshwater recovery ranged between 3.33% and 4%, indicating that water recovery is not significantly affected by increased feed salinity from groundwater (4,692 ppm) to RO brine feed (66,784 ppm). This indicates that the MD system is able to concentrate



A1: Wafra groundwater, A2: Wafra groundwater RO brine, A3: Doha beach well seawater, A4: Doha beach well seawater RO brine, A5: Shuwaikh surface seawater, A6: Shuwaikh seawater MSF brine.

Fig. 3: Desalination performance in electrical heating mode.

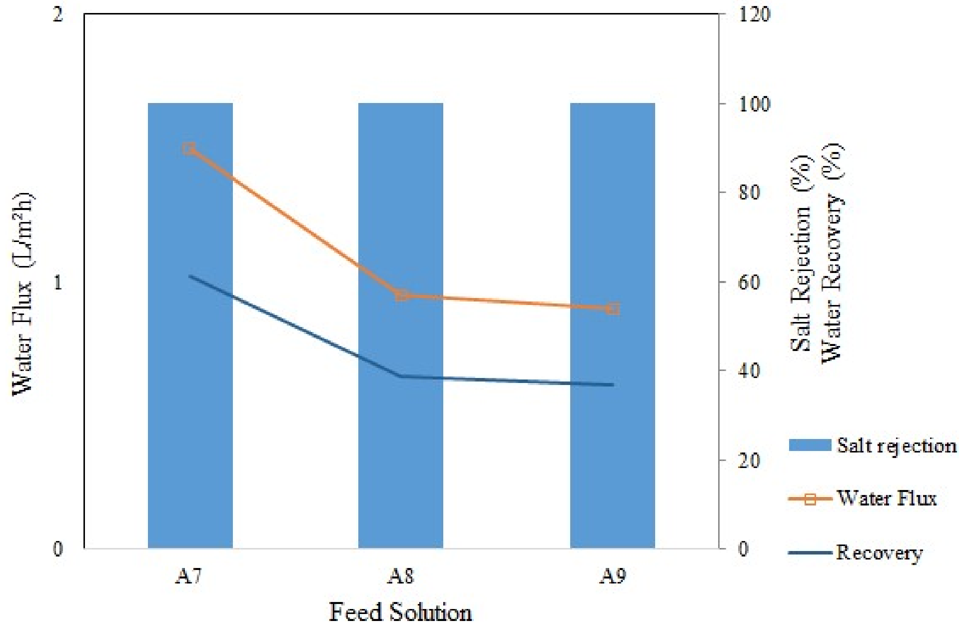
Table 2: Desalination Performance of the Investigated Feed Solution.

Sample Name	Water Flux [$L.m^2h^{-1}$]	Energy [kWh]	Salt Rejection [%]
Wafra groundwater	1.93±1	3.5±1	99.97±1
Wafra groundwater RO brine	1.78±2	3.5±1	99.96±1
Doha beach well seawater	1.60±2	3±1	99.98±1
Doha beach well seawater RO brine	1.16±4	3±	99.99±1
Shuwaikh surface seawater	1.42±2	3±1	99.98±1
Shuwaikh seawater MSF brine	1.21±1	3.5±	99.98±1

RO brine feed to a much higher concentration level without significantly compromising salt rejection and water recovery (Alobaidani et al. 2008, Schwantes et al. 2018, Duong et al. 2021, Ugarte et al. 2024, Hamwi et al. 2022).

During the experiment, the temperature loss on the brine-side solution was calculated by measuring the temperature of the feed-in, feed-out from the membrane, and brine-out. For all the tested experiments, the temperature loss was almost 5–6°C on the brine side, and temperature recovery was 93%. The higher recovery of temperature from the brine side is due to the module design and its configuration. The tested Aquastill MD membrane has a three-channel membrane configuration and acts as a heat exchanger during the desalination process. Therefore, the Aquastill MD membrane requires less energy for the desalination process compared with other module designs, such as hollow-fiber modules and simple plate-and-frame modules (Duong et al. 2021).

After completing the initial desalination studies, the MD system was applied for brine concentration using groundwater RO brine, seawater RO brine, and seawater MSF brine as feed solutions. Tests were conducted over 6 hours, data were recorded every 30 min, and the brine solution was recirculated to the feed tank. For each test, 75 L of feed solution was taken in a closed, insulated container, and temperature variation in the feed tank was measured every 30 min. During the experiments, the temperature of the feed increased over time, but the temperature difference between the membrane feed side and the brine side adjusted automatically due to the MD module configuration. The temperature on the permeate side increased due to the higher temperature between the feed side and the permeate-side solution. A slight reduction in water flux was observed compared to experiments without brine recirculation, but salt rejection exceeded 99%. Fig. 4 shows



A7: Wafra groundwater RO brine, A8: Doha beach well seawater RO brine, A6: Shuwaikh seawater MSF brine.

Fig. 4: Brine concentration performance in electrical heating mode.

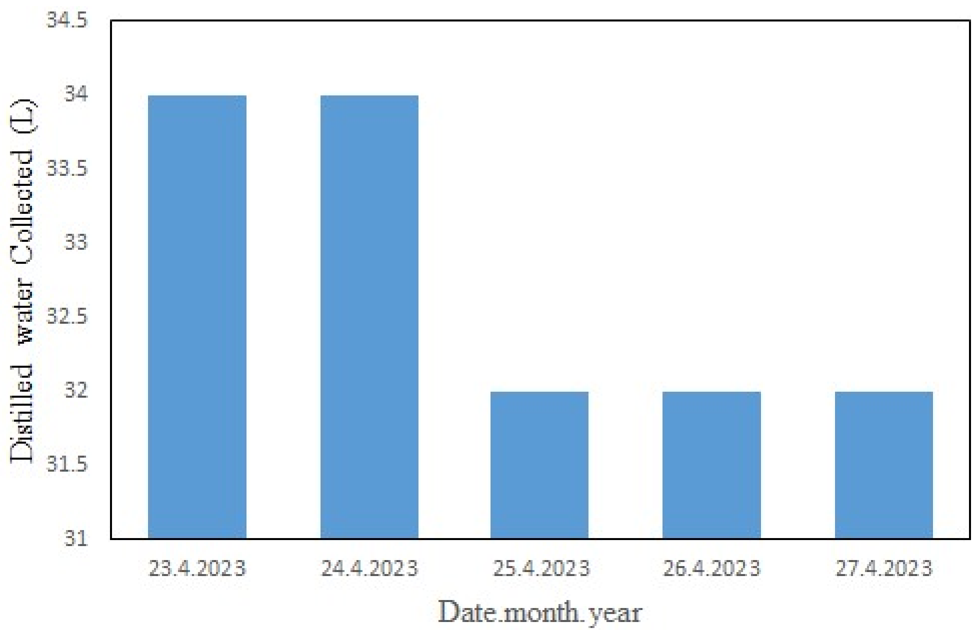
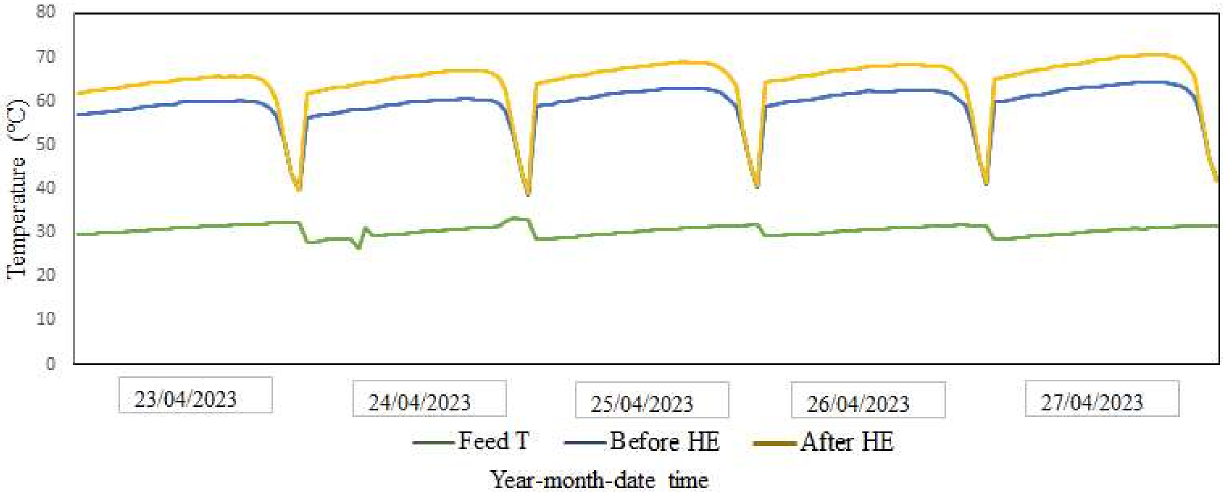


Fig. 5: Daily average distilled water production in solar mode.

the graphical representation of water flux, salt rejection, and overall recovery.

After completing the electrical-mode brine concentration study, the MD system was fixed on the rooftop of the DRP building, and its brine concentration performance was assessed using RO brine as feed. The MD system was operated for five days, running the system each day for six hours. The total feed volume was 500 L, and the brine from the system was recirculated back to the feed tank. The solar MD system operated from April 23 to April 27, 2023. During this period, the daytime temperature (T) ranged from 24.1 to 42.5°C (with a mean T of 30.83°C), humidity (H) ranged



T: temperature, HE: heat exchanger.

Fig. 6. Operating parameter during the solar MD operation.

from 23.1 to 69.7% (with a mean H of 43.32%), and the average radiation over all five days was 478.76 W.m^{2-}. The experimental results show that daily permeate production ranged from 32 to 34 L.day^{-1}, and each day produced nearly the same quantity of permeate/distilled water (Hamwi et al. 2022). This indicates that the increase in feed salinity did not significantly affect permeate quantity during the five-day operation period. This may be due to additional heat storage in the thermal tank after six hours of operation, which was utilised for the next day. There was no change in the water flux and salt rejection values throughout the study. This indicates that the membranes were not fouled or scaled due to the increased salinity and drastic changes in temperature during the day and night (changes in feed temperature). Further research is needed for year-long testing of the solar MD system and to study changes in membrane properties to observe fouling or scaling issues. The daily permeate production, variation of temperature, humidity, and system inlet and outlet temperatures are presented in Figs. 5 and 6.

Overall, the experimental results showed that the MD system is a promising technology for brine concentration applications. The integration of solar energy into the MD system for brine concentration will also help reduce the environmental impact. The research team recommends long-term (more than one year) operation of the solar MD system to accurately evaluate its performance and fouling behaviour for brine concentration applications.

CONCLUSIONS

The MD system was fabricated to operate in both electrical and solar heating modes. The desalination performance of the fabricated MD system was evaluated using different saline waters. The experimental results from the electrical heating mode showed that the fabricated MD system could desalinate saline water ranging from 4,692 ppm to 66,784 ppm without compromising salt rejection. Brine concentration studies using the electrical heating mode showed highly promising results, concentrating the feed brine solution up to 20% (near saturation level). The five-day operation of the solar MD system for RO brine concentration applications showed uniform water flux and salt rejection. This clearly indicates that solar MD technology is a promising and viable process for brine concentration.

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