

Solar-Driven Photothermal-Evaporation Coupling: Antibacterial-Evaporation Integrated Wood-Based Photothermal Materials for Seawater Desalination

Hongyan Zhu

Shanxi Datong University

Qihui Jiao

Shanxi Datong University

Jin Zhang

Shanxi Datong University

Shijie Li

Shanxi Datong University

Yu Wu

University of Electronic Science and Technology of China

Xiangyu Yang

Shanxi Datong University

Xinyu Li

lixingurd@163.com

Shanxi Datong University

Jianguo Zhao

Shanxi Datong University

Research Article

Keywords: Seawater desalination, Solar energy, Wood-based composite, Photothermal conversion, Antibacterial properties

Posted Date: April 16th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9103428/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Wood Science and Technology on October 21st, 2026. See the published version at <https://doi.org/10.1007/s00226-026-01817-z>.

Solar-Driven Photothermal-Evaporation Coupling: Antibacterial-Evaporation Integrated Wood-Based Photothermal Materials for Seawater Desalination

Hongyan Zhu^a, Qihui Jiao^a, Jin Zhang^a, Shijie Li^a, Yu Wu^b, Xiangyu Yang^a, Xinyu Li^{a*}, Jianguo Zhao^{a*}

a. Engineering Research Center of Coal-Based Ecological Carbon Sequestration Technology of the Ministry of Education, and Key Laboratory of Graphene Forestry Application of National Forest and Grass Administration, Shanxi Datong University, Datong 037009, China

b. School of Integrated Circuit Science and Engineering, and State Key Laboratory of Electronic Thin Films and Integrated Devices, University of Electronic Science and Technology of China, Chengdu 610054, China

* Correspondence: lixinyurd@163.com (Xinyu Li); jianguozhao9150@163.com (Jianguo Zhao);

Abstract

Tackling the challenges of global freshwater scarcity and energy consumption, efficient solar powered seawater desalination strategies are needed. However, current interface evaporation technology is limited by insufficient photothermal conversion efficiency, unclear energy loss mechanisms, and high material costs. In this work, we report a highly efficient and stable wood-based photothermal composite material, which is constructed by in-situ growth of manganese dioxide (MnO₂) nanoflowers on porous, low thermal conductivity poplar wood, combined with a blackening coating of iron tannic acid to construct manganese/ wood@Fe-GA photothermal evaporation system. The three dimensional MnO₂ structure enhances light harvesting while providing abundant active sites to stabilize Fe³⁺, synergizing with the wood's vertically aligned channels and low thermal conductivity to facilitate water transport and suppress heat loss. The composite achieves a high evaporation rate of 2.25 kg·m⁻²·h⁻¹ under one-sun illumination and maintains a stable performance of

1.84-1.97 kg·m⁻²·h⁻¹ in 15% NaCl solution over extended operation. We demonstrate that the formed Mn-O bonds regulate the local chemical environment to inhibit salt crystallization, thereby ensuring long-term stability in seawater desalination. By elucidating the relationship between structural performance and evaporation mechanism, this work provides theoretical insights and practical approaches for sustainable, high-performance, and low-cost desalination of photothermal materials.

Keywords: Seawater desalination; Solar energy; Wood-based composite; Photothermal conversion; Antibacterial properties

1. Introduction

The increasingly severe global shortage of freshwater urgently promotes the development of cost-effective and efficient freshwater production technologies (Ahmeda et al. 2020; Hou et al. 2023; He et al. 2025; Al-Absi et al. 2021). Solar energy is a widely available renewable resource and a sustainable alternative to fossil fuels with low carbon emissions, especially in the context of global warming (Mojumder et al. 2024). Compared to traditional energy intensive methods, solar driven steam power generation avoids the consumption of fossil fuels, providing a more environmentally friendly energy supply pathway (Wang et al. 2022; Huang et al. 2026; Sathish 2024). Solar-assisted freshwater production not only alleviates the water crisis but also reduces fossil fuel depletion and environmental pollution (Moon et al. 2025; Zhao et al. 2023; Amy et al. 2017; Ramanathan et al. 2018). Seawater desalination and wastewater reclamation have attracted extensive attention as promising strategies for clean water supply (Ghazi et al. 2022; Ramírez-Ruiz et al. 2023; Bundschuh et al. 2021; Li et al. 2024). High-efficiency solar-driven freshwater production strongly depends on advanced photothermal materials that enable efficient solar capture and conversion (Xu et al. 2024). The ideal solar absorber requires broadband light absorption, high photothermal efficiency, low cost, good hydrophilicity, porous structure, self floating, and angle insensitivity (Zhao et al. 2020; Ghasemi et al. 2014). Single-component materials can hardly meet these multifunctional demands, restricting their practical application. Therefore, increasing efforts have been devoted to multiphase composites, where synergistic structural and compositional design can achieve efficient solar-thermal conversion and desalination (Huxtable et al. 2003; Kim et al. 2020; Maqsood et al. 2025; Salper et al. 2025).

Populus tomentosa Carr. as a widely available and low-cost biomass substrate, has shown great potential for fabricating photothermal materials (Mahdian et al. 2024; Pozio et al. 2020; Li et al. 2026). The vertically arranged microchannels achieve efficient water transport, while the low intrinsic thermal conductivity helps to locate

heat at the liquid vapor interface, thereby improving energy utilization efficiency (Fratzl 2018). However, pristine wood suffers from limited light absorption and surface modification with photothermal agents is usually required to enhance solar energy harvesting (Karimi-Nazarabad et al. 2023; Wang et al. 2019). Although various composite-based solar evaporators have been developed, most studies only focus on single-function water evaporation. To bridge the gap between laboratory research and practical application, it is highly desirable to explore integrated systems with high efficiency, stability, low cost and multifunctionality. Especially, developing an easy-to-use, high-performance, and stable integrated solar evaporator for simultaneous seawater desalination and anti biofouling remains a key challenge (Zhou et al. 2018; Wu et al. 2020; Gao et al. 2019). MnO_2 is a promising candidate for multifunctional integration due to its facile synthesis, excellent photothermal properties and superior catalytic activity toward organic pollutant degradation (Ndayiragije et al. 2022; Irshad et al. 2021; Saleque et al. 2023). For instance, Zhang et al. (2024) fabricated a self-floating evaporator by decorating balsa wood with carbon nanotubes and MnO_2 , realizing simultaneous solar evaporation and pollutant degradation. Miao et al. (2019) and Wang et al. (2022) also reported MnO_2 -based composites with enhanced light absorption, salt resistance and photothermal performance. Despite these progresses, a key design challenge still exists: efficient interfacial evaporation requires heat localization to minimize heat loss, whereas effective catalysis relies on sufficient mass transfer between catalysts and bulk water, which often causes serious heat dissipation (Tao et al. 2018; Yan et al. 2022; Li et al. 2020; Chen et al. 2023; Chen et al. 2021). Therefore, the rational material and structural design for the co-optimization of heat and mass transfer to achieve multifunctionality without sacrificing evaporation efficiency is still the core scientific issue.

we report a multifunctional photothermal evaporator (denoted as Mn/wood@Fe-GA) based on natural *Populus tomentosa* Carr. Our design strategically integrates multiple functional units by engineering the in situgrowth of MnO_2 nanoflowers on the porous wood scaffold, combined with an iron-tannic acid

blackening coating. The three-dimensional porous architecture of the wood ensures efficient water transport and promotes heat localization. The coating provides superior broadband light absorption, while the in-situ formed MnO₂ nanostructures not only enhance structural stability but also supply accessible catalytic sites for effective pollutant degradation. Through systematic research, we have elucidated the complex structure performance relationship that controls the synergistic evaporation catalytic behavior. This work successfully demonstrates the simultaneous achievement of efficient solar driven water evaporation and significant degradation of organic pollutants, providing a novel design strategy and multifunctional material platform for the development of high-performance, multifunctional, and low-cost sustainable freshwater production systems.

2. Materials and Methods

2.1. Materials

Tannic acid (TA, 99%) is supplied by Aladdin, ferric chloride (FeCl₃·6H₂O, ≥99%), and sodium chloride (NaCl, ≥99.5%) are supplied by McLean Co., Ltd. Manganese sulfate (MnSO₄, ≥99.0%) was supplied by Xilong Scientific Co., Ltd. Potassium permanganate (KMnO₄, ≥99.5%) was supplied by Tianjin Chemical Reagent Supply and Sales Co. Methylene blue (MB, ≥98.5%) was supplied by Bohua Chemical Reagent Co., Ltd. Magnesium chloride (MgCl₂·6H₂O, ≥99.5%) was supplied by Tianjin Zhiyuan Chemical Reagent Co., Ltd. Potassium chloride (KCl, ≥99.5%) was supplied by Bohua Chemical Reagent Co., Ltd. Calcium chloride (CaCl₂·2H₂O, ≥99.5%) was supplied by Tianjin Fengchuan Chemical Reagent Technology Co., Ltd. Escherichia coli (E. coli) was supplied by Beijing Biomodel Organism Technology Co., Ltd. Glutaraldehyde fixative solution (C₅H₈O₂, 2.5%) was supplied by Fujian Fine Biological Technology Co., Ltd. Phosphate-buffered saline (PBS, 0.1 M) was supplied by Hunan Biocomma Holdings Co., Ltd. Ethanol (C₂H₅OH, ≥99.7%) was supplied by Tianjin Chemical Reagent Supply and Sales Co.

2.2 Fabrication of the Mn/wood@Fe-GA Photothermal Material

Square slices of *Populus tomentosa* Carr. (50 mm × 50 mm × 2 mm), obtained by cross-sectional cutting, were first boiled in deionized water at 80 °C for 2 hours to

remove partial impurities. The boiled wood slices were subsequently subjected to a freezing treatment at -20 °C for 24 hours. During this process, the water within the wood lumens undergoes a phase change to form ice crystals. Expansion of these crystals in volume causes the greater separation between the molecules of the water and contains pressure on the walls of the cell causing damage on the structures of the pit membrane. This new structure is used to ease faster transportation of water and impregnation solutions in the following steps. After repeating the boiling and freezing cycle three times, the wood was dried at ambient pressure to prevent deformation, completing the pretreatment process.

The pretreated *Populus tomentosa* Carr. slices were functionalized using a simple two-step immersion method. First, the wood samples were immersed sequentially in 0.1 M potassium permanganate (KMnO₄) solution and 0.1 M manganese sulfate (MnSO₄) solution at room temperature to achieve in-situgrowth of manganese dioxide (MnO₂) nanoflowers on the wood surface, thereby enhancing surface roughness and photothermal conversion efficiency. By varying the immersion time (denoted as xminutes) in the KMnO₄ solution, samples with different MnO₂ loadings were obtained, labeled as Mn_x/wood. Subsequently, the Mn_x/wood samples were immersed in a 2 wt% ferric chloride (FeCl₃) aqueous solution for 2 hours. After drying at ambient conditions, they were further immersed in a 2 wt% tannic acid (TA) aqueous solution for another 2 hours to allow the coordination of TA with Fe³⁺, forming a stable iron-tannin complex (Fe-GA) on the wood surface. Finally, the samples were dried under ambient pressure, yielding the final manganese dioxide/*Populus tomentosa* Carr.@iron-tannin complex photothermal material, denoted as Mn_x/wood@Fe-GA. A schematic illustration of the entire fabrication process is presented in Fig. 1.

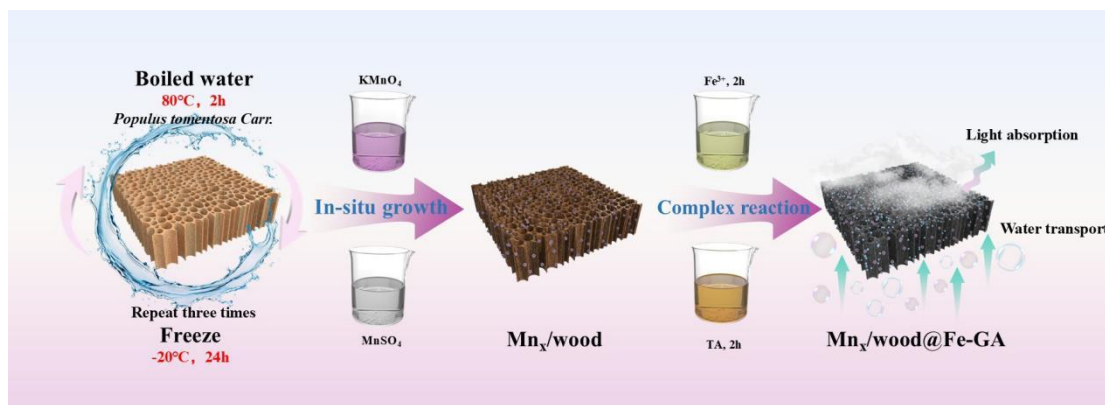


Fig. 1 Schematic diagram illustrating the fabrication strategy for the $\text{Mn}_x/\text{wood}@Fe\text{-GA}$ photothermal material

2.3. Characterization Methods

The microstructure of the samples was observed using a field emission scanning electron microscope (SEM, TESCAN MALA 3 LMH, Czech Republic). The elemental composition and content were quantitatively analyzed by energy-dispersive X-ray spectroscopy (EDS, INCA x-act, Oxford Instruments, UK). The functional groups present in the material was performed using FT-IR spectrometer (FTIR-650, Gangdong Science and Technology Development Co., China). The thermal conductivity was measured by a thermal conductivity meter (DRL-II, Xiang Instrument Co., China) based on the heat flow method. Thermogravimetric analysis coupled with differential scanning calorimetry was performed on a simultaneous thermal analyzer (TG-DSC, STA 449 F3, NETZSCH, Germany) to evaluate the thermal stability and determine the water evaporation enthalpy. A xenon lamp solar simulator (CHP-XM550, Changtuo Sci. &Tech. Co., Ltd., China) was employed to simulate the desalination process and record the mass change of water. The thermal infrared imager was used to capture the surface temperature and infrared images (FLIR-E6390, Friel Corporation, USA). The ultraviolet-visible-near infrared absorption/reflection spectra were obtained using a spectrophotometer (UV-Vis-NIR, UH4150, Hitachi, Japan). The surface wettability (water contact angle) was characterized by a video contact angle meter (JY-82C, Dingsheng Co., Ltd., China). The surface chemical states and elemental analysis were conducted by X-ray photoelectron spectroscopy (XPS, K-Alpha, Thermo Fisher Scientific, USA). The

concentrations of primary ions in the simulated seawater before and after desalination were quantified by inductively coupled plasma optical emission spectrometry (ICP-OES, Agilent 5110, Agilent Technologies, USA). The optical density (OD) of the bacterial suspension was measured using a multifunctional microplate reader (SpectraMax M2, Molecular Devices, USA).

2.4 Photothermal performance evaluation

Solar-driven water evaporation experiments were conducted under controlled ambient conditions (temperature: 25 ± 2 °C; relative humidity: 60%) with a simulated solar irradiance of $1.3 \text{ kW} \cdot \text{m}^{-2}$, measured using an optical power meter (FGH-1). To evaluate the performance in natural conditions, a 3.5 wt% NaCl solution was added to the water to simulate the seawater, instead of the pure water. Fig. 2 shows that a wood-based substrate template (48 mm×48 mm) had been attached at the base of the evaporation system with all the components entirely submerged in the simulated seawater (3.5% NaCl).

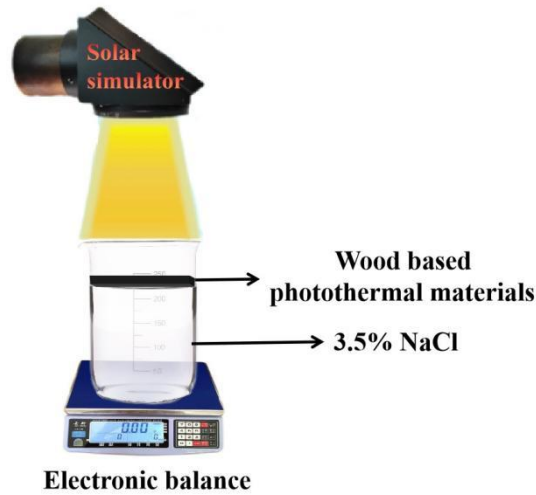


Fig. 2 Schematic diagram of experimental apparatus

The mass loss during evaporation was monitored in real-time using an electronic balance with a precision of 0.01 g. The photothermal evaporation efficiency (η , %) was calculated according to the following equation:

$$\eta = m h_{lv} / C_{opt} P_0 \quad (1)$$

where m is the net mass flux ($m = m_{light} - m_{dark}$, in $\text{kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$), h_{lv} represents the total liquid-vapor phase-change enthalpy, P_0 is the incident solar power ($\text{kW} \cdot \text{m}^{-2}$), and C_{opt}

denotes the optical concentration at the absorber surface. The average evaporation rate measured in the dark was subtracted to account for natural evaporation (Xu et al. 2017; Zhang et al. 2017).

The evaporation rate (V_e , $\text{kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) was determined from the mass change of water (Δm), the projected area of the photothermal material (S), and the evaporation time (t), as follows:

$$V_e = \Delta m / S \times t \quad (2)$$

3. Results and Discussion

3.1 Evaluation of the Photothermal Water Evaporation Performance of Mn_x/wood@Fe-GA

Mn_x/wood@Fe-GA photothermal material is a product synthesized using a simple process, which is environmentally friendly. The soaking time in potassium permanganate solution is one of the key parameters for optimizing photothermal performance. Experiments were done in a 3.5 wt% solution of NaCl to measure the performance of evaporation in realistic conditions. The mass loss curves of water at Fig. 3a when lighted at $1.3 \text{ kW}\cdot\text{m}^{-2}$ indicates that all samples using Mn_x/wood@Fe-GA ($x=10, 30, 60$) exhibited a much higher level of water loss through evaporation than the pristine poplar wood. This performance has been due to the porous nature of the microstructure of the wood that provides easy passage of water. The water is quickly pulled through these natural microchannels to the evaporation interface within the composite material to basically replenish the water loss and maintain a constant evaporation cycle. Moreover, the addition of MnO₂ streamlines the microstructure of the material. The use of iron-tannin complex in combination with the MnO₂ nanoflowers with the wood scaffold creates a more hierarchical and networked structure, which minimizes the resistance of water uptake, therefore, increasing the evaporation rate. Fig. 3b shows this observation by the surface temperature profiles of Fig. 3b, where the surface temperature of Mn_x/wood@Fe-GA material had a significantly higher and faster temperature rise than that of the untreated wood. Under one-sun comparable irradiation ($1.3 \text{ kW}\cdot\text{m}^{-2}$), Fig.

3c–d show that the evaporation rate of $\text{Mn}_x/\text{wood}@Fe\text{-GA}$ ($x=10, 30, 60$) were 1.70, 2.25, and 2.20 $\text{kg m}^{-2}\cdot\text{h}^{-1}$, which is much higher than that of the unmodified wood. It is worth noting that the highest evaporation rate was attained in $\text{Mn}_{30}/\text{wood}@Fe\text{-GA}$. Photothermal conversion efficiencies based on the differences between the natural evaporation and the corresponding values with $x=10$, $x=30$ and $x=60$ were ranked at 74.1, 98.0, and 96.5% respectively. The better results of the $\text{Mn}_{30}/\text{wood}@Fe\text{-GA}$ material prove the fact that MnO_2 loading is successful to enhance the surface roughness. This increased topography increases light absorption and light scattering through the material, resulting in increased light-harvesting capacity. This structural advantage has had a significant positive impact on the efficiency of photothermal conversion, making the material an excellent magnet for generating heat energy through sunlight to promote water evaporation. Therefore, it shows great potential in solar seawater desalination and other related technologies.

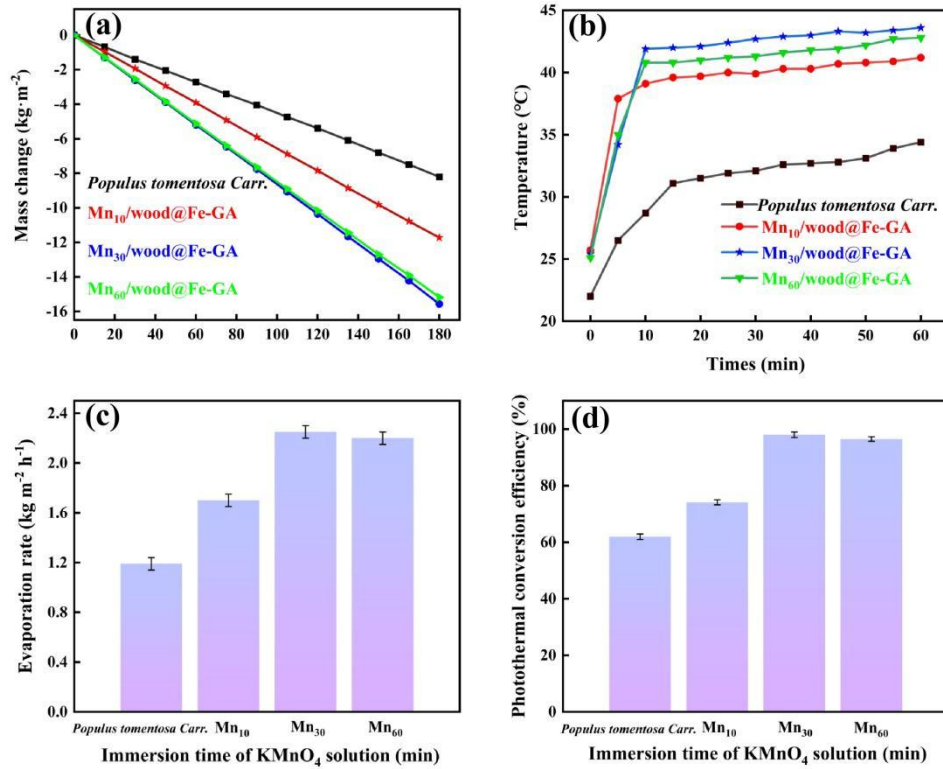


Fig. 3 *Populus tomentosa* Carr. and $\text{Mn}_x/\text{wood}@Fe\text{-GA}$ ($x=10,30,60$) at $1.3 \text{ kW}\cdot\text{m}^{-2}$ irradiation. (a) Moisture mass loss diagram; (b) Temperature rise curve; (c) Water evaporation rate curve; (d) Photothermal conversion efficiency

Fig. 4a–d show infrared thermal images giving that the immersion time in the

KMnO₄ solution (Mn_x) is useful to control the quantity of loading MnO₂ on the surface of wood. The coloring behavior of Mn_x/wood@Fe-GA photothermal materials undergoes a much stronger change trend with time than in the control level (*Populus tomentosa* Carr.). This means the MnO₂ nanoflower deposition improves the absorption and scattering of sunlight to the wood-based photothermal material significantly. Thermal conduction and diffusion transfers the heat deposited into the surrounding medium. This has been achieved because as shown in the three-dimensional nanoflower-like layered architecture of MnO₂, it allows a good transfer and distribution of heat, thus enabling the efficient use and exploitation of thermal energy hence affecting the total photothermal conversion efficiency. This synergistic activity produces the Mn_x/wood@Fe-GA material with a better thermal value. Comparative analysis of the infrared thermography data of samples that were prepared with varying immersion times (Mn_x) indicates that, the Mn₃₀/wood@Fe-GA sample has a higher thermal conduction rate as well as even distribution of temperature compared to the Mn₁₀/wood@Fe-GA and Mn₆₀/wood@Fe-GA samples. After 300 s of illumination, the Mn₃₀/wood@Fe-GA reached a higher and more homogeneous temperature of 41.8 °C, compared to 38.4 °C for Mn₁₀/wood@Fe-GA and 40.1 °C for Mn₆₀/wood@Fe-GA. This further confirms the superior thermal conduction performance of the Mn₃₀/wood@Fe-GA material. Based on these optimal properties, the Mn₃₀/wood@Fe-GA sample is hereafter denoted simply as Mn/wood@Fe-GA for subsequent discussion.

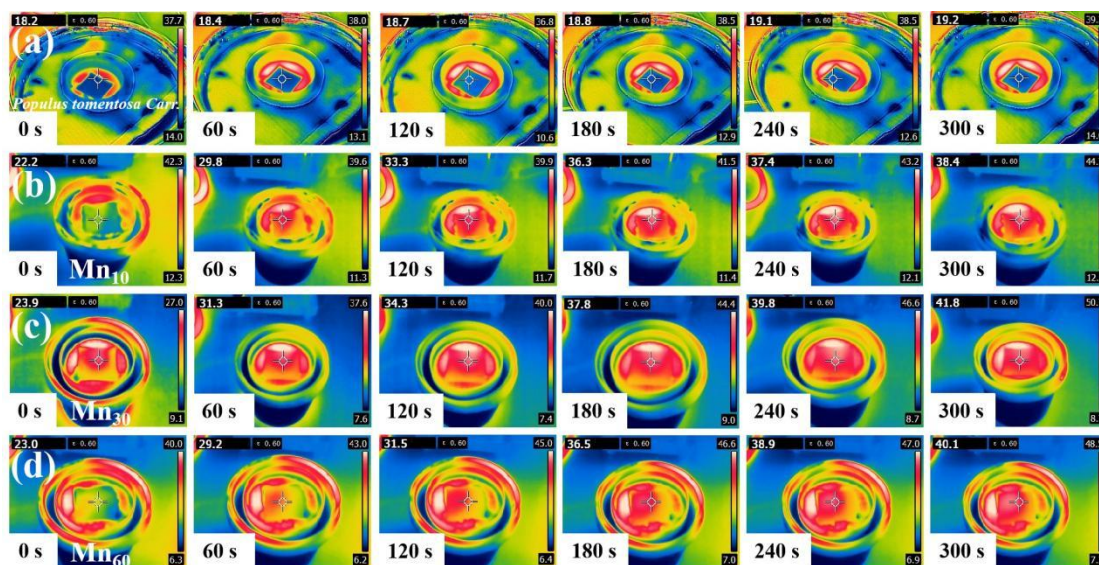


Fig. 4 Infrared thermal imaging images of (a) *Populus tomentosa Carr.*; (b) Mn₁₀/wood@Fe-GA; (c) Mn₃₀/wood@Fe-GA; (d) Mn₆₀/wood@Fe-GA photothermal material. The sampling interval is set to 1 min, and the measured solar power density is set to 1.3 kW·m⁻²

3.2 Structure and Physical Properties of the Mn/wood@Fe-GA Photothermal Material

Fig. 5a reveals the well-defined, vertically aligned porous structure of the *Populus tomentosa Carr.*, which serves as an excellent channel for water transport. As shown in Fig. 5b, MnO₂ was selectively deposited exclusively onto the cell walls of the wood's surface layer without penetrating its internal structure. The nanoflower-like architecture of the MnO₂ (Fig. 5c) provided abundant adsorption sites for the subsequently introduced Fe³⁺ ions, enhancing their stability. The presence of both MnO₂ and the iron-tannin complex was further confirmed by chemical composition analysis of the Mn₃₀/wood@Fe-GA material (Table 1). Importantly, the surface-level deposition of MnO₂ successfully preserved the intrinsic, uninterrupted porous microstructure of the wood substrate. SEM imaging and elemental mapping (Fig. 5d–h) confirmed the uniform distribution of the iron-tannin complex-formed by the coordination of tannic acid with Fe³⁺ and the MnO₂ nanoflowers. This homogeneous deposition is likely facilitated by the abundant hydroxyl groups on the wood surface, which promote the anchoring of tannic acid and its subsequent complexation with Fe³⁺. The formed iron-tannin complex significantly enhances the light absorption capability of the wood, contributing to an improved water transport

rate. Concurrently, the in situ grown MnO_2 nanoflowers increase the surface roughness of the substrate, thereby further optimizing the efficiency of light capture.

Table 1 Chemical compositions of *Populus tomentosa* Carr. and $\text{Mn}_{30}/\text{wood}@\text{Fe-GA}$ photothermal material

Materials	Composition (at%)			
	C	O	Fe	Mn
<i>Populus tomentosa</i> Carr.	61.0	39.0	/	/
$\text{Mn}_{30}/\text{wood}@\text{Fe-GA}$	62.1	37.27	0.35	0.28

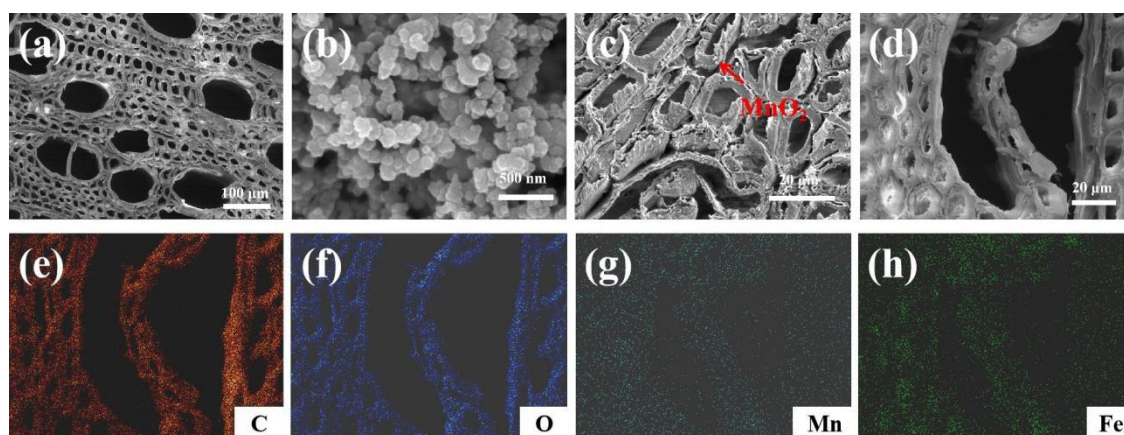


Fig. 5 SEM images of (a) *Populus tomentosa* Carr.; (b) $\text{Mn}_{30}/\text{wood}@\text{Fe-GA}$ photothermal material; (c) The nano-flower sphere structure of MnO_2 ; (d) $\text{Mn}_{30}/\text{wood}@\text{Fe-GA}$ photothermal material and Mappings of (e) C (f) O (g) Mn and (h) Fe

Moreover, lack of sufficient time of immersion in KMnO_4 solution led to incomplete deposition of MnO_2 nanoparticles (Fig. 6a–b). On the other hand, accumulation and deposition of MnO_2 were noted with the long time immersion and aggregation (Fig. 6c–d). Such excessive loading may include the structural inhomogeneity, which forms the points of stress concentration. These areas are also more vulnerable to thermal degradation which may affect the thermal stability of the material as a whole. The presence of hydrogen bonding between the constituents of the $\text{Mn}_x/\text{wood}@\text{Fe-GA}$ photothermal substance that allows the photoeradication to be done with stability was also verified by the FTIR spectroscopy (Fig. 7) (Chen et al. 2017). In the spectrum of pristine *Populus tomentosa* Carr., the characteristic peaks observed at 3430 cm^{-1} and 2920 cm^{-1} are attributed to the O-H stretching vibrations and C-H bonds in cellulose, respectively (Li et al. 2021). The peak at 1630 cm^{-1} corresponds to carboxyl groups present in cellulose and hemicellulose (Feng et al.

2024). Following the in-situgrowth of MnO_2 , the O-H peak in the $\text{Mn}_x/\text{wood}@\text{Fe-GA}$ samples exhibited a noticeable shift across different immersion times. A slight shift in the C=O peak was also observed. These spectral changes suggest the likely formation of hydrogen bonds between the wood substrate and the deposited MnO_2 .

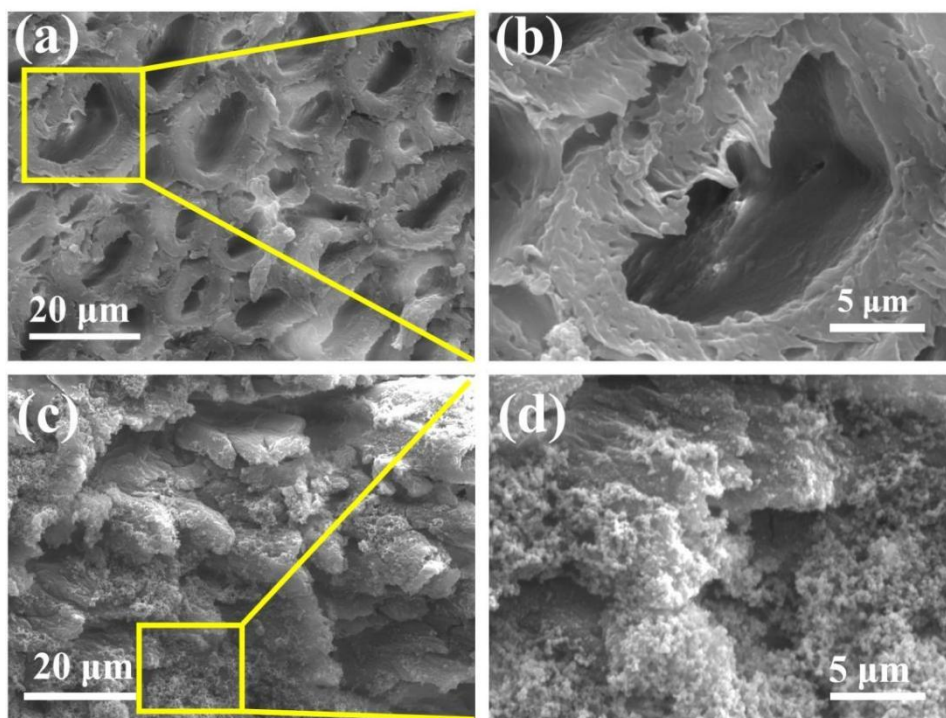


Fig. 6 SEM images of (a–b) $\text{Mn}_{10}/\text{wood}@\text{Fe-GA}$ photothermal material; (c–d) $\text{Mn}_{60}/\text{wood}@\text{Fe-GA}$ photothermal material

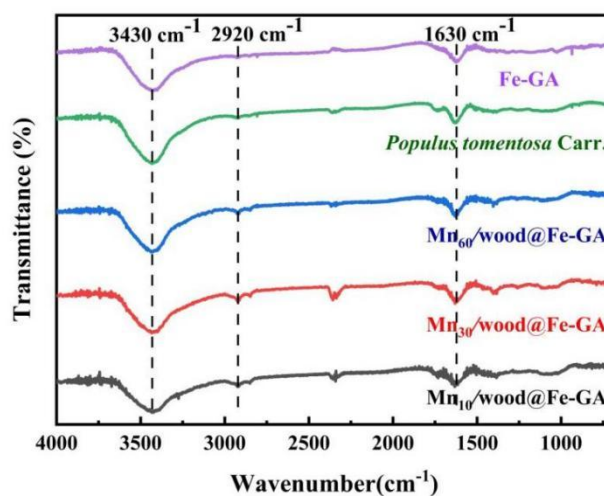


Fig. 7 Infrared spectra of Fe-GA, *Populus tomentosa* Carr. and $\text{Mn}_x/\text{wood}@\text{Fe-GA}$ photothermal material

The XPS analysis provides definitive evidence for the presence of MnO₂ in the Mn/wood@Fe-GA composite. The Mn 2p_{3/2} and Mn 2p_{1/2} peaks in the Mn 2p spectrum (Fig. 8c) are identified correspondingly at 642.0 eV and 654.0 eV respectively which supports that manganese in the sample exists in the primarily Mn⁴⁺ form. This observation is in agreement with the MnO₂ phase. More so, the Mn 3s spectrum (Fig. 8d) clearly shows a typical peak division with the separation energy (ΔE) of about 4.7 eV, which is typical of Mn⁴⁺, which once again strengthens the existence of MnO₂. The further support is provided by the O 1s spectrum (Fig. 8a) which shows the peak of the spectrum at a binding energy of 531.5 eV to be lattice oxygen (O²⁻). This lattice oxygen chemical environment is in agreement with that of Mn-O bonds. Together with the valence state analysis of Mn, this oxygen species is conclusively ascribed to MnO₂ phase, which gives other corroboration that it was actually formed in the composite material (Zhang et al. 2024).

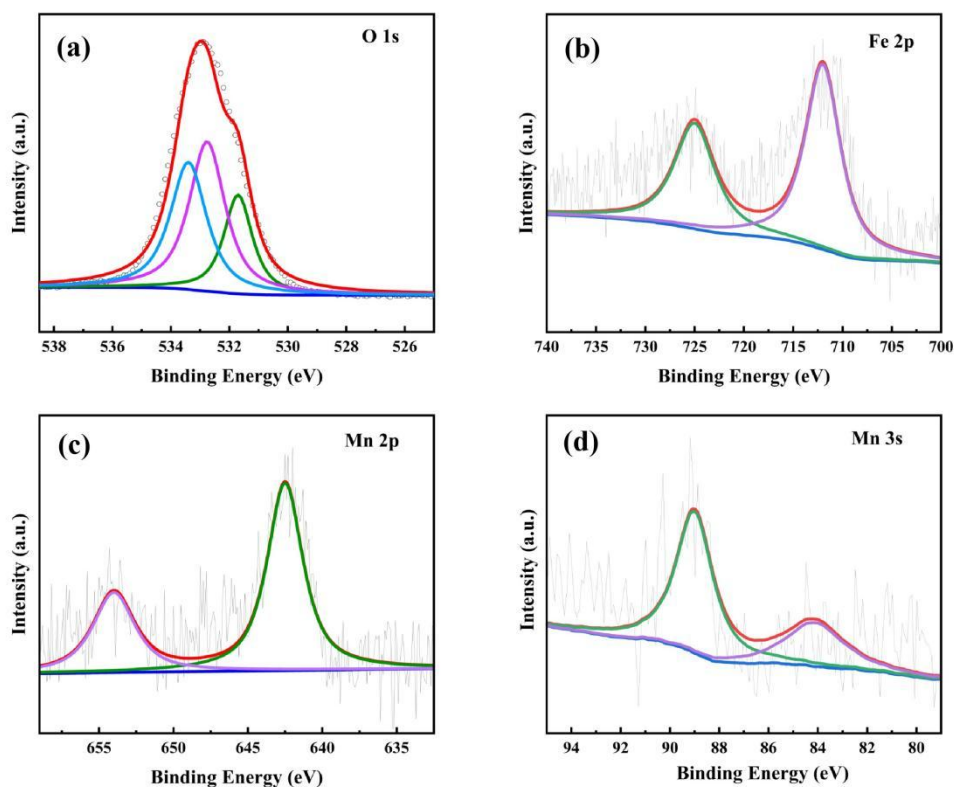


Fig. 8 XPS spectra of Mn/wood@Fe-GA photothermal material (a) O 1s; (b) Fe 2p; (c) Mn 2p; (d) Mn 3s

3.3 Stability and Wetting Properties of the Mn/wood@Fe-GA Composite

Fig. 9 illustrates the change of weight of pristine *Populus tomentosa* Carr. and the profile of change of the weight of Mn/wood@Fe-GA photothermal material with respect to the temperature. The Mn/wood@Fe-GA composite had a rate of mass loss that was low at the very beginning of the first stage (100-200 °C), in which case the pristine wood lost moisture easily. This means that the composite has a better thermal stability at the low-temperature area and this can be explained by the addition of MnO₂ to improve the thermal stability and oxidation resistance of the material. The mass loss rate of the Mn/wood@Fe-GA material was observed to increase with temperature ranged between 300-400 °C and this is because of the decomposition of its organic components. Both groups of samples showed mass loss above 500 °C, indicating that most of the organic matter had decomposed, and the remaining components had some resistance to thermal decomposition. The results of thermogravimetric analysis further confirmed the Mn/wood@Fe-GA The superiority of photothermal materials in practical applications.

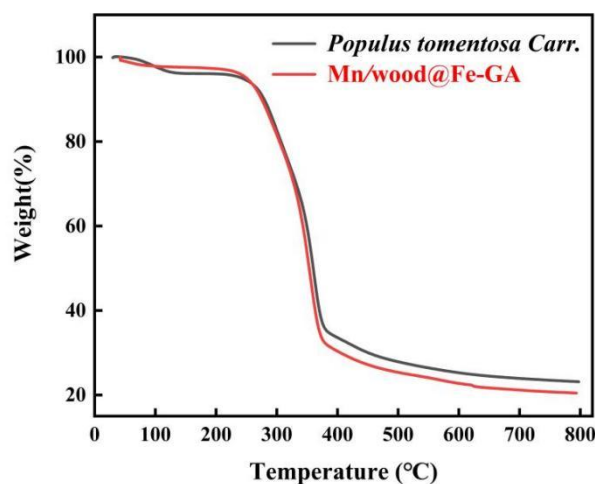


Fig. 9 TG curves of *Populus tomentosa* Carr. and Mn/wood@Fe-GA photothermal material

The Wettability, and water transport character of Mn/wood@Fe-GA photothermal material were both systematically examined. The rate of the expansion of a water droplet on Mn/wood@Fe-GA surface was much greater than the rate of the expansion of a water droplet on pristine *Populus tomentosa* Carr, as seen in Fig. 10. This increased wettability was additional confirmed through contact angle measurements made quantitatively at various stages. The contact angles of the

Mn/wood@Fe-GA sample (22.79° and 11.56°) were significantly smaller than that of pure wood (71.88° and 31.66°), which implied extremely hydrophilic surface. This high wettability has benefits in its use in solar-powered desalination of seawater in that it facilitates the high efficiency of supplying water to the evaporation front. A capillary rise experiment (Fig. 11a) also showed the high capability of fast water transport. When a dry absorbent paper was held in contact with the upper surface of the Mn/wood@Fe-GA material, the bottom of which was soaked in a methylene blue (MB) solution, the colored solution was quickly drawn up through the naturally occurring vertically oriented channels of the material in contact with the piece of paper. The pumping of this water is made possible through the deposition of MnO_2 nanoflowers which probably changes the mode of contact between the water and increases the capillary force of the water adsorption and supply in a short period of time (Chen et al. 2009). Moreover, in terms of thermal conductivity, it was found that Mn/wood@Fe-GA composite has a lower level of thermal conductivity compared to the pure wood (Fig. 11b). This attribute is essential in reducing the rate of heat loss due to a conductor to the bulk water and thus concentrating heat at the evaporation zone. The combination of efficient water supply and reduced heat loss enables the photothermal evaporation process to maintain stable temperature, thereby achieving high evaporation rate and high operational stability, which is crucial for ensuring sustainable seawater desalination operations.

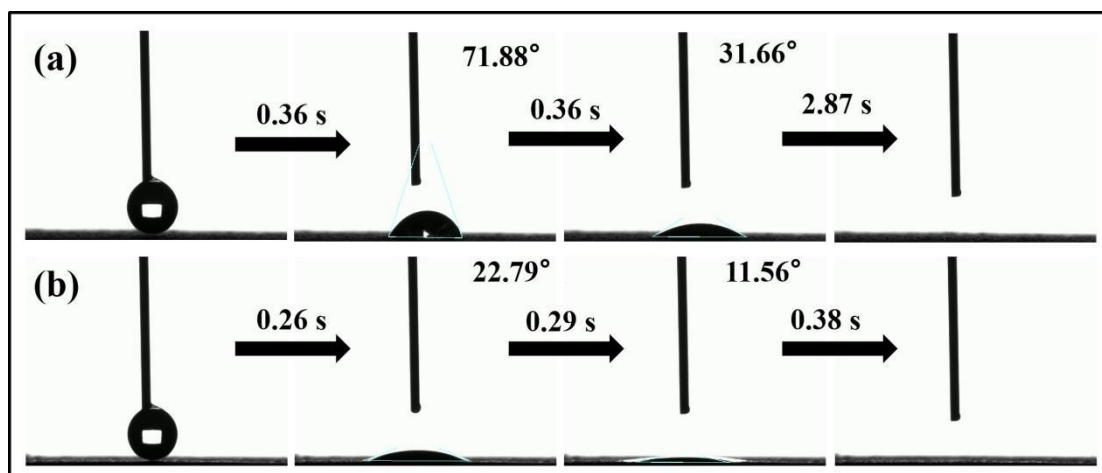


Fig. 10 Wetting performance test (a) *Populus tomentosa* Carr; (b) Mn/wood@Fe-GA photothermal material

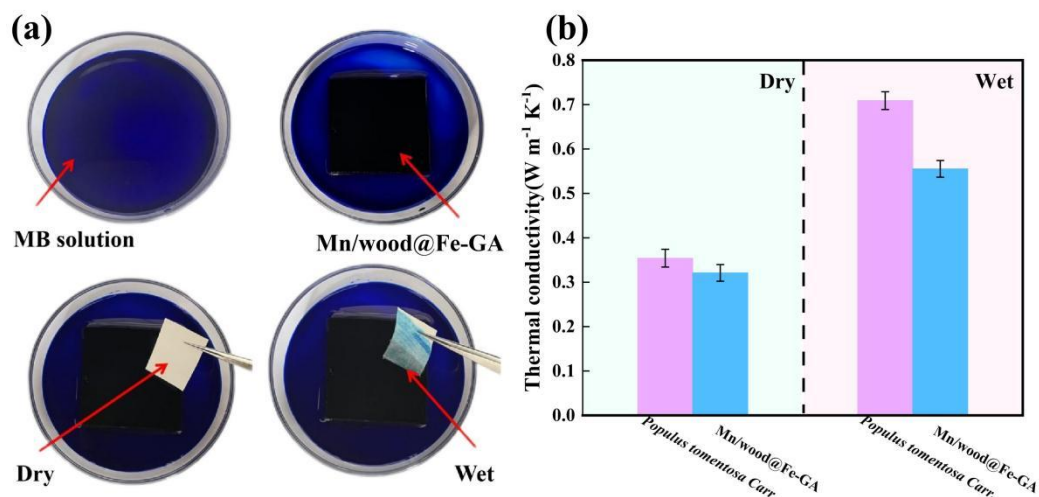


Fig. 11 (a) Extraction test of methylene blue (MB) solution; (b) Thermal conductivity test by *Populus tomentosa* Carr. and Mn/wood@Fe-GA photothermal material

3.4 Photothermal Conversion Performance of the Mn/wood@Fe-GA Material

Water purification via solar energy which uses sustainable and pollution free solar energy can be considered a good approach to the issue of freshwater shortages. Interestingly, in the process of solar desalination, the ionization of the salt is practically locked in the Mn/wood@Fe-GA photothermal material. Upon illumination termination or following the work of desalination, by immersing the material in large amount of clean water, the trapped ions can be released back into the bulk into the bulk solution by the action of concentration gradient. This regeneration property is an important aspect to avoid salt deposition and be able to reuse the material in the long term. The MnO₂ component can be instrumental to influence the local chemical environment, and this could prevent the crystallization, and deposition of salt in the pores of the wood. After the solar desalination process, the concentrations of key cations in the simulated seawater-Na⁺ (8443.59 mg/L), Mg²⁺ (953.79 mg/L), K⁺ (488.93 mg/L), and Ca²⁺ (355.07 mg/L)-were significantly reduced to 2.28, 0.097, 0.058, and 0.41 mg/L, respectively (Fig. 12a). The purified water is of drinking water grade as per the World Health Organization (WHO) standards suggesting the feasibility of the Mn/wood@Fe-GA material to be used in solar-driven desalination (Chen et al. 2020; Zhu et al. 2018). It was also found that the water evaporation behavior could be investigated by considering the DSC curves of pure water, pristine wood, and the Mn/wood@Fe-GA material (Fig. 12b). Heat flow signal that is

recorded on pure water exhibits a sharp and downward termination on reaching its peak implying fast and full evaporation. Conversely the wider maxims of both wood and composite imply otherwise different evaporation processes in the porous structures. It was found that the evaporation enthalpies of water in the pure wood and the Mn/wood@Fe-GA were 775 J/g and 781.1 J/g, respectively, which were much lower than the rate of evaporation of pure water (2450 J/g) (Zhou et al. 2019). Such a decrease is explained by the peculiar microstructure of the material. The MnO₂ nano flowers that have been in-situ grown offer plenty of adsorption sites to the Fe³⁺ ions, and such ions in turn form a stable complex of ions with Fe and tannic acid via the phenoxyl hydroxyl groups on tannic acid. This complexation reaction not solely introduces functional groups that can effectively stabilize the material structure, but also more efficiently regulate the aqueous phase state. Due to the extremely low energy required for water evaporation, it significantly improves the photothermal conversion performance.

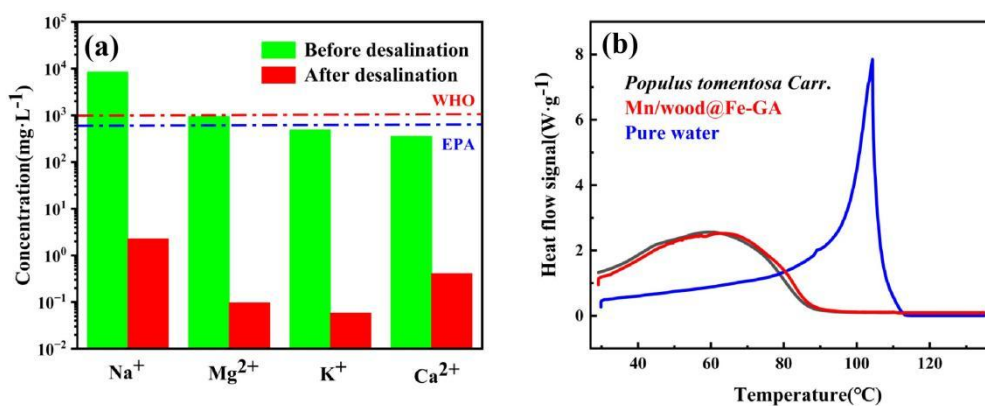


Fig. 12 (a) Ion concentrations in purified water were collected by simulating seawater and Mn/wood@Fe-GA photothermal material; (b) DSC curves for pure water, *Populus tomentosa* Carr. and Mn/wood@Fe-GA photothermal material

Photothermal materials have absorption/reflection properties over a range of the solar spectrum, which are important predeterminants of their energy conversion efficiency. To investigate the optical characteristics of the materials, UV-Vis-NIR diffuse reflectance spectroscopy was used to measure them. As seen in Fig. 13a, pure *Populus tomentosa* Carr. would only absorb considerably in the ultraviolet (below~400 nm) which is quite restrictive to its overall system of harvesting solar

energy. Contrastingly, Mn/wood@Fe-GA photo-thermal material is characterized with a significantly improved absorption covering the entire solar spectrum (200-2500 nm) which is a significant source of energy to transform into photothermal conversion. Full spectral range complementary reflection spectra (Fig. 13b) show that the Mn/wood@Fe-GA composite has low reflectivity value in most of the wavelengths with only moderate increases in infrared region (1000-1500 nm). The low reflectance suggests that a great part of incident solar radiation is absorbed by the material instead of being reflected and therefore the material has very high light to thermal energy conversion efficiency. Mn/wood@Fe-GA Photothermal materials have excellent high light absorption and low reflection absorption characteristics, providing an ideal foundation for practical applications in the field of photothermal conversion. This material is expected to become a potential solution to address the dual challenges of energy and environment.

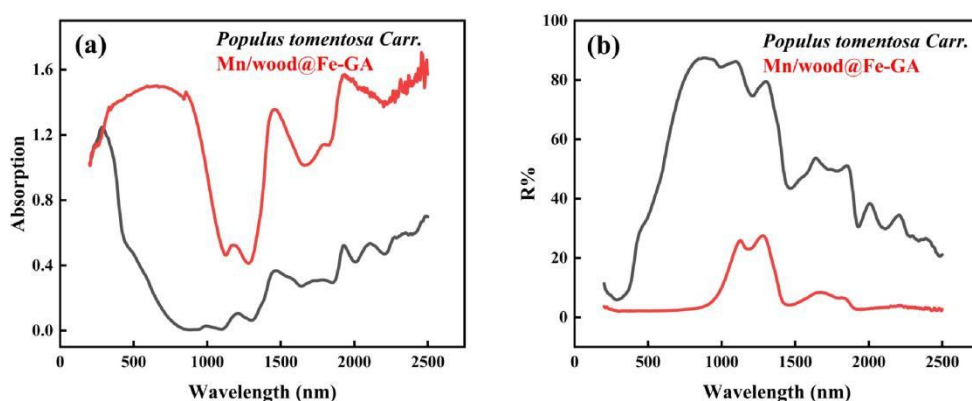


Fig. 13 UV diffuse reflectance(a) Absorption; (b) Reflectance spectra of *Populus tomentosa* Carr. And Mn/wood@Fe-GA photothermal material

3.5 Desalination Stability of the Mn/wood@Fe-GA Photothermal Material

One of the most important measures of the viability of the materials in use in desalination applications is long-term stability under conditions of high salt level in average. A systematic evaluation of the stability and operational functionality of the Mn/wood@Fe-GA photothermal material was done through a prolonged test in 15% NaCl solution (Fig. 14a). The evaporation rate was consistent at a range of 1.84 to 1.97 kg·m⁻²·h⁻¹, which showed a notable improvement in the evaporation of water and also strong stability in a high-salinity condition. This performance gives good

justification to its application in the seawater desalination. Moreover, the durability of the material was evaluated by putting it into constant running mode in 720 hours (Fig. 14b). In pure seawater conditions (3.5% NaCl), the Mn/wood@Fe-GA material did not undergo any significant transformation in the rate of evaporation in each of ten consecutive cycles, maintaining 96.04% of its original functionality. This confirms its excellent durability, as it can maintain a high evaporation rate even under long-term rinsing and different salt content conditions. These results highlight Mn/wood@Fe-GA The excellent characteristics of photothermal materials indicate that the research results of these materials will have a bright prospect of expanding from small-scale laboratory experiments to large-scale industrial applications.

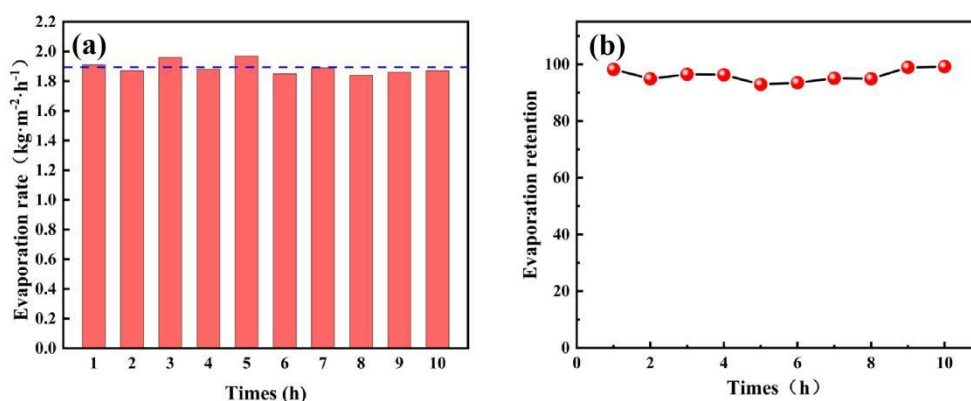


Fig. 14 (a) Long-term stability of desalination by Mn/wood@Fe-GA photothermal material (15% NaCl solution); (b) Retention rate of water evaporation rate after continuous flushing with Mn/wood@Fe-GA photothermal material for 720 h (after 10 cycles with an interval of 1 h each)

3.6 Antibacterial Properties of the Mn/wood@Fe-GA Photothermal Material

Fig. 15 shows the SEM images of pure *Populus tomentosa* Carr. and Mn/wood@Fe-GA photothermal material, respectively, in 20 hours after co-cultivating them with *Escherichia coli* (E. coli). Many E. colicells were found attached to the surface of the unpolluted wood and this has seriously blocked natural structure of the pore. Conversely, some bacterial cells were detected on the Mn/wood@Fe-GA composite, and no pore blockage was observed which meant that this surface was effectively inhibiting bacterial colonization. The capability of the materials to destroy the bacteria was also determined by determining the optical density of bacteria suspensions in the presence of the materials (Fig. 16). The larger

the OD₆₀₀ value, the stronger the bacterial growth. The OD₆₀₀ value of the original wood suspension is 0.197, while the OD₆₀₀ value of the suspension using Mn/wood @ Fe-GA material alone is 0.0546 (average of five measurements). Such a significant decrease proves that the composite material has a highly inhibitory effect on the growth of *Escherichia coli* (*E. coli*). This is attributed to the antibacterial effect of manganese dioxide nanoparticles, which can enter bacterial cell walls, disrupt the integrity of bacterial membranes, and interfere with metabolic processes, effectively inhibiting bacterial growth and reproduction. (Jayandran et al. 2015). The overall computational results associated with the unsurpassed antibacterial effects of the Mn/wood@Fe-GA photothermal substance to *E. coli*, in conjunction with its capacity to support obstructed water passageway, depict a huge prospect on its application in seawater desalination procedure by reducing biofouling as well as provides a stable functioning.

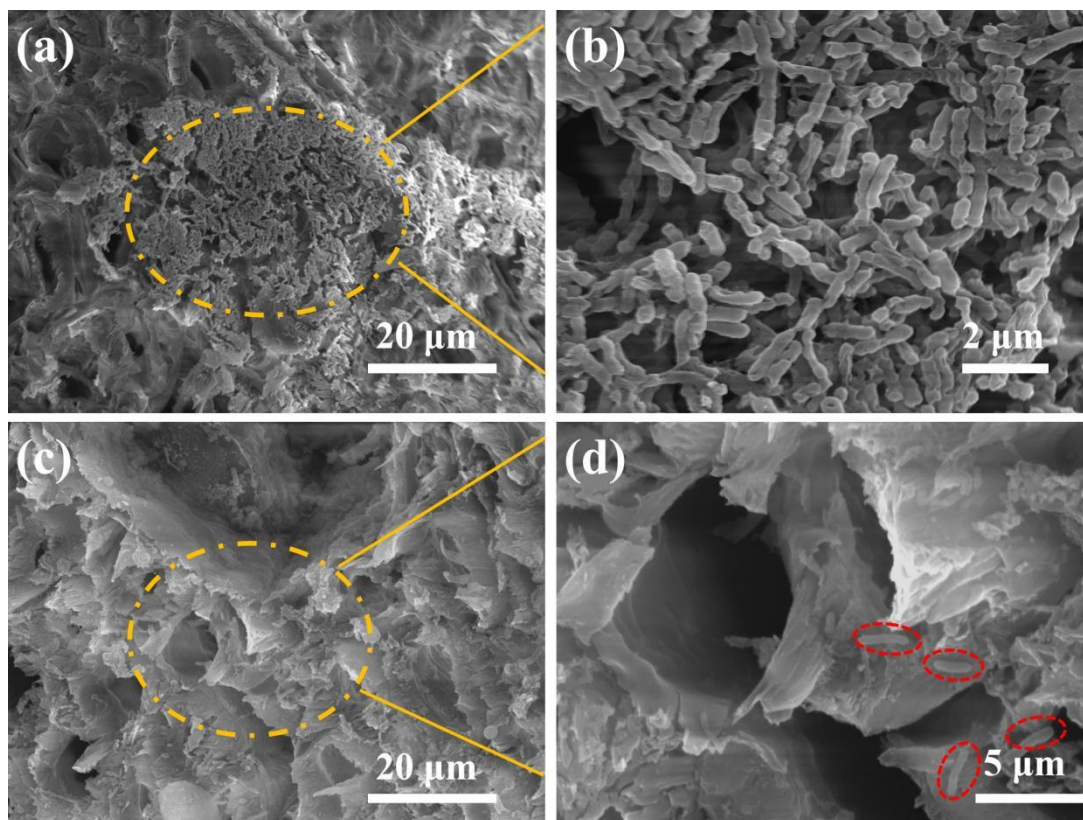


Fig. 15 SEM images were obtained after incubation with bacterial suspension (a–b) *Populus tomentosa* Carr; (c–d) Mn/wood@Fe-GA photothermal materials

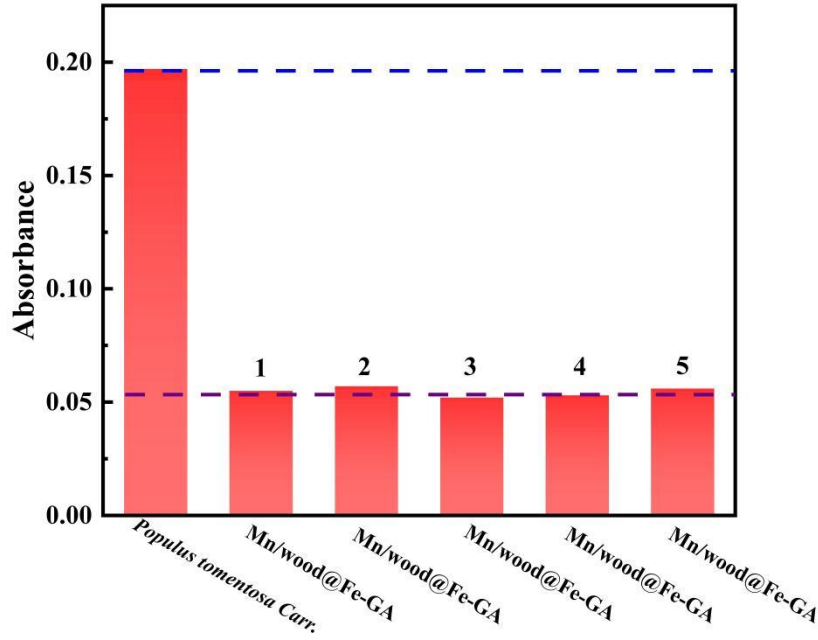


Fig. 16 Test for antibacterial properties of Mn/wood@Fe-GA photothermal materials

3.7 Simulation and Calculation of the Water Evaporation Rate in the Mn/wood@Fe-GA Composite

Under simulated solar illumination, the upper surface temperature (T_l) of the Mn/wood@Fe-GA photothermal material exceeds the ambient temperature (T_e), causing heat loss to the environment via thermal radiation and convection. However, the temperature of the material's side surface (T_2) remains lower than T_e , resulting in energy absorption from the surroundings through the same mechanisms. Based on the energy balance diagram depicted in Fig. 17, the evaporation rate (V_e) can be calculated using Equation (3) (Wu et al. 2019).

$$E_1 + E_2 = E_3 + \Delta Q_{heat} + Q_{evap} \quad (3)$$

Assuming the system reaches a steady state ($\Delta Q_{heat}=0$), Equation (4) is derived.

$$P_0 A \eta_{abs} + \sigma \varepsilon A (T_2^4 - T_e^4) = h A (T_l - T_e) + H_v V_e A \quad (4)$$

Using the following parameters—incident power density $P_0=1.3 \text{ kW}\cdot\text{m}^{-2}$, absorption efficiency $\eta_{abs}=0.98$, upper surface temperature $T_l=40.9 \text{ }^\circ\text{C}$, ambient temperature $T_e=26 \text{ }^\circ\text{C}$, side surface temperature $T_2=24 \text{ }^\circ\text{C}$, Stefan-Boltzmann constant $\sigma=5.67\times 10^{-8} \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$, latent heat of vaporization of water $H_v=2.46\times 10^6 \text{ J}\cdot\text{kg}^{-1}$, and

assuming an emissivity $\varepsilon=1$ and a convective heat transfer coefficient $h=10 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ while neglecting thermal conduction and transient effects, the calculated evaporation rate is $V_e=1.66 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$. This calculated value is particularly smaller as compared to the experimentally determined value of $2.25 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$. This difference can be explained by various factors outside the model; The manganese dioxide nanostructure highly limits solar thermal energy to the high-density area on the upper surface, while the low thermal conductivity of the material prevents lateral heat loss to the outside, thereby supporting the formation of narrow layers with high-temperature evaporation characteristics. In addition, the capillary properties of wood substrates contribute to water transport. This model may not have taken into account the local convection enhancement effect, light capture effect, and uneven temperature distribution caused by surface nanostructures. However, by integrating this computational model with the proposed energy evaporation mechanism, we not only obtained theoretical validation, but also provided scientific basis for designing new types of solar thermal materials that can be applied in fields such as solar seawater desalination, wastewater purification, and solar steam power generation.

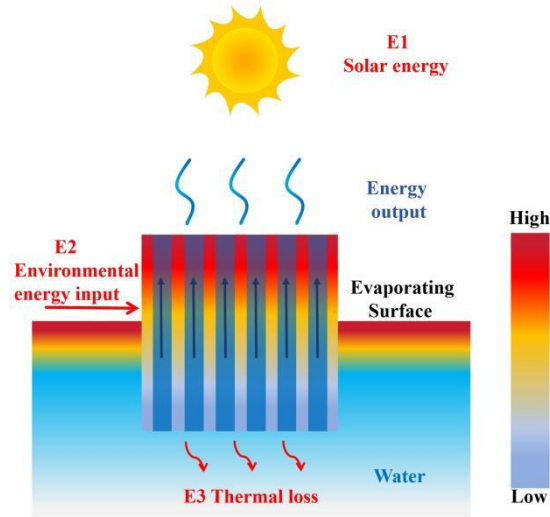


Fig. 17 Energy input-output evaporation mechanism diagram

3.8 Structure-Performance Correlation and Underlying Mechanism

Compared to other photothermal materials that have been reported (Table 2), a comparative analysis establishes the high level of performance of our wood-based composite in regard to evaporation rate and photothermal conversion rate. This

improved output is credited to the fact that the material has great antibacterial properties that guarantee a high level of long-term stability as indicated by the fact that there is minimal reduction in performance of the material after 720 hrs of rinsing. When responding to nanoscale metal oxides and coordination compounds that are introduced in photothermal system, the substrate surface chemical structure of *Populus tomentosa* Carr. is altered significantly. The contact angle reduces with the change in interfacial chemophysical potentials causing the Laplace pressure of the wood channels to increase because of the improved wettability. As a result, the rate of transporting brine is enhanced, mass transfer is enhanced, and rate of evaporating is enhanced and this has improved overall effectiveness of our wood based photothermal composite system. The delta of Laplace pressure ΔP is Equation 5:

$$\Delta P = \frac{2\gamma \cos \theta}{r} \quad (5)$$

In which, γ is the surface tension of the liquid, θ is the angle of contact and r is the radius of the capillary.

The multifunctional wood-based photothermal composite system is designed according to rational association between the construction and photothermal property. The photothermal system construct with references to *Populus tomentosa* Carr. as the substrate template applied in the plan is characterized by low thermal loss, thus enabling the exact control of the photothermal system performance of the material. In addition, the optical density of the bacterial suspension cultured by the MnO₂ containing photothermal composite was found to be 0.0546 only showing that MnO₂ is able to penetrate bacterial cell walls, causing serious inhibitory effects to cells, impeding membrane integrity and disrupting the metabolic pathways, making MnO₂ a viable means to suppress *E. coli* growth and colonization. This antibacterial factor helps a lot in improving the service life of photothermal composite. The overall effectiveness of the structural design and benefits of the proposed system in terms of performance are validated by the experimental.

Table 2 This work compares the properties of wood-based composite photothermal materials with those prepared by other different methods

Research Work	Ref	Weight change rate ($\text{kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$)	Evaporation Efficiency (%)
A three-dimensional (3D) biochar solar evaporator	(Hou et al. 2023)	1.57	85.9
A novel two-dimensional CDs/CB@BF photothermal fabric	(He et al. 2025)	2.05	95.72
A Cu-catecholate metal-organic framework-based photothermal membrane (Cu-CATM)	(Zhao et al. 2023)	2.43	92
Semiconductive in situ-polymerized MnO_2 nanowires/chitosan (SPM-CH) hydrogels	(Irshad et al. 2021)	1.78	90.6
MXene/ MnO_2 nanocomposite coated	(Saleque et al. 2023)	1.36	85.28
All-in-one self-floating wood-based solar-thermal evaporators	(Zhang et al. 2024)	2.74	--
H-CS/ MnO_2	(Wang et al. 2022)	2.43	93.46
MnO_2 -deposited wood	(Li et al. 2021)	1.22	81.4
An aluminophosphate-treated wood (Wood@AlP)	(Chen et al. 2020)	1.423	90.8
Mn/wood@Fe-GA	This work	2.25	98

4. Conclusions

This work presents a rationally designed photothermal composite that achieves efficient and durable solar-driven desalination through the synergistic integration of multiple functional components. Central to the design is the in-situ growth of MnO_2 nanoflowers on a porous, low-thermal-conductivity wood substrate, which enhances broadband light harvesting and minimizes angular dependence. This nanoarchitecture further stabilizes a conformal iron-tannate blackening coating, providing robust

photothermal activity. The optimized composite, fabricated under mild conditions via a 30-minute immersion in 0.1 M KMnO_4 , leverages the wood's vertically aligned microchannels for rapid water supply and heat localization. It delivers a high evaporation rate of $2.25 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ under one-sun irradiation, with a rapid surface temperature rise to $41.8 \text{ }^\circ\text{C}$ within 300 seconds. Crucially, the incorporated MnO_2 modulates the interfacial chemical environment to inhibit salt crystallization, enabling sustained performance in high-salinity brine. This integrated strategy which combines efficient evaporation with inherent anti-fouling capability-transcends the limitations of conventional, energy-intensive desalination methods. By providing a scalable, stable, and multifunctional material platform, this work offers a feasible approach to addressing freshwater scarcity and energy sustainability issues, and the established theoretical framework further supports the rational development of next generation solar evaporation technology.

Author Contributions: This research was conceived and designed with the participation of all the authors. Hongyan Zhu: Conceptualization, Writing-original draft; Qihui Jiao: Writing review, Formal analysis; Jin Zhang: Investigation; Shijie Li: Data curation; Yu Wu: Writing review; Xiangyu Yang: Investigation, Validation; Xinyu Li: Data curation, Supervision, Funding acquisition; Jianguo Zhao: Supervision, Funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: The Fundamental Research Program of Shanxi Province (Project Approval Number 202503021211221; 202403021212058).

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

Reference

- Ahmed FE, Hashaikheh R, Hilal N (2020) Hybrid technologies: The future of energy efficient desalination-A review. *Desalination* 495:114659–114681.
- Hou X-T, Sun H-Y, Dong F-Y, Wang H, Bian Z-Y (2023) 3D carbonized grooved straw with efficient evaporation and salt resistance for solar steam generation. *Chemosphere* 315:137732–137744.
- He Y-L, Zhou C-H, Chen Z, Rimeh I, Xing L, Yimingniyazi A, Parkash A, Ma P-C, Kadier A (2025) Invasive plant-derived carbon dots and carbon black co-deposited basalt fiber fabric as an efficient solar interface evaporator for high salinity water purification. *Sep Purif Technol* 365:132644–132658.
- Al-Absi RS, Abu-Dieyeh M, Al-Ghouti MA (2021) Brine management strategies, technologies, and recovery using adsorption processes. *Environ Technol Innov* 22:101541–101570.
- Mojumder JC, Mitchell TR, Aminossadati SM, Leonardi CR (2024) Numerical investigation of the effect of nanoparticle aggregation on the performance of concentrated photovoltaic-solar thermal collectors with spectral filtering. *Appl Therm Eng* 239:121944–121960.
- Wang P, Zhu J (2022) Solar thermal energy conversion and utilization-New research horizon. *EcoMat* 4:e12210–e12213.
- Huang S, Peng Z-R, Li Y-C, Lu J, Wang Z-H, Deng S-H, Li W-Y (2026) Research on multi-physics coupled heat transfer enhancement of the tilted solar chimney with phase change material. *Appl Therm Eng* 289:129804.
- Sathish T (2024) Sustainable hydrogen production by integrating solar PV electrolyser and solar evacuated tube collector with hybrid nanoparticles enhanced PCM. *Appl Therm Eng* 257:124317–124329.
- Moon J, Son SJ, Kim J, Park K (2025) Critical challenges in high-salinity seawater reverse osmosis systems: Technical, energy, and environmental reviews. *Desalination* 607:118811–118831.
- Zhao X-T, Jiang Y-Y, Wang T-Y, Lu Q-Y, Zhao K, Pan J-F (2023) Photothermal-photocatalytic route of MOF-based membrane with nanosheet array structures for solar-driven water purification. *Chem Eng J* 475:146268–146278.
- Amy G, Ghaffour N, Li Z-Y, Francis L, Linares RV, Missimer T, Lattemann S (2017) Membrane-based seawater desalination: Present and future prospects. *Desalination* 401:16–21.
- Ramanathan AA, Aqra MW, Al-Rawajfeh AE (2018) Recent advances in 2D nanopores for desalination. *Environ Chem Lett* 16:1217–1231.
- Ghazi ZM, Rizvi SWF, Shahid WM, Abdulhameed AM, Saleem H, Zaidi SJ (2022) An overview of water desalination systems integrated with renewable energy sources. *Desalination* 542:116063–116092.
- Ramírez-Ruiz C, Valencia CF, Cabrales S, Ramírez AF (2023) Bi-objective optimal design of desalination plants considering the uncertainty of renewable energy sources. *Energy Rep* 10:2467–2485.

- Bundschuh J, Kaczmarczyk M, Ghaffour N, Tomaszewska B (2021) State of the art of renewable energy sources used in water desalination: Present and future prospects. *Desalination* 508:115035–115060.
- Li W, Li T-T, Deng B-Y, Xu T, Wang G-H, Hu W-C, Si C-L (2024) Fabrication of a facile self-floating lignin-based carbon Janus evaporators for efficient and stable solar desalination. *Adv Compos Hybrid Mater* 7:1–14.
- Xu Y, Wang Z-Y, Wang X-B, Guo Z-Z, Irshad MS, Arshad N, Gong J, Liu H-F, Li G-F (2024) Harvesting solar energy with a Ni-MOF-based evaporator for efficient solar thermal storage and steam generation. *J Mater Chem A* 12:12064–12076.
- Zhao F, Guo Y-H, Zhou X-Y, Shi W, Yu G-H (2020) Materials for solar-powered water evaporation. *Nat Rev Mater* 5:388–401.
- Ghasemi H, Ni G, Marconnet AM, Loomis J, Yerci S, Miljkovic N, Chen G (2014) Solar steam generation by heat localization. *Nat Commun* 5:4449–4455.
- Huxtable ST, Cahill DG, Shenogin S, Xue L-P, Ozisik R, Barone P, Usrey M, Strano MS, Siddons G, Shim M, Keblinski P (2003) Interfacial heat flow in carbon nanotube suspensions. *Nat Mater* 2:731–734.
- Kim M, Yang K, Kim YS, Won JC, Kang P, Kim YH, Kim BG (2020) Laser-induced photothermal generation of flexible and salt-resistant monolithic bilayer membranes for efficient solar desalination. *Carbon* 30:349–356.
- Maqsood MF, Fong K-C, Ghafoor F, Azhar U, Rabani I (2025) Solar vapor generation: Advances in materials engineering and structural design for efficient water evaporation. *Mater Today Phys* 59:101938–101955.
- Salper E, Topçu E, Erçarıkçı E, Kıranşan KD (2025) A sustainable solar steam generator based on natural wool and AlNi-graphene for enhanced photothermal efficiency. *J Environ Chem Eng* 13:117926–117938.
- Mahdian M, Chen S-J, Zhang J-E, W.Kirk D, Shayegannia M, Kherani NP, Jia C-Q (2024) High-efficiency photothermal water evaporation under low intensity sunlight using wood biochar monolith. *Langmuir* 40:15059–15070.
- Pozio A, Aurora A, Prosini PP (2020) Hard carbon for sodium batteries: Wood precursors and activation with first group hydroxide. *J Power Sources* 449:227555–227564.
- Li X-Y, Li S-J, Zhang J, Zhu H-Y, Zhao J-G (2026) Hierarchically porous wood/CuBTC/GO composites for efficient and selective CO₂ capture. *Wood Sci Technol* 60:26–48.
- Fratzl P (2018) Wood made denser and stronger. *Nature* 554:172–173.
- Karimi-Nazarabad M, Goharshadi EK (2023) Ag and Ni doped graphitic carbon nitride coated on wood as a highly porous and efficient photoabsorber in interfacial solar steam generation. *J Porous Mater* 30:1835–1842.
- Wang Z, Yan Y-T, Shen X-P, Jin C-D, Sun Q-F, Li H-Q (2019) A wood–polypyrrole composite as a photothermal conversion device for solar evaporation enhancement. *J Mater Chem A* 7:1–8.
- Zhou X-Y, Zhao F, Guo Y-H, Zhang Y, Yu G-H (2018) A hydrogel-based antifouling solar evaporator for highly efficient water desalination. *Energy Environ Sci*

11:1985–1992.

- Wu L, Dong Z-C, Cai Z-R, Ganapathy T, Fang N-X, Li C-X, Yu C-L, Zhang Y, Song Y-L (2020) Highly efficient three-dimensional solar evaporator for high salinity desalination by localized crystallization. *Nat Commun* 11:1–12.
- Gao M-M, Zhu L-L, Peh C-K, Ho G-W (2019) Solar absorber material and system designs for photothermal water vaporization towards clean water and energy production. *Energy Environ Sci* 12:841–864.
- Ndayiragije S, Zhang Y-F, Zhou Y-Q, Song Z, Wang N, Majima T, Zhu L-H (2022) Mechanochemically tailoring oxygen vacancies of MnO_2 for efficient degradation of tetrabromobisphenol A with peroxydisulfate. *Appl Catal B* 307:121168–121183.
- Irshad MS, Wang X-B, Abbasi MS, Arshad N, Chen Z-H, Guo Z-Z, Yu L, Qian J-W, You J, Mei T (2021) Semiconductive, flexible MnO_2 NWs/chitosan hydrogels for efficient solar steam generation. *ACS Sustain Chem Eng* 9:3887–3900.
- Saleque AM, Ma S, Thakur AK, Saidur R, Han T-K, Hossain MI, Qarony W, Ma Y, Sathiyamurthy R, Tsang YH (2023) MXene/ MnO_2 nanocomposite coated superior salt-rejecting biodegradable luffa sponge for efficient solar steam generation. *Desalination* 554:116488–116497.
- Zhang T-T, Qu J, Wu J, Jiao F-Z, Li C-J, Gao F-L, Liu J, Yu Z-Z, Li X-F (2024) All-in-one self-floating wood-based solar-thermal evaporators for simultaneous solar steam generation and catalytic degradation. *Adv Funct Mater* 34:2403505–2403517.
- Miao L, Xie Y-F, Xia Y-T, Zou N, Wang J-L (2019) Facile photo-driven strategy for the regeneration of a hierarchical $\text{C}@\text{MnO}_2$ sponge for the removal of indoor toluene. *Appl Surf Sci* 481:404–413.
- Wang S, Deng H, Chang H-Y, Li Y-Y, Hui H-H, Dong Z-F, Pu P (2022) Co-hydrothermal carbonization of cotton stalks and MnO_2 for direct solar steam generation with high efficiency. *Sol RRL* 6:2100890–2100899.
- Tao P, Ni G, Song C-Y, Shang W, Wu J-B, Zhu J, Chen G, Deng T (2018) Solar-driven interfacial evaporation. *Nat Energy* 3:1031–1041.
- Yan S-W, Song H-J, Li Y, Yang J, Jia X-H, Wang S-Z, Yang X-F (2022) Integrated reduced graphene oxide/polypyrrole hybrid aerogels for simultaneous photocatalytic decontamination and water evaporation. *Appl Catal B-Environ* 301:120820–120832.
- Li N, Qiao L-F, He J-T, Wang S-X, Yu L-M, Murto P, Li X-Y, Xu X-F (2020) Solar-driven interfacial evaporation and self-powered water wave detection based on an all-cellulose monolithic design. *Adv Funct Mater* 31:2008681–2008692.
- Chen Z-Y, Wang J, Zhou H-J, Xie Z-M, Shao L, Chen A-Z, Wang S-B, Jiang N-N (2023) Janus nano-micro structure-enabled coupling of photothermal conversion, heat localization and water supply for high-efficiency solar-driven interfacial evaporation. *Adv Funct Mater* 33:2303656–2303668.
- Chen L, Yuan H, Chen S-Q, Zheng C, Wu X-K, Li Z-Q, Liang C-Y, Dai P-Q, Wang Q-T, Ma X, Yan X-H (2021) Cost-effective, high-yield production of

- biotemplated catalytic tubular micromotors as self-propelled microcleaners for water treatment. *ACS Appl Mater Inter* 13:31226–31235.
- Xu N, Hu X-Z, Xu W-C, Li X-Q, Zhou L, Zhu S-N, Zhu J (2017) Mushrooms as efficient solar steam-generation devices. *Adv Mater* 29:1606762.1–1606762.5.
- Zhang P-P, Li J, Lv L-X, Zhao Y, Qu L-T (2017) Vertically aligned graphene sheets membrane for highly efficient solar thermal generation of clean water. *ACS Nano* 11:5087–5093.
- Chen C-J, Li Y-J, Song J-W, Yang Z, Kuang Y-D, Hitz E, Jia C, Gong A, Jiang F, Zhu J-Y, Yang B, Xie J, Hu L-B (2017) Highly Flexible and Efficient Solar Steam Generation Device. *Adv Mater* 29:1701756–1701763.
- Li D-S, Han D-T, Guo C-W, Huang C-L (2021) Facile preparation of MnO₂-deposited wood for high-efficiency solar steam generation. *ACS Appl Energy Mater* 4:1752–1762.
- Feng Q, Tan S-C, Lu J-R, Li J-T, Wang J-Z, Chen C-C, Wu W-B, Xu Z-Y (2024) Orientational bamboo veneer evaporator for enhanced interfacial solar steam generation. *ACS Sustain Chem Eng* 12:3331–3343.
- Chen P-P, Chen L, Han D, Zhai J, Zheng Y-M, Jiang L (2009) Wetting behavior at Micro-/nanoscales: Direct imaging of a microscopic water/air/solid three-phase interface. *Small* 5:908–912.
- Chen T-J, Wu Z-Z, Liu Z-Y, Aladejana J-T, (Alice)Wang X-D, Niu M, Wei Q-H, Xie Y-Q (2020) Hierarchical porous aluminophosphate-treated wood for high-efficiency solar steam generation. *ACS Appl Mater Inter* 12:19511–19518.
- Zhu L, Sun L, Zhang H, Yu D-F, Aslan H, Zhao J-G, Li Z-L, Yu M, Besenbacher F, Sun Y (2018) Dual-phase molybdenum nitride nanorambutans for solar steam generation under one sun illumination. *Nano Energy* 57:842–850.
- Zhou X-Y, Zhao F, Guo Y-H, Rosenberger B, Yu G-H (2019) Architecting highly hydratable polymer networks to tune the water state for solar water purification. *Sci Adv* 5:5484–5491.
- Jayandran M, Haneefa M, Balasubramanian V (2015) Green synthesis and characterization of manganese nanoparticles using natural plant extracts and its evaluation of antimicrobial activity. *J App Pharm Sci* 5:105–109.
- Wu X, Gao T, Han C-H, Xu J-S, Owens G, Xu H-L (2019) A photothermal reservoir for highly efficient solar steam generation without bulk water. *Sci Bull* 64:1625–1633.