Versatile PVA/CS/CuO aerogel with superior hydrophilic and mechanical properties towards efficient solar steam generation

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Abstract
In recent years, pursuing a high evaporation rate of solar steam generation (SSG) has been the focus of research for relieving the freshwater shortage. Scientists struggled to find perfect photothermal materials while the importance of substrate during the steam generation was often overlooked. Therefore, in this work, an aerogel substrate composed of polyvinyl alcohol (PVA) and chitosan (CS) has been designed for solar steam generation. The compounded aerogels synthesized via freeze-drying method not only retain the inherent characteristics of lightweight, porosity, and high specific surface area, but also inherit the advantages of PVA in water lock effect as well as CS in moisture absorption. The obtained PVA/CS/CuO aerogel coupling with high light absorption of CuO exhibited excellent steam generation capabilities, largely benefited from the superiority of the aerogel substrate. Under 1 sun solar illumination (1 kW m\(^{-2}\)), it realized an evaporation rate as high as 2.14 Kg m\(^{-2}\) h\(^{-1}\), which is superior to recently reported semiconductor solar evaporation system. The solar-to-vapor energy conversion efficiency of 87.1% is obtained. Due to the versatility of CuO, PVA/CS/CuO aerogel not only has excellent light-to-heat conversion performance, but also has good effects in antibacterial.

KEYWORDS
bactericidal, desalination, PVA/CS/CuO aerogel, solar steam generation
Among many resources, solar energy is undoubtedly the richest and most durable one. If the inexhaustible solar energy is fully used, not only the energy crisis worldwide could be relieved but also global economic growth could be promoted. The photothermal conversion technology represented by direct solar steam generation (DSSG) enabling the desalination and purification renewably is an effective method for utilizing solar energy, which provides a promising way for the current water crisis. It could generate vapor at temperatures lower than the boiling temperature and then harvest clean water.

DSSG was successfully implemented by introducing the photothermal material (PTM) into the solar distillation system. The use of the PTM can effectively collect solar energy and convert it into heat energy, increasing the output of pure water. As core materials in DSSG system, the PTM used in high-efficiency DSSG experiments generally have the following characteristics: (1) excellent light absorption; (2) adequate water transportation; (3) large evaporation area attributed to the three-dimensional structure and (4) high thermal management capabilities. With the continuous efforts of predecessors, in the past few years, various nanomaterials, including carbon-based materials, metals, metal oxides/mixed metal oxides, and polymers, with strong light-absorbing properties in broad solar spectra have been extensively studied. For example, Gu et al. carbonized pomelo peel particles as photothermal conversion material then composted with the chitosan (CS) aerogel, exhibiting an evaporation rate of up to 1.78 kg m$^{-2}$ h$^{-1}$. This kind of biomass carbon material is environmentally friendly, low preparation costs and excellent light absorption properties, so it is more and more popular among scientific researchers.

Many noble metal nanomaterials are recognized as having strong plasmon resonance, which could effectively absorb more sunlight compared with bulk metal. In 2013, Halas’s group pioneered Au nanoparticle-enabled solar vapor generation which inspired wide research interest in solar water evaporation and beyond. In 2018, Zhou et al. decorated graphene oxide (GO) with gold nanorods, forming a plasmonic nanofluid with strong optical absorption and enhanced solar steam generation efficiency of 84.1% under 1 kW m$^{-2}$ illumination. In addition, non-noble metal oxide semiconductor materials are relatively cheaper and abundant, which can absorb light and produce electron-hole pairs. Solar energy, which is higher than the semiconductor band gap, causes the creation of electron-hole pairs above the band gap, which relax to the edge of the band and convert the extra light energy into heat. Electron-hole pairs in narrow band-gap semiconductors eventually recombine to generate heat. In 2016, Huang et al. synthesized titanium dioxide nanocages with high light capture ability to evaporate solar water. In 2018, Wang et al. reported a quartz glass membrane loaded with CuCr$_2$O$_4$ as an extremely thermally stable solar photothermal material, providing potential fouling control for practical solar evaporation and distillation applications. More recently, CuO has been widely used in wastewater treatment. Although great progress has been made in CuO materials with special morphologies, most of the previous work focused on the manufacture of specific structures for the required applications, and its research in water treatment is limited to photocatalytic application. For example, Cao et al. prepared CuO-coated superhydrophobic modified fabrics and studied its ability to degrade methylene blue aqueous solution under visible light irradiation. Encouragingly, Xu et al. designed a multifunctional PTM based on a copper mesh with abundant CuO nanowires exhibited a solar absorption of 93%, but the evaporation rate (0.7 kg m$^{-2}$ h$^{-1}$) was only about half that of the CuO tree system (1.42 kg m$^{-2}$ h$^{-1}$). It is concluded that the high thermal conductivity of the CuO nanowire mesh caused most of the generated heat to be transferred to the bulk water below.

In this research, we innovatively designed a PVA/CS aerogel composed with CuO for highly efficient solar steam generation. The excellent hydrophilic and thermal insulation properties of PVA/CS could regulate light and heat simultaneously. The PVA/CS/CuO aerogel was prepared by one-step liquid phase freeze-drying method, in which the CuO light absorber was well embedded in the PVA/CS molecular networks. This aerogel not only retains the inherent characteristics of light weight, high porosity, and high surface area, but also combines the advantages of robust mechanical properties of PVA and excellent hydrophilicity of CS. As an ideal evaporator, PVA/CS/CuO aerogel achieved evaporation rate of 2.14 kg m$^{-2}$ h$^{-1}$ evaporation rate, with ~95% absorptance over the ultraviolet and near infrared regions. Thanks to the excellent bactericidal ability of CuO, PVA/CS/CuO aerogel also has a good bactericidal effect on microorganisms in lakes, which would effectively connect the two fields of photothermal conversion and biological environment.

## RESULTS AND DISCUSSIONS

### Characterization

The XRD patterns of three CuO samples with the reaction temperatures at 180, 230, and 280°C are shown in Figure S1. Two main peaks are originated from CuO at the positions of 35.6° and 38.8°, with no stray peaks indicating that the
CuO obtained by this hydrothermal reaction method is the pure crystal phase of monolithic CuO. In addition, the morphology of PTM has a great influence on absorbance, so we also observed the morphology of CuO obtained at these three temperatures with SEM. As shown in Figure 1A-C, the CuO obtained at the three hydrothermal temperatures present a crosslink flower-like or rod-like morphologies. Morphological differences led to the different absorbance of the aerogels loaded with CuO as light-absorbing materials as given in Figure 1D. The UV-Vis-NIR absorption spectra showed that the light absorption capacity of the CuO sample with a hydrothermal temperature of 180°C was much stronger than that of the samples with the temperature at 230°C and 280°C. The reason is that PCC$_{180°C}$ with flower-like clusters increase the propagation path of light, extend the light path, and enhance the multiple scattering of light inside.

The pore structure of the material will affect the strength and water absorption of the absorber. The SEM images of CS/CuO aerogel, PVA/CuO aerogel and PVA/CS/CuO aerogel are shown in Figure 2A-C, respectively, the results showed that CS/CuO aerogel has a square macroporous structure, PVA/CuO aerogel has a dense layered structure, and PVA/CS/CuO aerogel has a slightly dense rectangular pore, corresponding to the hydrophilicity of the samples in Figure 2D-F. From the figures, we can see that the contact angle of CS/CuO aerogel possessing a macroporous structure is 0 degree, while the contact angle of PVA/CuO aerogel is at 55.8°. The PCC aerogel obtained by combining CS and PVA still shows good hydrophilicity with an ideal contact angle of 32.46° because of its dense porous texture.

The structure of the three aerogel materials also gives them different mechanical properties, including tension and pressure. In fact, the root cause for the failure of materials often encountered in our evaporation tests process is the weak tensile strength. Therefore, it is necessary to prepare PTM that are both of strength and hydrophilic. The mechanical properties of PTM are characterized by observing the force required to break the sample under external force by a digital force gauge (AIGU, Hong Kong) as recorded in Table S1. As can be seen from the Table S1, CS aerogel only needs 0.25 Newtons of force to break, while PVA needs 10 Newtons of force. PVA/CS aerogel has the advantages of strong mechanical properties of PVA, and also has good tensile resistance with 1.41 Newtons, 5.6 times as many as CS aerogel is. From the photo in Figure 2G-I, we can also find that the PVA aerogel and PVA/CS aerogel could withstand a total weight of 1000 grams, whereas the CS aerogel could not, which indicate the excellent anticompressibility caused by addition of PVA. This is mainly because the loose structure of chitosan aerogel is not enough to support the pressure of the weight, while the dense and tight three-dimensional structure of PVA aerogel and PVA/CS composite aerogel can be uniformly dispersed the pressure exerted by weights provides a reliable and stable water delivery device for the solar water evaporation system.
It can be seen from the above exploration experiment, PVA/CS compositied aerogel can perform very well as PTM supporter for DSSG with excellent water transportation ability. From SEM images in the Figure S3, we can see the closely linked chambers and paratetic upright channels for water storage and transportation. This PVA/CS composite strategy not only makes aerogels inherently porous, light, hydrophilic, but also enhances its mechanical strength by combining with PVA. To determine the distribution of individual elements, mapping of them were further observed by EDS. Uniform distribution of the C, O, and Cu elements in PCC_{0.5} aerogels is revealed in Figure S4, which is beneficial for light absorption. It is also proved that the CuO particles are uniformly loaded onto the aerogel frame structure. By observing the XRD pattern of PCC aerogel, we can also see the diffraction peak of CuO, which indicates that CuO elements have been completely compounded with PVA/CS aerogel (Figure S5).

To verify the effect of the CuO mass change in PVA/CS aerogels on light absorption, PCC_y aerogels loaded with 0.5, 1.0, 1.5, 2.0, and 2.5 g CuO were fabricated through freeze casting. As shown in UV-Vis-NIR spectra of
Figure 3A, the light absorption performance of PCC\(_{y}\) aerogel increases with the increase of the CuO compound amount (PCC\(_{0.5}\) ∼ 77.09%, PCC\(_{1.0}\) ∼ 76.99%, PCC\(_{1.5}\) ∼ 79.31%, PCC\(_{2.0}\) ∼ 79.3%, PCC\(_{2.5}\) ∼ 76.82%), while the PC aerogel has a lower light absorption performance (PC ∼ 57.91%). From the spectra, we can also conclude that the light absorption capacity of the PCC sample in the visible light range is enhanced with the addition of CuO.

The hydrophilicity of the material also has a great influence on the improvement of steam generation rate. Therefore, FTIR was conducted to comprehensively analyze the functional groups of PCC aerogel, which is shown in Figure 3B. The wide and strong characteristic enveloping peak at the wave number 3426 cm\(^{-1}\) is mainly the resonance absorption caused by the stretching vibration of hydroxyl O–H and amino N–H, indicating that the aerogel sample contains a large number of hydrogen bonds, free hydroxyl and amino groups. The oxygen-containing functional groups derived from PVA and CS can contribute to the improvement of hydrophilic properties for the PCC. The contact angle data in Figure S6 can also help illustrate this feature.

As shown in Figure S6, the contact angle of the samples (PCC\(_{0.5}\), PCC\(_{1.0}\), PCC\(_{1.5}\), PCC\(_{2.0}\), PCC\(_{2.5}\)) are 40.84, 35.13, 45.17, 52.28, and 58.50\(^{\circ}\), respectively. All of them are less than 90\(^{\circ}\), which indicates that the PCC aerogels are of good hydrophilicity. This conclusion is also consistent with the results of FTIR.

### 2.2 SSG experiment

#### 2.2.1 Steam generation performance tests of PVA/CS aerogel, CS/CuO aerogel, PVA/CuO aerogel, and PCC\(_{y}\) aerogels

SSG experiments were conducted on a mimetic tree system (MTS) for the simulated solar water evaporation experiment as shown in Figure 4A (The number 1 represents the PTM, the number 2 is foam for insulation, and the number 3 is a water vessel for water supply). The SSG experiments were typically conducted at an ambient temperature of 25°C and a relative humidity of about 50%. The SSG evaporation rate values of 1.59, 1.87, and 2.14 kg m\(^{-2}\) h\(^{-1}\) obtained corresponding to CS/CuO aerogel, PVA/CuO aerogel and PVA/CS/CuO aerogel in Figure 4B, respectively. CS/CuO aerogel has better water transport capacity due to its super-hydrophilicity. But because of its loose structure, it is easy to damage the shape of the sample during the experiment, which will lead to performance degradation. Compared to CS/CuO aerogel, the hydrophilicity of PVA/CuO aerogel is much weaker; however, we found that the high
evaporation rate of 1.87 kg m\(^{-2}\) h\(^{-1}\) was only obtained in the first test during the evaporation process, and it was lower than those in subsequent tests. Moreover, due to the speed of evaporating water is greater than that of water transportation, there was a slight shrinking phenomenon of the PVA aerogels. For PCC\(_y\) aerogel, it perfectly combines the PVA and CS, retaining their respective advantages, which can not only obtain hydrophilicity and porosity for water transport, but also ensure that the sample is not easily damaged during testing. Moreover, due to the combination of CuO, the sample has good light absorption ability; thus, obtaining an ideal evaporation rate.

After comparative testing of several groups of different samples, the evaporation rates of 1.20, 1.47, 1.67, 2.14, 1.67, and 1.49 kg m\(^{-2}\) h\(^{-1}\) are also obtained for PC, PCC\(_{0.5}\), PCC\(_{1.0}\), PCC\(_{1.5}\), PCC\(_{2.0}\), and PCC\(_{2.5}\) samples in Figure 4B, respectively. Clearly, the water evaporation rate is significantly enhanced with the deposition of CuO with efficiency of 87.1% calculated from the formula (6). However, when CuO deposition amount is over than 1.5 g, the evaporation rate of water and the solar-vapor conversion efficiency decreases. The decrement can be well explained by the fact that excessive CuO loading could reduce steam rate due to pore blockage preventing water from reaching the surface of the sample in time from Figure S7. And, the evaporation rate of bulk water in the dark could be calculated in Figure S8, reach \(\sim 0.05\) kg m\(^{-2}\) h\(^{-1}\).

To investigate solar thermal evaporation behavior in PCC aerogels under different intensities, an infrared camera was used to map the temperature field. As shown in Figure 4D, we can see that the surface temperature of PC reached the equilibrium state within 20 minutes, indicating an outstanding solar absorption ability by the composite material. The addition of light-to-heat conversion materials also increased the maximum surface temperature of the composite aerogel under 2.5 beams of light from about 36\(^\circ\)C to 46\(^\circ\)C. In addition, the heat losses of PCC\(_{1.5}\) aerogel based on these temperatures were also calculated, with the conduction loss from to the bulk water in the beaker at 35 W m\(^{-2}\), heat convection and heat radiation at 15.5 W m\(^{-2}\), 12.7 W m\(^{-2}\), calculated from the formula (3), (4), and (5) in experimental section, respectively, demonstrating a superior thermal insulation performance.

Meanwhile, in the Figure S9 we can also see that the surface temperature of the composite PCC aerogels are increased by 11, 14.9, and 19.1\(^\circ\)C, to 25.3\(^\circ\)C at 1, 1.5, 2, and 2.5 suns, within 5 minutes, respectively. The samples without CuO increased by 9, 14.1, 14, and 14.3\(^\circ\)C, respectively. That is to say, no matter how the power density of the light source is increased, the temperature increase remains basically unchanged without the heat absorption of the photothermal conversion material. However, the surface temperature of PCC aerogels could be further increased. Meanwhile, the evaporation rate of PCC aerogels under 1-2.5 sun illuminations were also recorded, reach up to 2.14, 2.43, 3.25, and 3.92 kg m\(^{-2}\) h\(^{-1}\), respectively.

The stability of the photothermal materials is also essential to assess the performance of the material. Forty repeated evaporation tests were conducted to measure the stability in Figure 4E, all evaporation rates are between 1.99 and 2.26 kg m\(^{-2}\) h\(^{-1}\), which indicates the good stability of our materials.

### 2.2.2 | Feasibility of other PVA/CS composite aerogels

To explore the universality of our method, the graphite powder, TiN powder and MnO\(_2\) powder were also mixed with PVA/CS solution to form aerogels via freeze-drying method, named as PVA/CS/C, PVA/CS/TiN, PVA/CS/MnO\(_2\), respectively. All the photothermal conversion materials show good light absorption ability. The light absorption capacity of PVA/CS/C, PVA/CS/TiN, PVA/CS/MnO\(_2\) aerogels with values of 90.79, 94.15, and 96.21\%, respectively, as showed in Figure 5A. In MTS, the evaporation rates of PVA/CS/C, PVA/CS/TiN, PVA/CS/MnO\(_2\) aerogels obtained by SSG experiments under one sun illumination are 1.96, 2.19, and 2.21 kg m\(^{-2}\) h\(^{-1}\), respectively, in Figure 5B-C. A good combination of mechanical property and hydrophilicity in absorbent aerogels with excellent light absorption ability would be beneficial for enhancing SSG performance.

### 2.3 | Applications of PCC aerogels

Solar steam generation has drawn widely focus on seawater treatment, herein, we prepared the simulated seawater for desalination with PCC\(_{1.5}\) composed aerogel (Figure 6A-B). The average evaporation rate of each sample reached up to 1.24 kg m\(^{-2}\) h\(^{-1}\) under 0.59 suns. The ICP results, used for the quantitative analysis of inorganic elements (Figure 6C), reveals that after the desalination, the concentrations of Na\(^+\), Mg\(^{2+}\), K\(^+\), Ca\(^{2+}\) are not only much less than the amount of ions in the original solution (Table S2), but also up to the World Health Organization (WHO) standards. High ion removal rates simultaneously obtained, corresponding to 99.16, 99.69, 99.32, and 95.63\%, respectively. Furthermore, the desalination cycle tests were also conducted,\(^{[38]}\) as shown in Figure 6D, all the evaporation rates are between 1.97 and 2.06 kg m\(^{-2}\) h\(^{-1}\), too.

Because CuO has excellent bactericidal ability,\(^{[38]}\) we also conducted experiments on the PCC aerogel samples to kill microorganisms in lake water: the aerogel and lake water were co-cultivated for 24 hours at 37\(^\circ\)C, and the
FIGURE 5  A, The UV-Vis-NIR spectra of the PVA/CS/CuO, PVA/CS/C, PVA/CS/TiN, PVA/CS/MnO₂ aerogels in wavelength from 250 to 2500 nm. B, The steam generation performances of PVA/CS/CuO, PVA/CS/C, PVA/CS/TiN, PVA/CS/MnO₂ aerogels under 1 sun illumination. C, The column diagram of evaporation rates of PVA/CS/CuO, PVA/CS/C, PVA/CS/TiN, PVA/CS/MnO₂ aerogel samples

FIGURE 6  A-B, Schematic diagram of condensate collection device using PCC aerogels. C, The salinity of different mineral elements before and after the desalination. D, 10 times cycling desalination performance of PCC₁.₅ under 1 sun irradiation

fluorescence microscope (NA030WD72, China) was used to evaluate bactericidal effect before and after co-cultivation. The desalination experiments results found that the number of microorganisms in the lake water co-cultured with PCC aerogel was significantly reduced (Figure S10).

In addition, we also used the PVA/CS/CuO aerogel to conduct solar evaporation experiments on artificial urine. The experiment was to evaporate artificial urine (XH-001) purchased from Xinheng Technology Co., Ltd., Dongguan, and conduct COD test on the collected condensate (The oxidant in the test was potassium permanganate). The COD results showed that the amount of organic matter in the water after evaporation was about 60 mg L⁻¹, compared with the more than 250 mg L⁻¹ of artificial urine stock (Figure S11).

3  |  CONCLUSION

In this paper, PVA/CS/CuO aerogel materials with photothermal conversion and antibacterial properties have been successfully prepared by freeze-drying method. The size of the material can be customized at will. The PVA/CS/CuO aerogel has the characteristics of low density, good hydrophilicity, stable performance and good light absorption ability in visible light. The influence of hydrothermal temperature on the morphology of CuO, and the influence of the doping amount of CuO on the steam generation rate of PVA/CS/CuO aerogel photothermal conversion material were investigated. The maximum evaporation rate of 2.14 kg m⁻² h⁻¹ was obtained when the addition amount of CuO was 1.5 g. What is even more exciting is that the possibility of combining PVA/CS aerogel with other light-absorbing materials indicated that our composite structural materials and its preparation method have great application prospects.

4  |  EXPERIMENTAL SECTION

4.1  |  Preparation of CuO

CuO in the shape of a rod was prepared by hydrothermal method. CuCl₂ was dissolved in deionized water stirring
for 10 minutes, then NaHCO₃ was added into the solution very slowly to prevent the solution from escaping producing large amounts of carbon dioxide during the reaction, after complete reaction, transferred the mixture into the hydrothermal reactor for 12 hours at the temperature of 180, 230, and 280°C, respectively. After the reaction, the obtained copper oxide turbidity liquid was transferred into the test tube for 2-3 times of centrifugation, and then put into the air-blast drying oven for drying, the dried copper oxide particles could be obtained.

### 4.2 Preparation of CS solution and PVA solution

CS powder was dissolved in aqueous acetic acid solution and then stirred for 12 hours to attain homogeneous CS solution. PVA powder was dissolved in deionized water and then stirred for 30 minutes in water bath at 85°C to attain homogeneous PVA solution.

### 4.3 Preparation of PVA aerogels and CS aerogels

The freeze-drying reaction of PVA aerogels and CS aerogels were obtained by a lyophilizer made in Germany (LGJ-10E). First, 10 mL PVA solution and 10 mL CS solution were stirred in a 25 mL beaker, respectively, then they were transferred into the molds. The PVA aerogels and CS aerogels obtained after 2-hours freezing, and followed with 24-hours drying process.

### 4.4 Preparation of PVA/CS (PC) aerogels

PC aerogels were also freeze-dried by a lyophilizer made in Germany (LGJ-10E). Ten milliliter PVA solution and 10 mL CS solution were weighted and then mixed up in the beaker. After completely stirring, dropped 1 mL glutaraldehyde solution into the PVA/CS mixture, then transferred all of the homogeneous mixtures to a lyophilizer for freeze-drying, the obtained samples were named as PC.

### 4.5 Preparation of PVA/CS/CuO (PCC) aerogels

As shown in Figure S12, a measuring cylinder was used to measure 10 mL PVA solution and 10 mL CS solution into a beaker and stirred evenly. Then, a certain amount of CuO particles (0.5, 1.0, 1.5, 2.0, and 2.5 g) obtained by hydrothermal method was weighed and dispersed in PVA/CS mixed solution. After stirring for 5 minutes, 1 mL glutaraldehyde solution was added and stirred for one minute. Then transferred the above mixture to the poly tetra fluoroethylene molds, put them into the freeze-dryer, after 2-hours freezing, 24-hours drying process, the PVA/CS/CuO composite aerogel was obtained. For reference, the PVA/CuO aerogel and CS/CuO aerogel were also prepared under the same condition without PVA or CS, respectively.

### 4.6 Characterization

The morphology and microstructure of the composed aerogel samples were observed by a Quanta FEG-450 (USA) field emission Scanning Electron Microscope (SEM), and the elements distribution also observed by Energy Dispersive Spectrometer (EDS). The X-ray diffraction (XRD) measurements were conducted on a Bruker D8-ADVANCE (Germany) with Cu Kα radiation. Fourier Transform Infrared (FTIR) spectroscopy was measured by a Bruker Tensor 27 (Germany) with a KBr disc in the range of 400-4000 cm⁻¹. The absorbance of samples from 2500 to 250 nm was measured via a Ultraviolet-Visible-Near-Infrared (UV-Vis-NIR) spectrometer (JASCO V-570, Japan). The absorptivity was calculated by $A = 1 - R - T$, where R and T are the reflectivity and transmissivity, respectively. The absorptivity values of different samples were calculated based on Equation (1).

$$\alpha = \frac{\int_{2500}^{250} [1 - R(\lambda) - T(\lambda)] P_{\text{sun}}(\lambda) d\lambda}{\int_{250}^{2500} P_{\text{sun}}(\lambda) d\lambda}$$ (1)

Here, $P_{\text{sun}}(\lambda)$ represents the normal solar irradiance defined by the ISO standard. The contact angle of the material was collected with a contact angle analyzer (JC2000D1, Powereach Co., China). The surface temperature distribution of each sample was captured by an infrared camera (E60, FLIR, USA.). Inductively coupled plasma atomic emission spectroscopy (ICP-AES, PerkinElmer, Optima 8000, USA.) was used for analyzing the composition of collected water after desalination treatment.

### 4.7 SSG experiment

The SSG experiments were typically conducted at an ambient temperature of 25°C and a relative humidity of about 50%. The aerogel samples were loaded onto a homemade mimetic tree system installed on a high-precision electric balance (Shimadzu, ATX224, Japan), with 0.1 mg resolution to enable real-time recording of the mass loss in
A solar simulator (CEAULIGHT, CEL-S500/350, China) with an AM1.5 optical filter was used as the simulation of the light. A piece of a Fresnel lens (diameter of 20 cm, focal length of 20 cm) was applied to focus the incident light. The power density was calibrated by an optical power densitometer (Newport, 843-R, USA) with a thermopile sensor (Newport, 919P-010-16, USA). The SSG experiment was conducted under 1 kW m\(^{-2}\) illumination for 1 hour testing for three times to calculate the steady evaporation rate. The evaporation rate can be obtained based on Equation (2):

\[
v = \frac{1}{A_{\text{evap}}} \frac{dm}{dt} = \frac{m}{A_{\text{proj}}}
\]

Here, \(v\) represents the evaporation rate (kg m\(^{-2}\) h\(^{-1}\)), \(A_{\text{evap}}\) represents the evaporation area of the sample, and \(t\) represents the lighting time for each test. \(m\) is the change of mass loss of water in the system under illumination (kg m\(^{-2}\)), and \(A_{\text{proj}}\) is the projected area. In the three-dimensional system, the evaporation area is the same as the projected area. The slope obtained by linear fitting the mass loss curve is the evaporation rate. Because the system itself is an open system, the heat exchange is in a dynamic state, so the heat loss is inevitable, heat losses by the three energy transfer modes (i.e., radiation, convection and conduction) were calculated by the following formulas:[18]

\[
P_{\text{rad}} = \varepsilon \sigma (T_2^4 - T_1^4) \tag{3}
\]

\[
P_{\text{conv}} = h(T_2 - T_1) \tag{4}
\]

\[
P_{\text{cond}} = \frac{C_n \Delta T}{tA} \tag{5}
\]

Where, \(\varepsilon\) represents the emissivity of the sample, \(\sigma\) is the Stefan-Boltzmann constant, \(T_2\) is average temperature of the top of absorber, \(T_1\) represents temperature of steam generated around the absorber surface, \(h\) is natural air convection heat transfer coefficient, \(C\) is specific heat capacity of water, \(n\) is water mass, \(\Delta T\) is elevated temperature of water (40 g) within 3600 s, \(t\) is illumination time, and \(A\) is projected area of water container with 40 g water.

The solar thermal conversion efficiency can be summarized as follows:\[5\]:

\[
\eta = \frac{v(C_p \times \Delta T + \Delta H_{\text{evap}})}{q} \tag{6}
\]

Where, \(C_p\) represents the specific heat of water (J kg\(^{-1}\) K\(^{-1}\)), \(\Delta H_{\text{evap}}\) represents enthalpy of evaporation of water (J kg\(^{-1}\)), \(\Delta T\) represents the rising surface temperature in sample surface, \(q\) represents energy density of input (W m\(^{-2}\)).

### 4.8 Antibacterial experiments

Bacterial experiments were obtained by co-culture. Specific implementation method was that a certain amount of PCC\(_{1.5}\) and 10 mL lake water were co-cultured at 37° C for 24 hours. The number of microorganisms in the original lake water and co-cultured lake water were observed under a fluorescence microscope. The whole experiment was kept dry and sterile.

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### Conflict of Interest

The authors declare no conflict of interest.

### Data Availability Statement

Research data are not shared.

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