

Article

An Inclined Polypyrrole-Coated Bacterial Cellulose Gel Enables High-Efficiency Oil–Water Emulsion Treatment

Biyi Huang ^{1,2,*} , Hongbin Liu ¹ , Ru Yang ¹, Yihang Lu ¹ and Shubin Yan ^{1,2}

¹ Department of Electrical Engineering, Zhejiang University of Water Resources and Electric Power, Hangzhou 310018, China; liuhb@zuwe.edu.cn (H.L.); yangru@zuwe.edu.cn (R.Y.); luyh@zuwe.edu.cn (Y.L.); yanshb@zuwe.edu.cn (S.Y.)

² Zhejiang-Belarus Joint Laboratory for Intelligent Equipment and Systems for Water Conservancy and Hydropower Safety Monitoring, Hangzhou 310018, China

* Correspondence: huangby@zuwe.edu.cn

Abstract

Emulsified oily wastewater from industrial activities remains challenging to treat because kinetically stable oil droplets hinder efficient separation, threatening water resources and ecological environments. To address this issue, this work develops an inclined solar-driven evaporator based on a polypyrrole (PPy)-coated bacterial cellulose (BC) gel (PPy-BC gel), which has enlarged effective evaporation areas and an environmental heat effect. Under one sun (1 kW m^{-2} under standard solar illumination), the PPy-BC gel achieves an evaporation rate of $2.14 \text{ kg m}^{-2} \text{ h}^{-1}$, which is 494% higher than that of the uncoated BC gel. In diesel-in-water emulsions with oil concentrations ranging from 0 to 15 vol%, the gel maintains stable evaporation performance, achieving an oil removal efficiency exceeding 99% across all tested concentrations. After 15 consecutive cycles of treating actual oily wastewater, no significant performance degradation is observed. The collected condensate exhibits excellent water quality, with removal efficiencies for total organic carbon (TOC), chemical oxygen demand (COD), and total dissolved solids (TDS), and ionic conductivity (IC) exceeding 94%. This work presents a solar-powered evaporation platform, which demonstrates potential in the stable treatment of complex oily wastewater, and offers a sustainable reference solution for decentralized industrial wastewater management.

Keywords: hydrogel; solar evaporation; emulsified oily wastewater; PPy; bacterial cellulose

1. Introduction

Water scarcity and water environmental pollution are among the major global challenges today. With rapid industrialization, large amounts of oily wastewater are discharged into the environment, posing serious threats to ecosystems and human health. In particular, emulsified oily wastewater contains micron- and even submicron-sized oil droplets stabilized by surfactants and interfacial forces. These stabilized droplets resist coalescence, forming kinetically stable emulsions that are much more difficult to separate than free oil–water mixtures [1–3]. Conventional separation techniques such as gravity settling, skimming, and membrane filtration are not only inefficient but also often energy-intensive when treating such emulsions [4,5]. Meanwhile, the volume of oily wastewater generated by industries including petrochemicals, oil refining, transportation, and metal processing continues to increase, further intensifying the urgent demand for sustainable and efficient purification technologies [6].



Academic Editor: Levente Csoka

Received: 8 June 2026

Revised: 10 July 2026

Accepted: 13 July 2026

Published: 15 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

In recent years, solar-driven interfacial evaporation technology has become a highly promising method in the field of wastewater treatment due to its ability to directly utilize solar energy to produce clean water [7–9]. During this evaporation process, solar energy is concentrated at the air–water interface, significantly reducing heat dissipation to the bulk liquid and thereby improving energy utilization efficiency [10–12]. More importantly, the liquid–vapor phase transition of water enables intrinsic separation from non-volatile contaminants, including salts, organic compounds, heavy metals, and oily pollutants. During solar-driven evaporation, water molecules in the liquid phase are selectively converted into vapor, whereas non-volatile contaminants remain in the concentrated liquid phase due to their negligible volatility. The generated water vapor is subsequently condensed into purified water, thereby achieving simultaneous water purification and oil–water separation [13]. Therefore, solar evaporation provides a versatile platform for the synergistic treatment of wastewater and the production of freshwater, as well as absolute film separation of dyes/salts and emulsions with a superhigh water permeance through graded nanofluidic channels [14–17].

Although solar-driven interfacial evaporation has demonstrated significant effectiveness in seawater desalination and wastewater purification, its application in treating oily emulsions remains challenging [18,19]. Unlike saline water, oil–water emulsions contain highly dispersed fine oil droplets, which tend to accumulate at the evaporation interface, leading to pore blockage, hindered water transport, and degraded photothermal performance [20]. Moreover, prolonged exposure to oily contaminants often causes surface fouling and reduced stability, severely limiting the practical implementation of solar evaporators for oily wastewater treatment. Therefore, developing photothermal evaporators with high water transport efficiency, strong antifouling ability, and long-term operational stability is the key to achieving sustainable treatment of emulsified oily wastewater.

To address the above issues, this paper combines the excellent photothermal conversion capability of polypyrrole (PPy) with the highly porous and hydrophilic network structure of bacterial cellulose (BC) gel to develop a polypyrrole-coated bacterial cellulose gel (PPy-BC gel) as a solar-driven evaporator. BC is a renewable and biodegradable biopolymer produced by microbial fermentation, featuring excellent environmental compatibility, abundant hydroxyl groups, and a three-dimensional nanofibrous network. These intrinsic characteristics make BC an attractive and sustainable scaffold for solar-driven water treatment applications [8,21]. The interconnected BC nanofiber framework provides continuous capillary-driven water transport pathways, while the PPy coating efficiently captures solar energy and converts it into localized heat. This synergistic structure not only facilitates rapid water transport and effective heat localization but also prevents oily contaminants from reaching the water–air evaporation interface through underwater oleophobicity of PPy-BC gel, thereby maintaining stable evaporation performance during prolonged operation [20]. To evaluate the feasibility of the PPy-BC gel for treating actual oily wastewater, an oil-in-water (diesel) emulsion was selected as a representative model system. The separation performance of the PPy-BC gel was systematically investigated by assessing its evaporation rate, oil removal efficiency, cyclic stability, and water purification performance at different emulsion concentrations. The practical performance was finally evaluated by outdoor experiments.

2. Materials and Methods

2.1. Preparation of PPy-BC Gel and BC Gel

BC gel was prepared by a fermentation method. First, *Gluconacetobacter xylinum* was statically cultured at 30 °C for 4–7 days to obtain a BC gel, following the procedure reported previously [22]. After fermentation, the obtained hydrogel was repeatedly washed with

deionized water until neutral pH, and then stored for further use. To prepare the PPy-BC gel, polypyrrole (PPy) was in situ polymerized onto the BC matrix [23]. The fabrication process is shown in Figure 1. Briefly, 2.28 g of ammonium persulfate (APS) and 0.7 mL of pyrrole (Py) were separately dissolved in 100 mL of deionized water to prepare an APS solution and a pyrrole solution, respectively. A BC gel sample with an area of 20 cm² was placed in a Petri dish, and 10 mL of the APS solution and 5 mL of the Py solution were sequentially added. The molar ratio of APS to pyrrole was approximately 1:1. The polymerization reaction was carried out at 4 °C for 24 h. The resulting PPy-BC hydrogel was thoroughly washed with deionized water 3 times to remove residual reactants, yielding the final product.

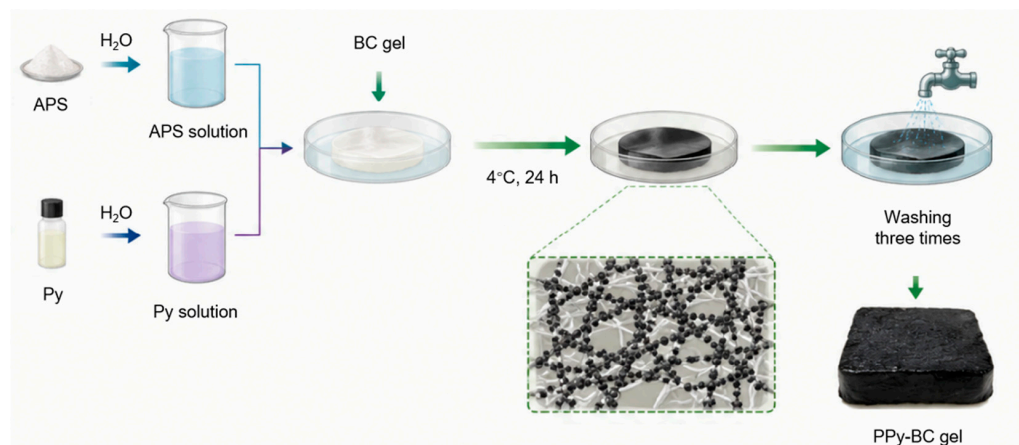


Figure 1. The fabrication process of PPy-BC gel.

2.2. Characterization

The optical absorption spectra of the wet PPy-BC gel and BC gel were recorded using a UV–Vis–NIR spectrophotometer (PerkinElmer, Shelton, CT, USA). For SEM characterization, the hydrogel samples were freeze-dried and sputter-coated with a thin Au layer prior to observation using a scanning electron microscope (ZEISS Gemini SEM 300, Jena, Germany). The surface functional groups of the freeze-dried BC gel and PPy-BC gel were characterized by Fourier transform infrared spectroscopy (FT-IR, Thermo Scientific Nicolet iS10, Waltham, MA, USA) over the wavenumber range of 400–4000 cm^{−1}. Surface wettability was evaluated through water contact angle measurements performed on a dynamic contact angle analyzer (OCA20, Data Physics, Filderstadt, Germany).

2.3. Solar-Driven Evaporation and Purification Experiments

The solar evaporation performance was evaluated under laboratory conditions using a Xenon lamp (PLS-SXE300/300UV, Beijing, China) equipped with an AM 1.5 G filter (Perfectlight, Beijing, China) to provide simulated sunlight. The irradiation intensity was calibrated with a solar power meter (CEL-FZ-A, China Education AU-Light Technology Co., Ltd., Beijing, China). All experiments were conducted at an ambient temperature of approximately 25 °C and a relative humidity of around 60%. During the evaporation process, the mass change of the samples was continuously monitored using an analytical balance (LICHEN-FA2004, Xiamen, China). The evaporation rate ($\dot{m}$, kg m^{−2} h^{−1}) was calculated by Equation (1), where dm is the weight loss of the water (kg), S is the projected area (m²), and dt is evaporation time (here, 3600 s) [24].

$$\dot{m} = \frac{dm}{S \cdot dt} \quad (1)$$

The efficiency is calculated by Equation (2) where $\dot{m}$ is evaporation rate ($\text{kg m}^{-2} \text{h}^{-1}$), h_{lv} is total enthalpy for water evaporation (here, it is taken as 2440 kJ kg^{-1}), and q_{solar} is solar irradiation (kW m^{-2}).

$$\eta = \frac{\dot{m} \cdot h_{lv}}{q_{\text{solar}}} \quad (2)$$

Diesel-in-water emulsions with diesel concentrations of 0, 5, 10, and 15 vol% were prepared by dispersing the required amount of diesel into deionized water containing 0.1 wt% Tween 80. The mixtures were homogenized at 10,000 rpm for 10 min, followed by ultrasonication for 30 min to obtain stable emulsions (as feed solution) before each experiment. Since the emulsions were prepared following a standard laboratory procedure, the droplet size distribution was not characterized in the present work. Unless otherwise stated, all evaporation experiments were performed in triplicate, and the data are presented as the mean $\pm$ standard deviation (SD). The COD of the feed solution and collected condensate was analyzed according to the standard HACH protocol (Method 8000) [24]. TOC concentrations were quantified using a TOC analyzer (TOC-VCPH, Shimadzu Corp., Kyoto, Japan). The IC and TDS were determined using an electrical conductivity meter (DDBJ-350F, Lei-ci, Shanghai, China). Long-term cyclic evaporation experiments were performed under one sun illumination using actual oily wastewater supplied by Sinopec (Beijing, China). The oil content of this wastewater was approximately 250 mg/L. Actual oily wastewater was used without further pretreatment. The detailed composition of the wastewater was not disclosed by the supplier and therefore was not available. Each sample was tested for 15 consecutive cycles, and each cycle lasted 8 h. To assess the practical applicability of the developed evaporator, outdoor evaporation experiments were further conducted in Hangzhou, China. The weather parameters were monitored using a local weather station throughout the testing period, while the freshwater production performance and evaporation performance were simultaneously recorded. A schematic illustration of the outdoor experimental setup has been added as Figure 5a. The evaporation rate was measured following the same procedure as the indoor experiments, whereas freshwater production was determined from the amount of distilled water collected at the bottom of the device.

3. Results and Discussions

3.1. Structural and Surface Characterization

SEM images of the pristine BC gel and PPy-BC gel are presented in Figure 2. The pristine BC gel exhibits a typical three-dimensional interconnected nanofibrous network structure (Figure 2a), in which numerous pores are formed by randomly entangled cellulose nanofibers. Such a porous architecture provides numerous capillary channels for water transport and facilitates continuous water replenishment during solar evaporation. After the in situ polymerization of Py, the morphology of the BC gel changes significantly. As shown in the SEM image in Figure 2b, the surface of the cellulose nanofibers is uniformly covered with PPy nanoparticles, rendering the surface rough while retaining the original porous framework. The uniform deposition of PPy indicates successful polymerization onto the BC substrate, which is expected to enhance light absorption without blocking the water transport channels. The retained interconnected structure facilitates rapid water supply and efficient water vapor escape during the evaporation process. Figure 2c shows that a water droplet is rapidly absorbed by the PPy-BC gel within approximately 1 s, indicating excellent hydrophilicity and wettability. Such rapid water spreading enables continuous capillary-driven water supply to the evaporation interface, minimizes local dry-out during evaporation, and contributes to stable photothermal evaporation performance. This superior hydrophilic property can be attributed to the hydrophilic cellulose network

and porous microstructure, which together promote the transport of water from the bulk solution to the evaporation interface via capillary action. Meanwhile, the underwater superoleophobicity of the material also ensures its superior oil–water separation capability (inset of Figure 2b).

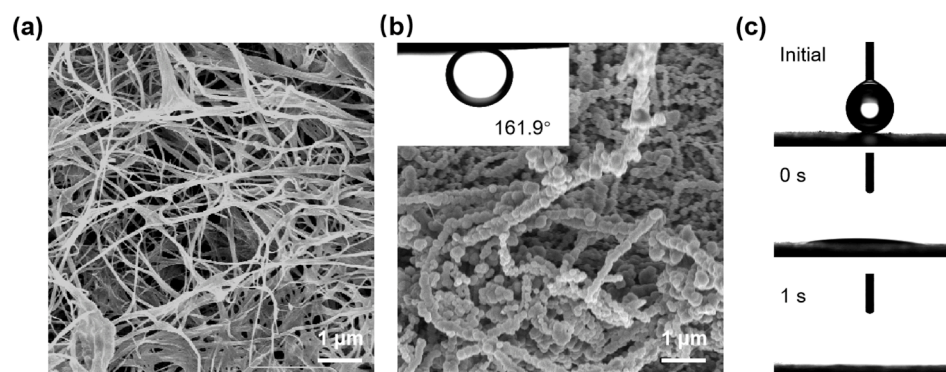


Figure 2. The characterization of the PPy-BC gel. (a) The SEM images of the BC gel. (b) The SEM images of the PPy-BC gel; inset: the oil contact angle of PPy-BC gel underwater. (c) Time-dependent water absorption process on the PPy-BC gel surface.

Figure 3a presents the Fourier transform infrared (FTIR) spectra of BC and PPy-BC. For BC, the broad absorption band at 3343 cm^{-1} is assigned to the O–H stretching vibration, the peak at 2894 cm^{-1} corresponds to the C–H stretching vibration, and the band at 1637 cm^{-1} is attributed to the C=O stretching vibration. In addition, the strong absorption at approximately 1055 cm^{-1} is assigned to the symmetric stretching vibration of the C–O–C glycosidic bonds, which is a characteristic feature of the cellulose backbone. For PPy-BC, a new absorption band appears at 1540 cm^{-1} , corresponding to the C=C skeletal stretching vibration of the pyrrole rings, while the characteristic peaks of BC are markedly weakened [18]. These results confirm the successful deposition of polypyrrole onto the BC surface. Figure 3b demonstrates the light absorption and photothermal conversion performance of the PPy-BC gel. In the ultraviolet–visible–near-infrared (UV–Vis–NIR) region (300–2500 nm), the PPy-BC gel exhibits strong and broadband light absorption, with an average absorbance exceeding 90%. The excellent light-harvesting capability originates from the intrinsic conjugated structure of PPy, which effectively converts incident solar energy into thermal energy. Under 1 sun illumination, the surface temperature of the PPy-BC gel rapidly rises to approximately $50\text{ }^{\circ}\text{C}$, as shown in the infrared thermal image in the inset. Benefiting from broadband solar absorption, excellent hydrophilicity, and interconnected water transport channels, the PPy-BC gel is expected to demonstrate outstanding performance in solar-driven evaporation and oily wastewater treatment.

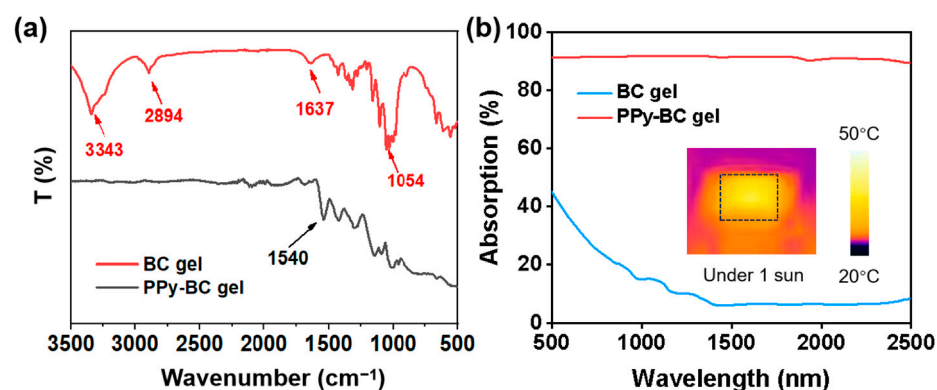


Figure 3. (a) FTIR spectra and (b) UV–Vis–NIR spectra of the PPy-BC and BC gel.

3.2. Indoor Performance

The evaporation performance of the sample under solar energy drive is shown in Figure 4. As illustrated in Figure 4a, the solar evaporator adopts an inclined photothermal structure, consisting of a light absorber (BC gel or PPy-BC gel), a water transport channel (non-woven fabric), and a supporting layer. The PPy-BC gel efficiently absorbs solar radiation and converts it into heat, with BC gel serving as a control. The non-woven fabric continuously delivers water from the underlying solution to the evaporation surface via capillary action, ensuring a stable water supply. To elucidate the effect of the inclined configuration on evaporation performance, the absorber is placed at a tilt angle (θ) above the liquid surface. Compared with a horizontal configuration, the inclined geometry not only facilitates effective sunlight capture but also increases the contact area with the surrounding air, promoting heat and water vapor transfer and thereby enhancing evaporation performance. Figure 4b presents the mass change curves of different systems under one sun illumination. As operation time increases, the mass of each system decreases linearly, indicating a relatively stable evaporation process. The evaporation rate (ER) is calculated from the slope of the mass change curves. Among them, the pure water system without any coatings exhibits the lowest evaporation rate of $0.36 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$, whereas the BC gel ($1.02 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$) and PPy-BC gel ($2.14 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$) show substantially higher rates, which are approximately 183% and 494% higher than that of pure water, respectively. This improvement is primarily attributed to the excellent solar absorption characteristics of the PPy coating, which converts more light energy into heat, thereby accelerating interfacial evaporation [25]. The apparent solar-to-vapor conversion efficiency of PPy-BC gel (144%) calculated by Equation (2) exceeds 100%, which is attributed to the additional environmental heat harvested and larger evaporation area. Therefore, this parameter no longer represents the intrinsic photothermal conversion efficiency of the evaporator. Considering that the present system is intentionally designed to utilize both solar irradiation and environmental thermal energy, the evaporation rate is adopted as the primary performance metric.

The effect of tilt angle on the evaporation performance under 1 sun illumination is illustrated in Figure 4c. As the tilt angle increases from 0° to 60° , the evaporation rate gradually increases from approximately $1.8 \text{ kg m}^{-2} \text{ h}^{-1}$ to about $4.2 \text{ kg m}^{-2} \text{ h}^{-1}$. The results indicate that increasing the tilt angle significantly promotes evaporation performance. On the one hand, the tilted structure increases the contact area between the solar evaporator and the surrounding air, expanding the effective evaporation area [14]. On the other hand, a larger tilt angle enhances heat exchange between the evaporation surface and the environment, allowing more ambient heat to be absorbed and providing additional energy for water evaporation [26]. Furthermore, the tilted configuration facilitates rapid water vapor diffusion, reducing local humidity accumulation and further enhancing the evaporation rate. Although a higher tilt angle resulted in a higher evaporation rate, a tilt angle of 30° was selected for the subsequent experiments as a compromise between evaporation performance, structural stability, and practical operation. This moderate inclination provides substantial performance enhancement while maintaining a compact and stable device configuration. Figure 4d displays the effect of solar radiation intensity on evaporation performance. Within the range of $0.5\text{--}2.0 \text{ kW m}^{-2}$, the evaporation rate increases continuously with light intensity, rising from $1.35 \text{ kg m}^{-2} \text{ h}^{-1}$ to $4.0 \text{ kg m}^{-2} \text{ h}^{-1}$. Overall, PPy-BC gel can operate stably under various light intensities.

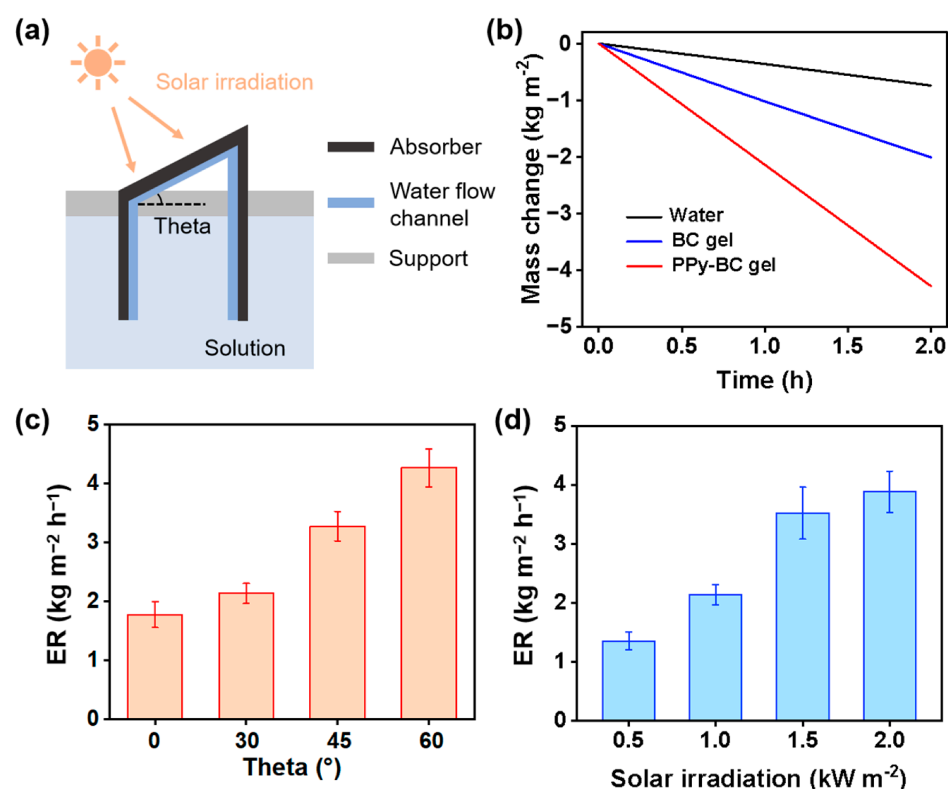


Figure 4. The evaporation performance of the homemade solar evaporators. (a) The structural diagram of the solar evaporator; (b) mass change curves of the pure water system and the solar evaporator based on PPy-BC gel and BC gel; evaporation rate of the solar evaporator based on PPy-BC gel with (c) different tilt angles and (d) different solar irradiation.

Figure 5 shows the oil–water separation performance of PPy-BC gel under sunlight. As illustrated in Figure 4a, under one sun illumination, when the oil volume fraction increases from 0 to 15%, the evaporation rate (ER) decreases from $2.14 \text{ kg m}^{-2} \text{ h}^{-1}$ to $1.95 \text{ kg m}^{-2} \text{ h}^{-1}$, with an overall decrease of less than 10%. This indicates that the gel exhibits good oil-fouling resistance and stable interfacial evaporation performance, thereby providing a reliable foundation for practical oil–water separation applications. Furthermore, within the oil concentration range of 0–15 vol%, the oil rejection ratio of the PPy-BC gel consistently exceeds 99%, with negligible variation as the oil concentration changes (Figure 5b). This finding implies that even under high-oil-content conditions, the oil phase is effectively retained by the PPy BC gel, while the condensate generated from evaporation remains highly pure. These results further demonstrate that the selective surface wettability of the PPy-BC gel enables efficient oil retention while maintaining stable solar evaporation. As summarized in Table 1, the system we proposed (under the condition of 5 vol% oil content) outperforms the evaporators previously reported in terms of evaporation performance.

Table 1. The evaporation performance of other Janus-based solar evaporators under 1 sun.

Evaporator	Application Scene	Evaporation Rate ($\text{kg m}^{-2} \text{ h}^{-1}$)
F@CMPsHM-CHM [27]	oil-in-water emulsions	1.4
SA/PPy/C@CF [28]	oil-in-water emulsions	1.77
PGCF [29]	oil-contaminated water	1.5
JCPF [30]	oil-contaminated water	1.58
HDJE [20]	high-salinity oily wastewater	1.73
rGO-SS [31]	oil-in-water emulsions	1.44

Table 1. Cont.

Evaporator	Application Scene	Evaporation Rate ($\text{kg m}^{-2} \text{h}^{-1}$)
d-CA/G-3% membrane evaporator [32]	oil-in-water emulsions	1.38
MXene/gelatin aerogel [33]	oil/water mixture	1.7
Our work	oil-in-water emulsions	2.05

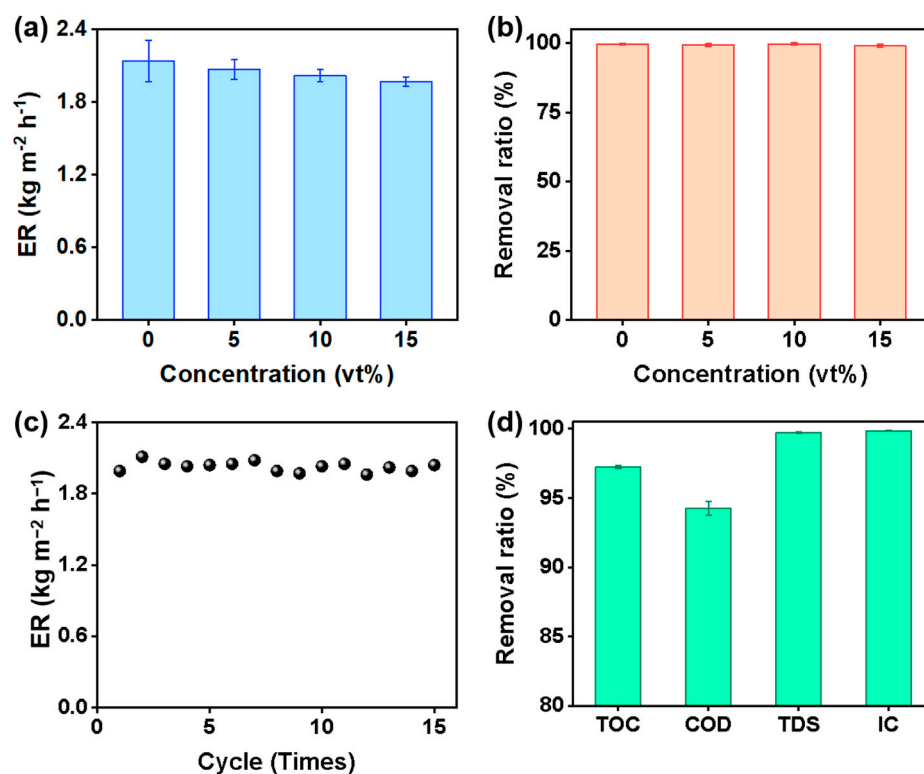


Figure 5. The solar-driven oil and water separation performance of PPy-BC gel under 1 sun illumination. (a) Evaporation rate of the PPy-BC gel in oil–water mixtures with different oil concentrations; (b) oil removal ratio of the PPy-BC gel in oil–water mixtures with different oil concentrations; (c) cyclic evaporation rate of the PPy-BC gel in actual oily wastewater. One cycle = 8 h. (d) TOC, COD, TDS, and IC removal ratios of the PPy-BC gel in actual oily wastewater.

Figure 5c presents the long-term cyclic evaporation performance of the PPy-BC gel using actual oily wastewater. Over 15 cycles, the evaporation rate remained consistently between 1.9 and 2.1 $\text{kg m}^{-2} \text{h}^{-1}$, comparable to that obtained with the laboratory-prepared oily emulsion. These results suggest that the PPy-BC gel possesses good resistance to oil fouling under the tested experimental conditions, maintaining stable interfacial evaporation during repeated treatment of both model emulsions and actual oily wastewater. Figure 5d and Table 2 evaluate the water purification performance after evaporation treatment. After evaporation treatment, the TOC, COD, TDS, and IC decreased from 315 mg L^{-1} , 980 mg L^{-1} , 1850 mg L^{-1} , and 3680 $\mu\text{S cm}^{-1}$ to 8.9 mg L^{-1} , 56 mg L^{-1} , 7.4 mg L^{-1} , and 11 $\mu\text{S cm}^{-1}$, respectively. The removal ratios of TOC and COD both exceeded 94%, while those of TDS and IC approached 100%. The high TOC and COD removal rates indicate that most organic pollutants were effectively retained, and the evaporation–condensation process significantly reduced the organic load in the wastewater. Simultaneously, the near-complete removal of TDS and IC demonstrates that inorganic salts and dissolved ions were almost entirely blocked, achieving efficient purification. Although the condensate showed substantially improved water quality, further polishing may be required depending on

the intended reuse or discharge standards, particularly with respect to residual organic indicators such as COD.

Table 2. The water quality parameters of actual oily wastewater and condensate.

Parameter	Actual Oily Wastewater	Condensate
TOC	$315.0 \pm 3.8 \text{ mg}\cdot\text{L}^{-1}$	$8.9 \pm 0.7 \text{ mg}\cdot\text{L}^{-1}$
COD	$980.2 \pm 2.4 \text{ mg}\cdot\text{L}^{-1}$	$56.1 \pm 2.2 \text{ mg}\cdot\text{L}^{-1}$
TDS	$1850.1 \pm 4.7 \text{ mg}\cdot\text{L}^{-1}$	$7.4 \pm 0.4 \text{ mg}\cdot\text{L}^{-1}$
IC	$3680 \pm 6.2 \text{ }\mu\text{S}\cdot\text{cm}^{-1}$	$11.1 \pm 0.4 \text{ }\mu\text{S}\cdot\text{cm}^{-1}$

Note that compared with pressure-driven membrane filtration systems [13], the present PPy-BC gel uses a solar-driven evaporation–condensation pathway to purify water without external pressure input. This phase-change-based process intrinsically rejects non-volatile oils, salts, and dissolved contaminants, enabling simultaneous oily wastewater treatment and freshwater collection in a decentralized manner. There were also some wettability-gradient evaporators for petrochemical wastewater treatment [34]. In comparison, our design can achieve stable evaporation and oil rejection without complicated multicomponent assembly.

3.3. Outdoor Verification Experiment

To evaluate the practical applicability of the PPy-BC gel under real environmental conditions, outdoor solar evaporation experiments were conducted. The experimental setup is illustrated in Figure 6a. The outdoor experiment was conducted under cloudy weather. During operation, the PPy-BC gel-based solar evaporator was placed inside a transparent enclosure, where solar energy was absorbed and converted into heat to drive water evaporation. The generated vapor subsequently condensed on the inner surface of the enclosure and was collected as freshwater, enabling simultaneous water purification and recovery. The environmental conditions during the outdoor test are presented in Figure 6b–e. During the testing period, the solar irradiance reached a peak value of approximately 140 W m^{-2} around noon (Figure 6b), which is considerably lower than the standard 1 sun irradiance (1000 W m^{-2}). The evaporation performance observed in this phase can therefore be regarded as the actual behavior of the evaporator under low-irradiance conditions, serving as a complementary assessment to the experimental results obtained under 1 sun illumination. The ambient temperature gradually decreased from the afternoon onward (Figure 6c). Meanwhile, the relative humidity increased from approximately 76% to 90% (Figure 6d), which may have suppressed evaporation by reducing the vapor pressure gradient between the evaporation interface and the surrounding atmosphere. In addition, the wind speed fluctuated between 0 and 3.5 ms^{-1} (Figure 6e), providing dynamic conditions for vapor transport and heat exchange. Despite these continuously changing environmental conditions, the PPy-BC gel maintained stable outdoor evaporation performance, as shown in Figure 6f. The evaporation rate, which varied from 0.23 to $0.71 \text{ kg m}^{-2} \text{ h}^{-1}$, was primarily governed by the solar irradiance profile, while the ambient temperature exerted a secondary modulating effect. Under all tested conditions, the PPy-BC gel consistently produced freshwater, confirming its ability to operate stably in real outdoor environments.

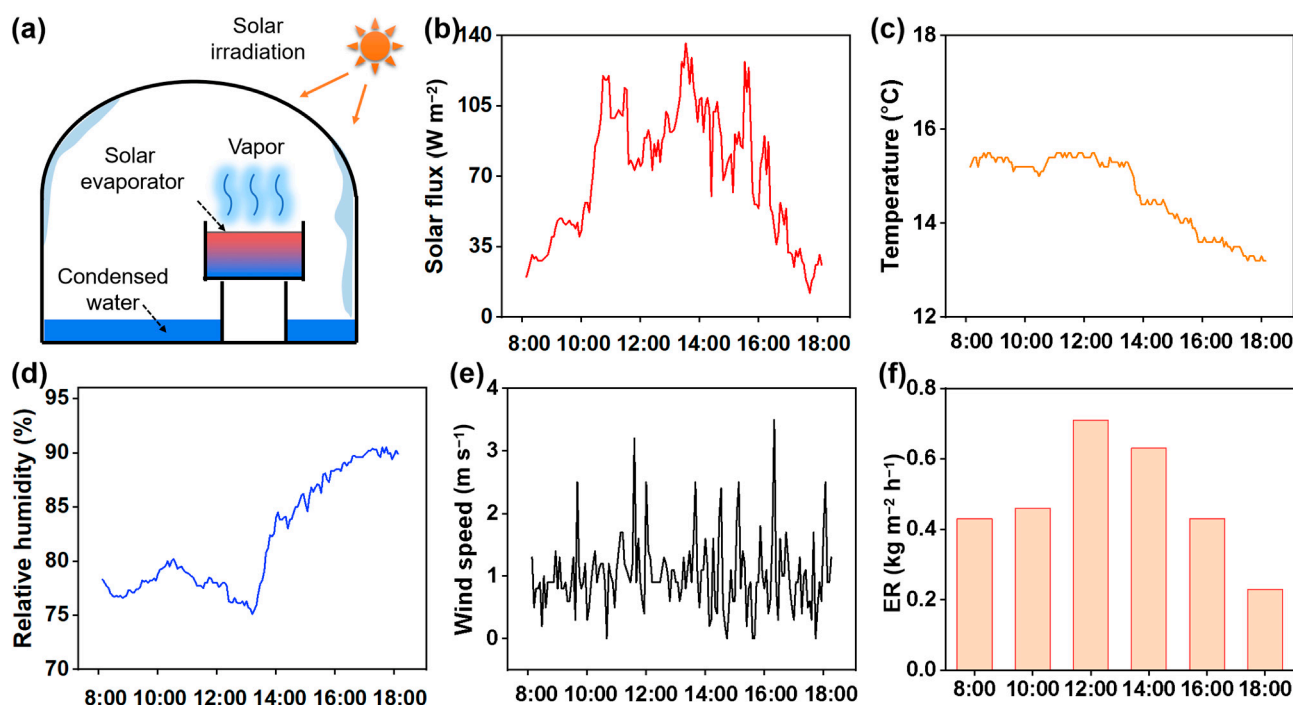


Figure 6. The outdoor experiments. (a) The structural diagram of the outdoor solar evaporator based on PPy-BC gel; (b) solar flux in the outdoor experiments; (c) temperature in the outdoor experiments; (d) relative humidity in the outdoor experiments; (e) wind speed in the outdoor experiments; (f) the evaporation rate in the outdoor experiments.

4. Conclusions

In this study, an inclined solar-driven evaporator based on a polypyrrole-coated bacterial cellulose gel (PPy-BC gel) was developed for the efficient treatment of emulsified oily wastewater and simultaneous freshwater production. By integrating the excellent photothermal conversion capability of polypyrrole with the renewable, biodegradable, and highly porous bacterial cellulose scaffold, the evaporator enables efficient solar energy utilization, continuous capillary-driven water transport, and stable interfacial evaporation under complex oily wastewater conditions. Unlike conventional solar evaporators that mainly focus on improving photothermal conversion, this work demonstrates that the synergistic combination of sustainable material design and an inclined architecture effectively enhances interfacial mass transfer and environmental heat harvesting while suppressing oil fouling. As a result, the PPy-BC gel exhibits stable evaporation performance, excellent oil–water separation capability, and long-term operational stability over a wide range of oil concentrations and during repeated treatment of actual oily wastewater. More importantly, the proposed system operates solely under solar irradiation without additional energy input, providing an energy-efficient and environmentally friendly strategy for decentralized oily wastewater treatment. The use of renewable and biodegradable bacterial cellulose further improves the sustainability of the material platform and reduces its environmental footprint. Overall, this work offers a practical design strategy for integrating sustainable materials with passive solar-driven evaporation, providing new insights into the development of high-performance solar evaporators for industrial wastewater purification and freshwater production.

Author Contributions: Conceptualization, B.H. and H.L.; methodology, B.H.; data curation, R.Y.; writing—original draft preparation, B.H.; writing—review and editing, Y.L.; project administration, S.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China, grant number 52506284, and Scientific Research Fund of Zhejiang Provincial Education Department, grant number Y202456859.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries regarding the data can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

TOC	Total Organic Carbon
COD	Chemical Oxygen Demand
TDS	Total Dissolved Solids
IC	Ionic Conductivity
PPy	Polypyrrole
BC	Bacterial Cellulose

References

1. Jiménez, S.; Micó, M.M.; Arnaldos, M.; Medina, F.; Contreras, S. State of the art of produced water treatment. *Chemosphere* **2018**, *192*, 186–208. [\[CrossRef\]](#) [\[PubMed\]](#)
2. Baig, N.; Salhi, B.; Sajid, M.; Aljundi, I.H. Recent Progress in Microfiltration/Ultrafiltration Membranes for Separation of Oil and Water Emulsions. *Chem. Rec.* **2022**, *22*, e202100320. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Yang, Z.; Tarabara, V.V.; Bruening, M.L. Adsorption of anionic or cationic surfactants in polyanionic brushes and its effect on brush swelling and fouling resistance during emulsion filtration. *Langmuir* **2015**, *31*, 11790–11799. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Erfani, H.; Madhu, N.R.; Khodayari, S.; Qureshi, M.A.; Swetanshu; Singh, P.; Jadoun, S. Separation and removal of oil from water/wastewater in the oil industry: A review. *Environ. Technol. Rev.* **2024**, *13*, 325–343. [\[CrossRef\]](#)
5. Zhang, J.; Liu, L.; Si, Y.; Yu, J.; Ding, B. Electrospun nanofibrous membranes: An effective arsenal for the purification of emulsified oily wastewater. *Adv. Funct. Mater.* **2020**, *30*, 2002192. [\[CrossRef\]](#)
6. Adetunji, A.I.; Olaniran, A.O. Treatment of industrial oily wastewater by advanced technologies: A review. *Appl. Water Sci.* **2021**, *11*, 98. [\[CrossRef\]](#)
7. He, F.; Wu, X.C.; Gao, J.; Wang, Z.X. Solar-driven interfacial evaporation toward clean water production: Burgeoning materials, concepts and technologies. *J. Mater. Chem. A* **2021**, *9*, 27121–27139. [\[CrossRef\]](#)
8. Li, F.; Lin, H.; Sui, Z.; Wu, W. Synergistic solar spectrum utilization converts seawater into green hydrogen. *DeCarbon* **2026**, *11*, 100151. [\[CrossRef\]](#)
9. Li, J.; Li, M.; Koh, J.J.; Wang, J.; Lyu, Z. 3D-printed biomimetic structures for energy and environmental applications. *DeCarbon* **2024**, *3*, 100026. [\[CrossRef\]](#)
10. Li, J.L.; Du, M.H.; Lv, G.X.; Zhou, L.; Li, X.Q.; Bertoluzzi, L.; Liu, C.H.; Zhu, S.N.; Zhu, J. Interfacial Solar Steam Generation Enables Fast-Responsive, Energy-Efficient, and Low-Cost Off-Grid Sterilization. *Adv. Mater.* **2018**, *30*, 1805159. [\[CrossRef\]](#)
11. Zhu, L.L.; Gao, M.M.; Peh, C.K.N.; Ho, G.W. Recent progress in solar-driven interfacial water evaporation: Advanced designs and applications. *Nano Energy* **2019**, *57*, 507–518. [\[CrossRef\]](#)
12. Li, L.; Yu, Z.; Jin, B.; Yu, X.; Su, Y.; Cheng, S. Hierarchical Photothermal Network Spontaneously Facilitates Co-Extraction of Clean Water and Boron. *Adv. Funct. Mater.* **2025**, *35*, 2505776. [\[CrossRef\]](#)
13. Zhang, T.M.; Guo, R.Y.; Ying, G.B.; Lu, Z.Y.; Peng, C.; Shen, M.X.; Zhang, J.F. Absolute film separation of dyes/salts and emulsions with a superhigh water permeance through graded nanofluidic channels. *Mater. Horiz.* **2022**, *9*, 1536–1542. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Yu, Z.; Li, Y.; Zhang, Y.; Xu, P.; Lv, C.; Li, W.; Maryam, B.; Liu, X.; Tan, S.C. Microplastic detection and remediation through efficient interfacial solar evaporation for immaculate water production. *Nat. Commun.* **2024**, *15*, 6081. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Li, J.; Zhu, B.; Qiao, H.; Xu, Z.; Wang, Z.; Hu, Y.; Zhang, H.; Jiang, H.; Li, W.; Wang, Y.; et al. Solar-Driven Interfacial Evaporation: Functional Materials, Structural Innovations, Synergistic Light–Heat–Mass Transfer Mechanisms, and Practical Applications. *Carbon Neutraliz.* **2026**, *5*, e70154. [\[CrossRef\]](#)

16. Cai, B.; Zhao, W.; Yuan, Z.; Xiao, J.; Li, D.; Cui, Y.; Wang, Y.; Jiang, C.; Zeng, Y.; She, Y.; et al. Tailoring Defective Tungsten Oxide Aerogel Evaporator for Enhanced Solar Steam Generation and Heavy Metal Adsorption Toward Agricultural Irrigation. *Carbon Neutraliz.* **2026**, *5*, e70149. [[CrossRef](#)]
17. Qian, Y.; Li, Q.; Wei, F.; Wang, H.; Dai, J.; Zhang, W. A Review: Strategies for Weaving Structure and Dimension Designing of Fabric-Based Three Dimensional Solar-Driven Interfacial Evaporator. *Carbon Neutraliz.* **2025**, *4*, e70044. [[CrossRef](#)]
18. Lin, F.; Mao, H.; Luan, C.; Zhong, C.; Zhou, W.; Yu, Z.; Chen, G. Isolating the Salt and Oil Discharging Area Enables the Continuous and Effective Purification of Saline Oily Wastewater. *Environ. Sci. Technol.* **2025**, *59*, 13754–13764. [[CrossRef](#)] [[PubMed](#)]
19. Yu, Z.; Guo, S.; Zhang, Y.; Li, W.; Lu, H.; Tan, S.C. Rhus Chinensis-Inspired Vertical Hierarchical Structure for Solar-Driven All-Weather Co-Harvesting of Fresh Water, Clean Salts, and Authigenic Electricity. *Adv. Mater.* **2025**, *37*, e06762. [[CrossRef](#)] [[PubMed](#)]
20. Yu, Z.; Gu, R.; Su, Y.; Li, Y.; Liu, G.; Cheng, S. Natural-inspired hierarchic double-Janus solar evaporator for stable clean water production from high-salinity emulsions. *J. Hazard. Mater.* **2024**, *474*, 134739. [[CrossRef](#)] [[PubMed](#)]
21. Iqbal, D.; Zhao, Y.T.; Zhao, R.H.; Russell, S.J.; Ning, X. A Review on Nanocellulose and Superhydrophobic Features for Advanced Water Treatment. *Polymers* **2022**, *14*, 2343. [[CrossRef](#)] [[PubMed](#)]
22. Zhang, D.; Cai, Y.X.; Liang, Q.Q.; Wu, Z.T.; Sheng, N.; Zhang, M.H.; Wang, B.X.; Chen, S.Y. Scalable, Flexible, Durable, and Salt-Tolerant CuS/Bacterial Cellulose Gel Membranes for Efficient Interfacial Solar Evaporation. *ACS Sustain. Chem. Eng.* **2020**, *8*, 9017–9026. [[CrossRef](#)]
23. Yu, Z.; Su, Y.; Gu, R.; Wu, W.; Li, Y.; Cheng, S. Micro–Nano Water Film Enabled High-Performance Interfacial Solar Evaporation. *Nano-Micro Lett.* **2023**, *15*, 214. [[CrossRef](#)]
24. Cheng, S.A.; Yu, Z.; Lin, Z.F.; Li, L.X.; Li, Y.H.; Mao, Z.Z. A lotus leaf like vertical hierarchical solar vapor generator for stable and efficient evaporation of high-salinity brine. *Chem. Eng. J.* **2020**, *401*, 126108. [[CrossRef](#)]
25. Yu, Z.; Shi, L.; Ning, R.; Huang, H.; Sun, Z.; Chen, J.; Zhou, T.; Tan, S.C. Interfacial evaporation-induced localized multi-field coupling enables efficient co-recovery of freshwater and nitrates. *Nat. Commun.* **2026**, *17*, 1667. [[CrossRef](#)] [[PubMed](#)]
26. Cui, X.; Dong, S.; Cao, N.; Zhang, X.; Wang, J.; Fu, H.; Yan, B.; Yu, Z.; Yu, M.; Chen, G. Advanced solar-driven interfacial evaporation technology for resource and energy recovery. *Energy Environ. Sci.* **2026**, *19*, 446–459. [[CrossRef](#)]
27. Luo, W.W.; Zhang, J.; Liu, M.C.; Yi, A.L.; Jiao, R.; Zhu, Z.Q.; Li, J.Y.; Sun, H.X.; Li, A. Excellent solar-driven interface evaporation by an oil repellence Janus photothermal membrane for oily wastewater treatment. *Chem. Eng. J.* **2024**, *483*, 149211. [[CrossRef](#)]
28. Zhang, Z.J.; Zhang, Z.B.; Zeng, J.; Ma, S.; Chen, M.; Zhou, D.; Yan, Y.; Chen, Z.; Tang, C.M.; Xu, J.Q. Salt-tolerant, scalable Janus fabric evaporators for desalination and multi-species wastewater purification. *React. Chem. Eng.* **2023**, *8*, 3018–3027. [[CrossRef](#)]
29. Xu, Y.X.; Xu, T.; Guo, Y.; Liu, W.P.; Wang, J. Scalable and biomimetic anti-oil-fouling photothermal fabric for efficient solar-driven interfacial evaporation. *Sep. Purif. Technol.* **2023**, *312*, 123289. [[CrossRef](#)]
30. Hu, N.N.; Zhao, S.L.; Chen, T.C.; Lu, X.N.; Zhang, J.L. Janus Carbon Nanotube@poly(butylene adipate-co-terephthalate) Fabric for Stable and Efficient Solar-Driven Interfacial Evaporation. *ACS Appl. Mater. Interfaces* **2022**, *14*, 46010–46022. [[CrossRef](#)] [[PubMed](#)]
31. Li, L.X.; Su, Y.Q.; Jin, B.C.; Yu, Z.; Cheng, S.A. Recycling waste carbon fibers for solar-driven clean water production by one-step electrochemical process. *Sep. Purif. Technol.* **2024**, *351*, 128019. [[CrossRef](#)]
32. Cui, Z.X.; Zhou, J.Q.; Wang, H.R.; Liu, X.L.; Gong, C.X.; Wang, Q.T.; Zeng, S.; Si, J.H. Facile fabrication of electrospinning cellulose acetate/graphene composite nanofiber membrane with high solar-to-thermal conversion and oil resistance performance for efficient solar-driven water evaporation. *Sol. Energy Mater. Sol. Cells* **2023**, *263*, 112597. [[CrossRef](#)]
33. Xue, N.; Cui, H.Z.; Dong, W.C.; Chu, W.L.; Li, M.H.; Jiang, H.Q.; Wei, N. Multifunctional hydrophilic MXene/Gelatin composite aerogel with vertically aligned channels for efficient sustainable solar water evaporation and Oil/Water separation. *Chem. Eng. J.* **2023**, *455*, 140614. [[CrossRef](#)]
34. Luan, C.J.; Lin, F.W.; Mao, H.Y.; Wang, X.D.; Chen, Z.Y.; Bigaliev, A.B.; Eminov, A.M.; Chen, G.Y. Balanced water transport and evaporation by directionally wettability-gradient assembled evaporator for cascaded anti-oil and desalination. *Water Res.* **2026**, *288*, 124573. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.