Photothermal Carbon Black Coatings Enable Efficient Solar-Driven Membrane Distillation

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Characterization of the CB powder and composite membranes

The crystallographic structure of the CB powder was examined using X-ray diffraction (XRD). The measurements were performed on a B2 Bucker diffractometer equipped with Cu Kα radiation (λ = 1.540 Å), operating at 30 mA and 40 kV, over a 2θ range of 4° to 90°. The average crystallite size (D) was estimated using the Williamson–Hall (W–H) method [1].

$$\beta\cos\theta=\left(\frac{K_s\lambda}{D}\right)+(4\varepsilon\mathrm{Sin}\theta) \tag{1}$$

where *β,* ε, *θ,* and *K* are the half maximum, microstrain, Scherrer's constant, and full width at Bragg's angle, respectively.

Furthermore, the dislocation density, defined as the total length of dislocation lines per unit volume, is calculated using the corresponding equation [1].

$$\delta = \frac{1}{D^2} \tag{2}$$

Fourier Transform Infrared (FTIR) spectroscopy (THERMO NICOLET, 50) was used to investigate the structure of the CB powder and the presence of functional groups,. To assess the surface morphology and microstructure of the as-prepared samples, high-resolution scanning electron microscopy (SEM) was carried out using a FEI Quanta FEG 250 system, which has a solid angle of 0.28 sr. This technique provides localized elemental analysis, complementing morphological observations by confirming the chemical homogeneity of the sample.

The surface wettability of the membranes was assessed by measuring the static water contact angle (θ) using the sessile drop method with deionized water (DI-water) as the probe liquid. Measurements were performed at room temperature using a contact angle goniometer, with at least five measurements per sample to ensure reproducibility.

Liquid Entry Pressure (LEP)

To quantitatively assess the risk of pore wetting due to the hydrophilic PVA component in the coating, the LEP was theoretically estimated using the modified Young–Laplace equation [2]:

$$LEP = \frac{-2\gamma B Cos\theta}{r_{max}} \quad (18)$$

Where γ is the surface tension of deionized water (0.072 N/m at 25 °C), θ is the measured water contact angle, r_{max} is the maximum effective pore radius, B is the pore geometry factor (0.6 for stretched PTFE membranes to account for non-cylindrical pore geometry).

Experimentally, LEP of the commercial and coated PTFE membranes was determined experimentally using the static method originally proposed by Smolders and Franken [3]. LEP was measured for all the membranes by using a dead end cell (HP4750 Stirred Cell) system, which was connected to a nitrogen gas cylinder as inert gas to apply the required pressures using distilled water as a liquid. A custom-designed stainless-steel filtration cell (Fig. S1) was employed with membrane diameter of 4.9 cm. The membrane samples were cut to the appropriate size and securely clamped between the two chambers using O-rings to prevent lateral leakage. Prior to measurement, the membrane was placed in the cell, and the feed chamber was filled with the test liquid (distilled water). Compressed nitrogen gas (N_2) was used as the pressure source and connected to the feed side through a precision pressure regulator. A digital pressure gauge with a resolution of at least 0.01 bar was used to monitor the applied transmembrane pressure. The LEP measurement was conducted by initially applying a low pressure of approximately 0.3 bar to the feeding side, followed by a systematic stepwise increase in increments of 0.068 to 0.1 bar. To ensure thermodynamic equilibrium and enhance reproducibility, a constant holding time of 5 minutes was maintained at each pressure level. During this process, the permeate side was continuously monitored for the onset of continuous liquid flow detected via visual droplet observation, conductivity shifts, or direct flux measurement with LEP ultimately recorded as the minimum pressure required to sustain a steady flow through the membrane.

Fig. S1. The Dead-end filtration apparatus for LEP measurement

2.6. Performance of the Membrane Distillation

A custom membrane distillation (MD) system was employed to perform bench-scale experiments, as previously described in our earlier work. The MD cell (Fig.S2) was fabricated from acrylic and had an effective membrane area of 0.0036 m². Deionized (DI) water was used on the distillate side, while the feed side contained either a sodium chloride solution or a synthetic saline solution with a salinity ranging from 35,000 to 40,000 ppm. The feed solution was circulated through the MD system at a flow rate of 0.2 L/min under various feed temperatures, while the distillate side temperature was maintained at 30 °C. The permeate mass was continuously recorded at one-minute intervals using a digital balance connected to a computer, allowing precise calculation of the permeate flux. After each experimental run, the system was cleaned with DI water containing 1% HCl and subsequently rinsed thoroughly with DI water to prevent cross-contamination between experiments. The water flux, Jw (LMH), and the salt rejection Rs (%), was calculated as follows [4]:

$$J_w = \frac{\Delta\, m}{S.\Delta t} \tag{21}$$

$$R_s = \frac{C_f - C_p}{C_f} \times 100 \tag{22}$$

Δ_m is the permeate's weight increase during a specific time (t), C_f and C_P are the salt concentration in the feed and permeate (g/L), respectively. The schematic of the MD unit is illustrated in Fig. S2 [5].

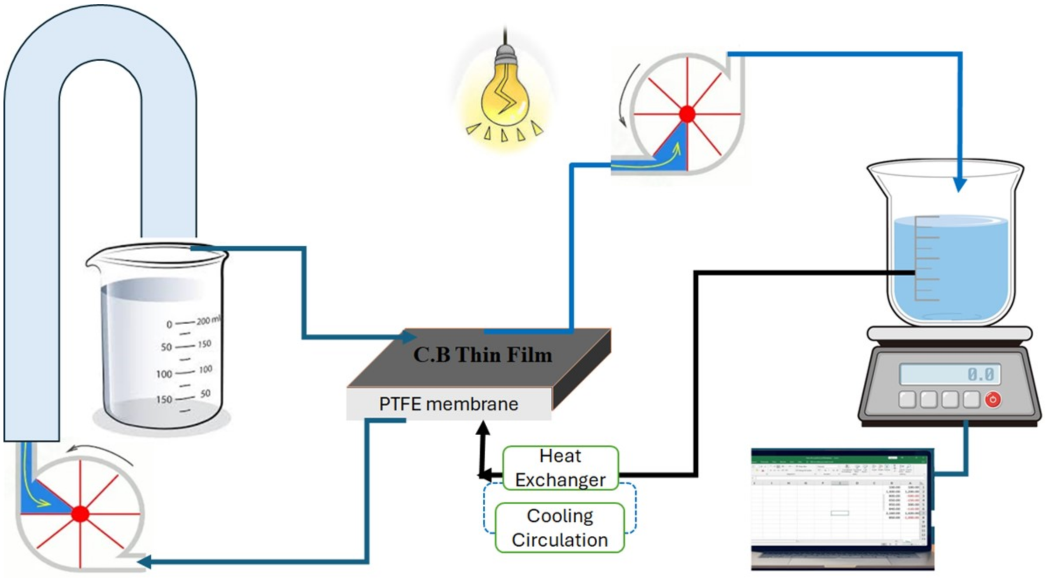

Fig.S2A. Schematic of the direct contact membrane distillation (DCMD) apparatus used for photothermal testing under simulated solar illumination.

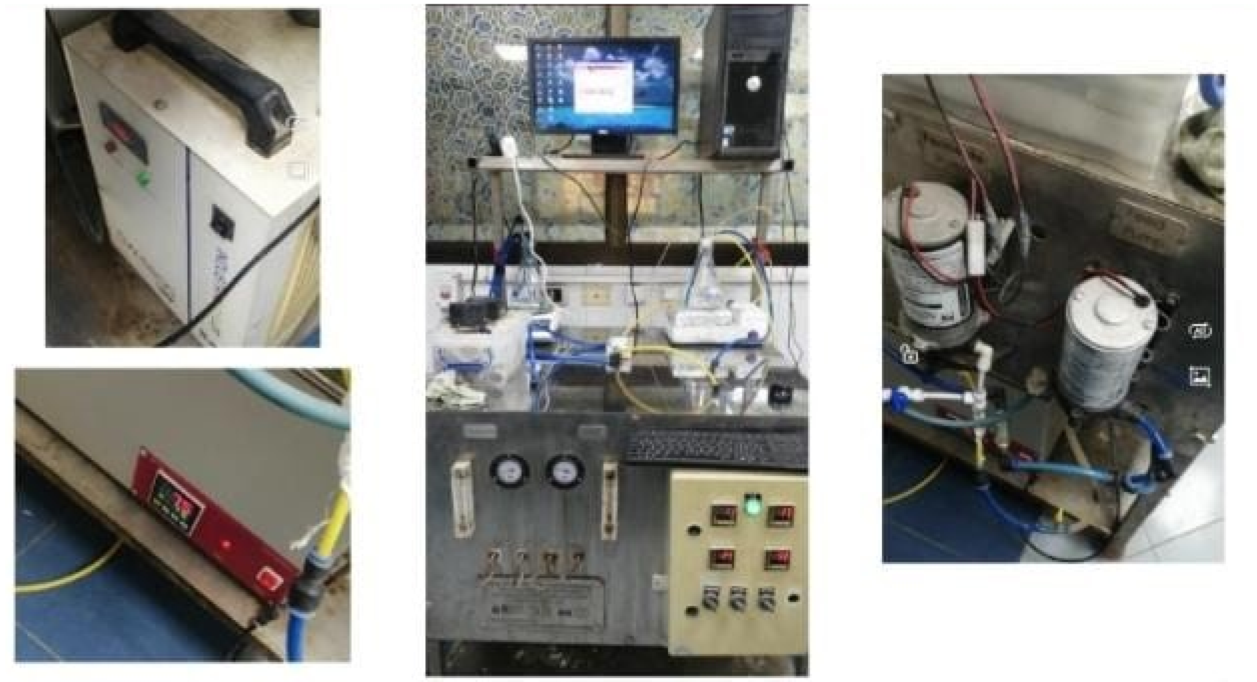

Fig.S2B. Lab Set up of the direct contact membrane distillation (DCMD) apparatus used for photothermal testing under simulated solar illumination.

2.7. Photothermal experiments

In the solar membrane distillation (MD) experiments, the feed temperature was held at 40 °C, establishing a baseline temperature of approximately 30 °C within the system. A cold-water bath containing glass coils maintained the distillate stream at 10 °C by circulation. Illumination of the membrane was achieved using 50 W , 100 W and 200 W lightbulbs positioned 10 cm above the transparent membrane cell. This setup produced incident light intensities of 50 ,100 and 200 mW/cm² at the membrane surface, as transmitted through a clear acrylic cover. For precise irradiation quantification on the membrane, a Thorlabs PM100D power meter (Lübeck, Germany) was used to measure light intensity.

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