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# Photothermal Diatomite/Carbon Nanotube Combined Aerogel for High-Efficiency Solar Steam Generation and Wastewater Purification

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Solar-driven interface evaporation is a sustainable and green method for seawater desalination and wastewater purification which has attracted great attention due to the expectation to solve the global fresh water crisis. Currently, its commercial application is still limited by high cost, a complicated preparation process, and unsatisfying photothermal conversion efficiency, which are difficult to be achieved simultaneously. Herein, a nontoxic, high efficient, low cost, and facile strategy to fabricate a solar steam generator is demonstraterd, in which biocompatible agar powder, carbon nanotubes, and diatomite are combined to achieve an aerogel. All materials involved are commercially available. The aerogel exhibits a water evaporation rate of 1.67 kg m<sup>-2</sup> h<sup>-1</sup> with 91% conversion efficiency under one sun illumination, and can produce drinkable water from sea water, lake water, and even strong acid/alkaline water with nearly 100% rejection of organic dyes. Most importantly, the cost to produce such an aerogel is only 6.67 \$  $m^{-2}$ , and is expected to produce 5–8 kg  $m^{-2}$  of fresh water per day under natural sunlight, which is enough for a family of three to live normally for one day. Present high-efficient and economic water purification system provides promise for commercial application in seawater desalination and wastewater purification.

## 1. Introduction

Both fresh water and petroleum fuels are the most important resources for human society today. While new clean energies

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are being developed and hopeful to replace petroleum-based fuels, the shortage of fresh water resources is becoming increasingly critical. More than 25% of the world's population are enduring fresh water shortage.<sup>[1–3]</sup> As a renewable and clean energy source with inexhaustible advantage, solar energy could be absorbed and converted into heat to accelerate the evaporation of water, thus realizing desalination and wastewater purification. In recent years, the use of photothermal conversion materials to collect solar energy at the water-air interface and thus generate water vapor has attracted extensive attention.

Although a higher solar intensity can be achieved artificially to improve the efficiency of photothermal conversion, a solar intensity of more than 1 sun is difficult to achieve in practical applications due to the naturally diffused sunlight.<sup>[4–6]</sup> Therefore, in order to achieve high-efficiency water evaporation efficiency, the following factors

need to be considered: 1) Excellent light absorption capacity to guarantee sufficient water evaporation; 2) Good hydrophilicity and sufficient water delivery channels ensure sufficient water supply; 3) Low thermal conductivity to prevent heat diffusion from the light-absorbing material itself to the water body; 4) Floatability and stability, ensuring the heat is positioned on the surface of the photothermal material and ensuring the solar steam generator can be effective for a long time.<sup>[7]</sup>

Base on aforementioned principles, to achieve effective solar steam generator, great efforts have been dedicated to material selection and structure design. Based on different photothermal conversion mechanisms, people have developed different materials of photothermal conversion. Metal materials, due to their ability to absorb electromagnetic radiation, have been widely used in various forms of solar energy absorbing materials. Among them, Au has become the most widely reported photothermal metal due to its excellent photothermal conversion efficiency and size/structure controllability.<sup>[8–11]</sup> Metal oxide and chalcogenide semiconductor photothermal nanomaterials have shown good development prospects in recent years due to their low cost, fine-tunable absorption spectrum, and large extinction coefficient in the near-infrared region.<sup>[12–14]</sup> 1D and 3D carbon-based structures have been also designed and fabricated for



photothermal applications. Biomaterials and natural products are environmentally friendly and sustainable carbon sources. They have a unique structure and are ideal for high-efficiency photothermal applications. Through hybridization and carbonization, excellent photothermal conversion efficiency can be obtained.<sup>[15-22]</sup> In addition to these photothermal materials, other materials such as ceramics and organic polymers are also widely used.<sup>[23-25]</sup> According to the position where the solar absorbing material is placed in the liquid medium, the photothermal system can be divided into three categories. The first system disperses light-absorbing materials in a working fluid, called nanofluids.<sup>[26-28]</sup> The second system places the light-absorbing material on the surface of a large amount of fluid, which is called an interface system.<sup>[8,9,29]</sup> The third system separates the lightabsorbing material from the bulk fluid and is called the isolation system.<sup>[21,30,31]</sup> Despite great progress has been achieved, there are still numerous challenges for commercial application, such as high costs, complex preparation processes, large-area production, and stability under harsh conditions, and these requirements are difficult to be satisfied in single system according to previous reports.

In present work, we report an aerogel-based solar steam generation device to address above difficulties. As a natural mineral, diatomite (DE) has a wide source of raw materials and low cost. At the same time, DE has a large number of micropores arranged in an orderly manner inside, which has the characteristics of light weight, strong adsorption capacity, and stable chemical properties.<sup>[32–36]</sup> The carbon nanotubes (CNTs) are inherently hydrophobic, while the acidified multiwalled CNTs could be hydrophilic and can provide good light-absorbing properties.<sup>[37–42]</sup> Agar powder, an algal gel extracted from algae plants, has good biocompatibility and thus could act as a coagulant.<sup>[43–46]</sup> We combined DE and acidified CNTs by a freezedrying method using agar powder as a gel agent to prepare target aerogel. Due to the strong light absorption of CNTs, ultralow thermal conductivity, excellent hydrophilicity, microporous structure of DE. The aerogel exhibits a water evaporation rate of 1.67 kg m<sup>-2</sup> h<sup>-1</sup> with 91% conversion efficiency under one sun illumination, and can produce drinkable water from sea water, lake water, and even strong acid/alkaline water with nearly 100% rejection of organic dyes. Most importantly, the cost to produce such aerogel is only 6.67 \$ m<sup>-2</sup>. In addition, present aerogel demonstrated excellent cycling stability and the ability to handle water purification in various complex environments.

### 2. Results and Discussion

The fabrication procedure is shown in **Figure 1**. From SEM image in **Figure 2a**, it can be observed that the impurities on the surface of DE after purification treatment are significantly reduced compared with that without purification as shown in Figure S3, Supporting Information. The diameter of DE is about 30  $\mu$ m with a large number of holes distributed on the surface. The holes are benefit for enhancing light absorption due to multiple reflections of light interior DE. Since the purchased DE is powder and cannot float directly on the water surface. Therefore, it is combined with 3D aerogel with porous structure as an important part to support photothermal materials. In this work, purified DE and acidified CNTs were dispersed in agar solution at 80 °C. After cooling to room temperature, DE and CNTs



Figure 1. Preparation process of aerogel solar evaporator.







**Figure 2.** Characterization of the solar evaporator. a) SEM image of purified DE. b) SEM image of composite aerogel. c) Cross sectional view of aerogel. d-f) XRD, FTIR, and Raman spectra of different samples. g) Light absorption spectrum of aerogel, and the inset is digital images of pure DE aerogel and composite aerogel. h) Hydrophilic wetting angle of aerogel. i) The aerogel floats on the water. The inset is a aerogel on leaf tip.

included hydrogel were acquired due to gelation of agar. Then an aerogel could be produced by freeze-drying and the DE was embedded in the aerogel as shown in Figure 2b. The crosssectional view in Figure 2c indicates that there are interconnected macropores in the aerogel, which facilitate the upward transport of water. The agar powder is used as a "binding agent" to hold the dispersed DE and CNTs. The excellent hydrophilicity of the DE and the large pore channels between the agar powder ensure continuous supply of water during evaporation. Figure 2d shows the XRD spectra of DE, CNTs and agar powder. The agar powder has a classic strong peak near 20°, and the diffraction peaks of DE are located at  $2\theta = 21.80^{\circ}$  and  $36.04^{\circ}$ , indicating that the main component of DE is SiO<sub>2</sub>. CNTs show strong diffraction peaks at  $26.2^{\circ}$  and  $42.9^{\circ}$ , corresponding to the (002) and (100) crystal planes. Figure 2e shows the FTIR spectra before and after DE purification. The broadband absorption peaks of DE at 3400 and 1630 cm<sup>-1</sup> are related to the stretching vibration of water hydroxyl (-OH). The peaks at 1091 and 475  $\rm cm^{-1}$  are attributed to the stretching vibration of the -Si-O-Si bond. The peak at  $793 \text{ cm}^{-1}$  is caused by the vibration of SiO-H. Figure 2f shows the Raman spectra of DE, CNTs and composite aerogels. It can be seen that DE has no characteristic peaks. CNTs have two prominent characteristic peaks, located at 1355 and 1554 cm<sup>-1</sup>, respectively. It is the D-band and G-band peaks of the carbon material, and there are two characteristic peaks in the composite material, which proves the successful preparation of the composite material.

The light absorption capacity of photothermal materials is one of the most important parameters for solar evaporators. Embedding DE and CNTs into agar powder aerogel not only ensures hydrophilicity, but also enhances the light absorption capacity. Figure 2g shows the light absorption spectra of DE, dry and wet aerogel materials in the range of 300–1500 nm. The pure DE has a 67% light absorption capacity, and the composite aerogel after the addition of carbon nanotubes shows a light absorption capacity over 95%, which indicates that the addition of CNTs can effectively improve the light absorption ability. Digital images of pure DE aerogels and composite aerogels are shown in the inset of Figure 2g. The light absorption further increases to 98% after wetting with water because the light



scattering is significantly reduced after passing through the material-gas interface in the wetted state, and this value has more practical reference value because the photothermal laver is always wetted by water during the solar evaporation. The prepared aerogel exhibits excellent hydrophilicity, which can be confirmed by the wetting angle in Figure 2h. Due to the excellent hydrophilicity of diatomaceous earth, water drops from top have a wetting angle of 45.8° in the transient state and can be completely absorbed less than 1s as shown in Figure S4, Supporting Information. Self-floating property is also very important for thermal evaporation, and the prepared aerogel can float on the surface of water shown in Figure 2i, and Figure S5, Supporting Information. The inset of Figure 2i exhibits a photograph that the dry aerogel is extremely light and can be placed on the leaf tips of plants. We further tested the mechanical properties of the aerogel in Figure S6. Supporting Information. The as-prepared aerogel exhibits high mechanical property which can support a 500 g of weight without any collapsing of its original structure after removing the load. The mass of the aerogel with a size of  $20 \times 20 \times 3 \text{ mm}^3$  in the dry and wet state is shown in Figure S8, Supporting Information. The density of the aerogel in the dry state is only  $0.08 \text{ g cm}^{-3}$ , and the aerogel in the wet state can absorb water more than ten times higher than its original weight, which ensures sufficient water supply during solar evaporation. The density of aerogel in wet state is  $0.94 \text{ g cm}^{-3}$ . The good hydrophilicity and light absorption ability provide the possibility to improve the evaporation efficiency.

To verify the solar evaporation performance of aerogel, solar evaporation experiments were conducted. The experimental setup is shown in **Figure 3a**. The DE/CNT aerogel was cut into small pieces with dimensions of  $20 \times 20 \times 3 \text{ mm}^3$ . DE with good hydrophilicity acts as a water transport channel to enable a continuous flow of water from the water body to the CNT/DE aerogel through capillary effect. For comparison, solar evaporation experiments were also performed on pure water and pure DE aerogel under the same condition, and the corresponding results are shown in Figure 3b,c. The solar evaporation rate of pure water under 1 sun irradiation was 0.45 kg m<sup>-2</sup> h<sup>-1</sup>, which is consistent with the previous report. The solar evaporation rate of pure DE measured 0.69 kg m<sup>-2</sup> h<sup>-1</sup>, which is about 1.5 times



Figure 3. a) Solar evaporator under test conditions. b) The evaporation efficiencies of pure water, DE aerogel, DE/CNT aerogel under illumination. c) Water evaporation efficiency and photothermal conversion efficiency. d) Temperature variation of DE aerogel and DE/CNT aerogel in air under illumination. nation. e) Temperature variation of DE aerogel and DE/CNT aerogel in water under illumination.

higher than that of pure water, indicating the ability of DE aerogel to generate solar vapor. The CNT/DE aerogel achieved an evaporation rate of  $1.67 \text{ kg m}^{-2} \text{ h}^{-1}$ , a value that is 3.7 times higher than that of pure water evaporation and 2.4 times higher than that of DE aerogel. This mainly due to: 1) the good hydrophilicity of DE can ensure sufficient water supply; 2) the low thermal conductivity of DE ( $0.076 \text{ W m}^{-1} \text{ K}^{-1}$ ) reducing the heat loss of a large amount of water; 3) the existence of multi-walled CNTs increases the overall light absorption and allows the device to have good thermal locality.

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Infrared temperature photographs were taken to observe the temperature variation during evaporation process. Figure 3d is temperature variation of DE aerogel and DE/CNT aerogel in air under illumination. The CNT/DE aerogel takes only 30 s to reach a temperature of 70.7 °C under 1 sun intensity, which is 33 °C higher than that of DE aerogel. After placing in the evaporation device with a large amount of water, the CNTs/DE aerogel reaches a steady-state temperature of about 36.2 °C in 15 min under 1 sun light intensity, which is 9.2 °C higher than DE aerogel as shown in Figure 3e. The heat generated by the solar thermal conversion is mainly concentrated on the evaporator surface, which can be clearly observed in the red marked area of the infrared image. We believe that the main reason for such a large temperature difference between dry aerogel and wet aerogel is due to the porous structure of the aerogel and the heat absorption process of evaporation. In the wet aerogel state, since most of the aerogel is occupied by water, most of the heat is transferred to water and then evaporates, which leads to a large temperature difference between the dry and wet states of the aerogel. The calculated photothermal conversion efficiency of DE aerogel can reach 27.5% and that of pure water is 21.3%. Compared to DE aerogel, the CNT/DE aerogel achieves a higher conversion efficiency of 91.0% due to the addition of multiwalled CNTs. The finite element simulation is used to numerically simulate the heat distribution of the aerogel evaporator under 1 sun intensity, as shown in Figure S9, Supporting Information. The heat flow simulation of the composite aerogel was carried out using finite element simulation, and the 3D structure of the aerogel was first constructed. The heat transfer module simulates the evaporation process of aerogel in air and water, and the simulation results show the temperature distribution of aerogel at different time lengths. When the aerogel is placed on the water surface, the water will be immersed in the aerogel. Therefore, the heat energy converted by solar energy must first heat this part of the water, so the temperature at the top will be lower than the temperature directly irradiated in the air. The simulated results are in agreement with the experimental results.

Although higher solar intensities can be achieved artificially, evaporative devices can show very low vapor production under weaker natural light conditions because the real outdoor solar intensity is usually difficult to reach 1 sun intensity due to seasonal and regional influences received. Therefore, the ability to produce higher vapor yields under lower solar radiation conditions is extremely important for practical applications. We tested the evaporation rate of CNT/DE aerogel at different solar light intensities (0.8, 1, and 1.2 sun). The results show that although the solar evaporation rate decreases slightly as the light intensity decreases, the evaporation rate can still reach 1.57 kg m<sup>-2</sup> h<sup>-1</sup> even at a weak intensity of 0.8 sun, a value that

is more informative under practical application conditions as shown in Figure 4a. On the other hand, it is quite important to study the ability of aerogel in purifying different types of water bodies. Four different types of water were tested, including strongly acidic water, strongly alkaline water, river water and seawater. The solar evaporation performance on different water bodies irradiated at 1 sun intensity for 1 h is shown in Figure 4b. Evaporation is the process by which molecules on the surface of a liquid transform from liquid to gas and escape. According to the theory of gas dynamics, evaporation is caused by the thermal movement of molecules. As the temperature increases, the probability of collisions between liquid molecules increases. The presence of ions weakens the evaporation capacity of the liquid surface. As the concentration increases, the phase change rate of the solution decreases, and the evaporation rate declines. Among them, the mass loss of strongly acidic water  $(1.62 \text{ kg m}^{-2} \text{ h}^{-1})$  and strongly alkaline water  $(1.30 \text{ kg m}^{-2} \text{ h}^{-1})$ is slightly lower than that of pure water. In contrast, the mass loss

in lake water (1.44 kg m<sup>-2</sup> h<sup>-1</sup>) and seawater (1.60 kg m<sup>-2</sup> h<sup>-1</sup>)

was closer to that of pure water. To prove that CNT/DE aerogel plays an important role in the purification of water, the ohmic resistance of different water bodies before and after evaporation was measured and compared. It can be seen from Figure 4d that the ohmic resistance of the sample after purification is significantly higher than that of the sample before purification, which indirectly proves the effect of purification on water quality. It can be found that the ohmic resistance of the sample after purification is higher than that of ordinary drinking water. The high purity of the water obtained after evaporation proves the ability of present CNT/DE aerogel to produce fresh water in different water bodies in Figure 4d,e. The evaporated water from acidic water (pH = 1) and alkaline water (pH = 14) showed a pH value close to 7, demonstrating the good filterability of the aerogel under harsh conditions. The aerogel evaporator also did not show decomposition or deformation after evaporation with excellent corrosion resistance. To further determine the solar evaporation performance of CNT/DE aerogel evaporator in seawater, aerogel evaporator was used in various salinities (1, 3.5, 4.1, and 23 wt%) at 1 sun intensity corresponding to Baltic Sea, Standard Seawater, Red Sea, and Dead Sea, respectively. In Figure 4g, it can be seen that the evaporation rates at 1 sun intensity are 1.57, 1.66, 1.32, and 1.35 kg m<sup>-2</sup> h<sup>-1</sup>, respectively, indicating the potential ability for desalination of seawater.

The ion concentrations of representative cations and anions before and after desalination were also investigated and shown in **Figure 5**a–c. it can be confirmed that the four ion concentrations (Na<sup>+</sup>, K<sup>+</sup>, Ca<sup>2+</sup>, and Mg<sup>2+</sup>) after purification were reduced by two to three orders of magnitude, and the ion rejection rate was over 99.97%, which is in full compliance with the World Health Organization (WHO) standards for potable water. There was no significant salt accumulation was observed on the surface of the evaporator after prolonged exposure to standard seawater salinity under 1 sun intensity, proving that the CNT/DE aerogel evaporator has excellent resistance to salt fouling in practical applications as shown in Figure S8, Supporting Information. To further investigate the purification performance, three kinds of dyes were selected for the wastewater purification test, namely rhodamine B, methylene blue and methyl orange.







**Figure 4.** a) Evaporation efficiency under different sunlight intensity. b) Evaporation efficiency under different water bodies. c) Evaporation efficiency and photothermal conversion efficiency. d) Ohmic resistance values of different water bodies. e,f) Acidity and alkalinity of water before and after filtering. g) Evaporation efficiency of four types of marine water.

As it can be seen from Figure 5d-f, the color of the purified water was transparent, while the characteristic absorption peaks of rhodamine B (450-600 nm), methylene blue (550-700 nm) and methyl orange (350-550 nm) completely disappeared, proving that the concentration of organic dyes in the purified water was extremely low. We further repeated 10 cycles of solar water evaporation experiments, each lasting 60 min as shown in Figure 5g. After multiple cycles, the evaporation rate of the solar evaporator can still be maintained at 1.66 kg m<sup>-2</sup> h<sup>-1</sup>, exhibiting a very stable water evaporation capacity. In order to further prove the potential practical application of the solar evaporator in seawater desalination under natural sunlight, a prototype solar thermal desalination device was subsequently designed as shown in Figure 5h and Figure S10, Supporting Information. The entire device only needs a transparent acrylic plate, and the water can be filled and clean water collected through two perforated rubber plugs. After the solar evaporator is placed in natural sunlight, water vapor will be quickly generated and condensed on the acrylic sheet. Another simple installation diagram of the laboratory is shown in Figure S11, Supporting Information. For application test, the time with the strongest light intensity in one day (from 10 a.m. to 6 p.m.) is chosen. The actual sunlight intensity and outdoor temperature are shown in Figure S11, Supporting Information. The test process uses eight pieces of aerogels with 7.5 cm diameter. After 8 h light evaporation, about 136 g of clean water is obtained, and the water output is about 4.5 kg m<sup>2</sup>. It can be inferred that 1 m<sup>2</sup> of aerogel can produce at least 5–8 kg of clean water under all-day light.

Considering that the CNT/DE aerogel floating on the interface of the water body is in direct contact with water, it is inevitable that some heat will be dissipated in a large amount of water, lowering the evaporation efficiency of the solar evaporator. In order to avoid this part of heat loss, we designed another isolation structure by pouring the gel directly on the melamine sponge and freeze-drying it as shown in **Figure 6**a. As shown in Figure 6b, the temperature at the top of the aerogel reaches 40.5 °C. The melamine sponge acts as a heat insulation layer to minimize the heat transfer. The melamine sponge also has





Figure 5. a,b) The filtering capacity of solar evaporator for cations and anions. c) The ion rejection rate of solar evaporator. d-f) The effect of solar evaporator on rhodamine B, methylene blue, and methyl orange catalytic ability. g) Cyclic stability performance of solar evaporator. h) Experimental prototype of solar evaporator.

good hydrophilicity, which can ensure the water supply to the hot evaporation surface. The modified evaporator shows a higher surface temperature and the evaporation rate is  $1.72 \text{ kgm}^{-2} \text{ h}^{-1}$  at 1 sun intensity in Figure 6c. The temperature difference between the heating surface and the water body is reduced to 6 °C as shown in Figure 6d, which is much lower than that without melamine sponge as a heat insulation layer, indicating this structure can minimize the heat transfer from the heating surface to water.

In addition, the cost and comprehensive performance of the solar evaporator are the key parameters for the practical application. Table S2, Supporting Information, summaries the performance comparison of reported results with present work. Apparently, these works achieved different optimal aspects. To give a clear comparison, the cost of present material is calculated and shown in Supporting Information, which is expected to cost only 6.67 \$ m<sup>-2</sup>. The main materials for preparing present aerogels are naturally formed or easy acquiring, so the raw materials are abundant and the cost is obviously low. A graphical comparison is shown in Figure S13, Supporting Information. By

comparing the comprehensive performance of five aspects, such as evaporation rate, photothermal conversion efficiency and cost, it is clear the present work provides a better way to fabricate solar evaporator more possible for practical application.

#### 3. Conclusion

In conclusion, we developed a high efficient, low cost, and facile strategy to fabricate solar steam generator with CNTs and DE combined aerogel. Due to the microporous structure and excellent hydrophilicity possessed by DE and the enhanced photothermal conversion capacity with the addition of CNTs, the aerogel achieved a high solar light absorption capacity (98% in the solar spectrum range of 300–1500 nm). Its rich microporous structure and inherent hydrophilicity guaranteed sufficient water supply and excellent solar evaporation performance at 1 sun intensity (evaporation rate of 1.67 kg m<sup>-2</sup> h<sup>-1</sup> and photothermal conversion efficiency of 91.0% at 1 sun intensity). The aerogel also demonstrated the ability to purify polluted lake and sea water,

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Figure 6. a) Improved solar evaporator. b) Infrared picture of surface temperature of CNT/DE sponge evaporator. c) Water evaporation efficiency of CNT/DE sponge evaporator. d) Comparison of water temperature before and after improvement.

strongly acidic and alkaline water, and industrial wastewater containing organic dyes. The cost to produce such aerogel is only 6.67 m<sup>-2</sup> and is expected to produce 5–8 kg m<sup>-2</sup> of fresh water per day under natural sunlight, which is enough for a family of three to live normally for one day, and thus has great potential for practical applications.

#### 4. Experimental Section

*Materials*: DE was purchased from Tianjin Fuchen Chemical Reagent Co., Ltd. Multi-walled CNTs were purchased from Shenzhen Nanoport Co., Ltd. Agar powder was purchased from China Huishi Biochemical Reagent Co., Ltd. Concentrated sulfuric acid, concentrated nitric acid, and hydrogen peroxide were purchased from Beijing Chemical Plant. All chemical reagents are chemical grade and used without further treatment.

*Purifying DE*: Ten grams of DE was added to a solution including 70 mL  $H_2SO_4$  and 30 mL  $H_2O_2$  followed by stirring at 80 °C for 5 h. This step helped to expose and introduce more hydroxyl groups on the surface of the DE. The DE was then washed and dried in vacuum at 70 °C for 24 h.

Acidification of CNTs: Three grams of multiwalled CNTs were ultrasonically dispersed in 130 mL  $H_2SO_4$  and  $HNO_3$  solution for 10 min, followed by condensation reflux at 90 °C in an oil bath for 2.5 h. After washing, the solution was dialyzed to neutral. The photograph of CNT aqueous dispersion before and after acidification are shown in Figure S1, Supporting Information, indicating the excellent hydrophilicity of acidified CNTs.

Aerogel Preparation: 0.6 g purified DE, 1 g agar powder, and 8 mL of acidified CNTs (5 mg mL<sup>-1</sup>) were dispersed into a 50 mL mixture solution of deionized water and ethanol with volume ratio of 7:1, and stirred at 80 °C for 30 min. Then, the mixture was poured into a petri dish, and allowed to cool to promote gelation. The resulting hydrogels were then freeze-dried. The fabrication procedure is shown in Figure 1a. The aerogels were prepared in different proportions, which are summarized in Figure S2 and Table S1, Supporting Information. According to evaluation, we chose 0.6 g DE and 6 mL CNT to prepare aerogel for subsequent testing.

Preparation of Various Water Bodies: Deionized water was used in all experimental preparations. Sea water was taken from the South China Sea (Hainan Province, China). Lake water was taken from South Lake (Changchun, Jilin Province, China). The 1, 3.5, 4.1 and 23 wt% sodium chloride solutions were used to simulate the Baltic Sea, Standard Sea, Red Sea and Black Sea, respectively. Acidic liquids were 0.1 M hydrochloric acid solutions with pH 1-2. Alkaline liquids were 0.1 M sodium hydroxide solutions with pH 3–14. Methylene blue, methyl orange, and rhodamine B solution (10 mg L<sup>-1</sup>) were used to simulate organic effluents, and all experiments were carried out under the indoor humidity of 35–40% and temperature of 25 °C.

*Characterization*: The sample was characterized by scanning electron microscope (SEM S4800), X-ray diffraction (XRD, D/max-2000 diffractometer), Raman spectra (LABRAM HR Evolution), Fourier transform infrared spectrum (FTIR, Nicolet-67000), Contact angle meter (JC2000C1), UV-vis spectrometer (Agilent, Cary 5000, USA),thermal conductivity meter (TC3100, Xia Tech, Xi'an, China). Vapor generation experiments were performed on a laboratory fabricated device with a solar simulator (CEL-PE300L-3A) with an optical filter for standard AM 1.5 G spectroscopy.

Solar Evaporation Experiments: Solar evaporation experiments were performed under simulated sunlight of  $1 \text{ kW m}^{-2}$  (1 sun). The aerogel was placed on the water surface of a beaker (45 mm diameter). The entire device was exposed to simulated sunlight. The loss of weight was recorded. The aerogel surface temperature was tested and recorded with an infrared camera. The aerogel floats on the surface of water, and the light-absorbing material converts solar energy into heat for localized heat evaporation as shown in Figure 1b.

*Insulated Solar Evaporation Experiments*: PS foam was used as the insulator. The hydrogel was poured on a melamine sponge to avoid direct contact of the aerogel with large amounts of water and to prevent further heat diffusion.

*Finite Element Simulation*: A model was established by known conditions and physical quantities, and a heat transfer module was used to simulate the evaporation process and the surface temperature distribution at different times. The aerogel was deemed as a porous medium with a heat flux of 1 kW m<sup>-2</sup>.

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#### Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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#### Conflict of Interest

The authors declare no conflict of interest.

#### **Data Availability Statement**

Research data are not shared.

#### Keywords

aerogels, photothermal conversion, solar steam generation, wastewater purification

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