Supporting Information

Porous dome array evaporator for high-performance photothermal water evaporation and thermoelectric power generation

Boli Nie[a], Weiwei Zhang[a,b*], Xiangyu Dou[b], Yanming Meng[b], Xi Zhao[b], Yan-Chao Wu[a], Hui-Jing Li[a*]

[a] *Weihai Marine Organism & Medical Technology Research Institute, Harbin Institute of Technology, Weihai 264209, P. R. China*
[b] *School of Chemistry and Chemical Engineering, Qufu Normal University, Qufu 273165, P. R. China*

E-mail: qfzhangweiwei@163.com, lihuijing@iccas.ac.cn.

1. Experimental Section

Preparation of 3D SCS:

Sucrose is extracted from sugarcane using traditional techniques. Clean the sugarcane thoroughly and cut it into small pieces. Then, put the juice into a juicer to extract and filter out impurities and solid particles from the juice. Heat the purified juice to evaporate the water and concentrate it into syrup, and then cool it down to allow crystallization and form sucrose crystals. Finally, separate the surcose crystals from the remaining syrup through centrifugation and dry it to obtain sucrose products.

First, add 25~30 g of sucrose in a polytetrafluoroethylene mold (diameter of 4 cm and height of 9 cm), and then add 15 mL of concentrated sulfuric acid to this mold. After stirring for 10 s, the outlet of the polytetrafluoroethylene mold is covered with an iron block weighing 2 kg to obtain porous sulfate carbonate sucrose (Abbreviated as SCS). Next, cool to room temperature and rinse multiple times with deionized water to remove various impurities. Then, soak it in a beaker containing 1 L of deionized water for 24 h to remove SCS from the polytetrafluoroethylene mold. Finally, use an art knife to cut into different heights (0.5~5 cm) and decorate the upper surface with a dome array (3 * 4 array with a diameter of 8 mm) to obtain a 3D SCS evaporator (3.8 cm in diameter). The density of SCS is 0.531 g/cm^3.

Characterizations:

The morphology of SCS was determined by a field emission scanning electron microscope (FESEM, JSM7100F, Japan). The pore structures of SCS was characterized by a mercury porosimeter (Micromeritics AutoPore IV 9500). The composition of sucrose and SCS was examined by X-ray photoelectron spectros copy (XPS, ESCALab 250Xi). The optical absorption (A, %) from 250 to 2000 nm were measured by an ultraviolet−visible−near-infrared (UV−vis−NIR) spectrometer equipped with an integrating sphere (Cary 7000). Fourier transform infrared (FT-IR) was employed to characterize the functional groups of the sucrose and SCS (Nicolet IS 10, USA). Ion concentrations in seawater and condensed water were determined using inductively

coupled plasma-optical emission spectrometry (Aglient-7800, MS, USA). Contact angles were measured by a contact angle meter (Kruss DSA 25, German) via the static sessile drop method. Thermal images were captured by an infrared camera (IR camera, ST9660).

Measurement of thermal conductivity:

The thermal conductivity of dry and wet SCS is measured using the "sandwich method".[1] Place the SCS between two glass slides (1 mm thick, thermal conductivity of 1.05 W m^{-1} K^{-1}) and place it on a thermostatic heating stage. The steady-state temperatures of the three interfaces of the sandwich structure are monitored using a thermocouple and an infrared (IR) camera at a series of heating temperatures. The thermal conductivity of dry and wet SCS can be obtained based on the Fourier equation:

$$q^{''}(\hat{r},t) = - k\nabla T(\hat{r},t)$$

In the equation, $q''(\hat{r},t)$ represents the heat flux, which is the heat flow per unit area of an isothermal surface per unit time in the direction of decreasing temperature gradient. k represents the thermal conductivity of the material. $\nabla T(\hat{r},t)$ is the temperature gradient, which is a vector perpendicular to the isothermal surface.

Performance testing for water evaporation:

During indoor solar evaporation tests, the 2D and 3D SCS was placed in a polytetrafluoroethylene mold (100 mL, 4 cm diameter) with 80 mL of distilled water inside and then irradiated by a solar simulator (CEL-HXF300-T3, China) at a room temperature of ~25 °C. The simulated solar light intensity was measured and calibrated by a THORLABS PM400 optical power meter. The mass changes were monitored by an electronic balance connected to the computer. The surface temperature of the 3D SCS was recorded with the infrared radiation camera (IR camera, ST9660). For the evaporation tests conducted without solar illumination, the positions of the evaporators remained unchanged, but the light source was turned off. All indoor evaporation tests were carried out under consistent environmental conditions, with an environmental temperature of 25 °C and a relative humidity of 45%, as monitored by a temperature and

humidity meter. The outdoor evaporation tests were implemented at the campus. To evaluate the practical desalination performance of 3D SCS, a full-day outdoor simulated seawater desalination test (3.5 wt% NaCl) was conducted from 8:00 to 17:00. In order to reduce the experimental error, we measured each of the same conditions three times and took the average value for analysis.

Performance testing for seawater desalination and wastewater treatment:

To test the purification performance of 3D SCS for seawater desalination and wastewater treatment, it was placed in separate containers filled with different solutions (simulated seawater, 1 M of HCl and NaOH, MB and RhB organic dye solutions), and were continuously irradiated for 1 h under a light intensity of 100 mW cm^{-2}. The simulated seawater, with an average salinity of 3.5 wt% (components: 27.5 g of NaCl, 5.5 g of MgSO$_4$, 0.9 g of KCl, and 1.1 g of CaCl$_2$ in 1 L of deionized water). The condensed water after evaporation was collected, and its water quality was tested. For the seawater desalination experiment, an Inductively Coupled Plasma Emission Spectrometer (ICP-ES) was used to determine the concentrations of major ions (Na$^+$, Mg^{2+}, K$^+$, Ca^{2+}) in both simulated seawater and the condensed water collected after evaporation. For the purification of acidic and alkaline wastewater, a pH meter was used to accurately measure the pH of the condensed water collected before and after evaporation. To simulate the purification of organic wastewater, dye solutions of MB and RhB were prepared with a concentration of 20 mg L^{-1}. An UV-Vis spectrophotometer was used to accurately measure the organic content of the condensed water collected before and after evaporation.

Analysis of the photothermal conversion efficiency and equivalent evaporation enthalpy

The photothermal conversion efficiency of 3D SCS was calculated by the following formula:

$$\eta = \frac{m\Delta H_{equ}}{C_{opt}P_o} \tag{1}$$

where m is the mass flux, ΔH_{equ} defines the equivalent evaporation enthalpy of water in SCS, P_o is the solar irradiation power of 1 sun (1 kW m^{-2}), and C_{opt} refers to the optical concentration on the absorber surface. Due to the higher evaporation rate of 3D SCS than the theoretical value (1.5 kg m^{-2} h^{-1}), if the corresponding enthalpy of water evaporation at 42.3~57.8 °C is used, the evaporation efficiency of 3D SCS will be higher than 1. To get the ΔH_{equ} of water in 3D SCS in this study, the evaporation experiments in the dark environment are conducted overnight following the instruction of Zhao et al.'s work.[2] The ΔH_{equ} of water in 3D SCS can be estimated by evaporating water under dark condition assuming identical power input (U_{in}):[2-4]

$$U_{in} = \Delta H_{vap}m_o = \Delta H_{equ}m_g \qquad (2)$$

where ΔH_{vap} and m_o are the evaporation enthalpy and evaporation rate of water under the dark condition, m_g is the evaporation rate of 3D SCS within the same environmental condition. In this study, the values of ΔH_{vap} and m_o are 2450 kJ kg^{-1} and 0.130 kg m^{-2} h^{-1} respectively. The m_g values and the calculated ΔH_{equ} values were displayed in Table S4.

COMSOL simulation of relative water pressure in the 3D SCS

In order to investigate relative water pressure in the microstructural range of 3D SCS, taking into account the restriction of capillary channels on water, the relative water pressure of 3D SCS can be described by the following formula:[5]

$\rho \nabla \cdot u = \nabla \cdot [-pI + K] + F$

$\rho \nabla \cdot u = 0$

$K = \mu(\nabla u + (\nabla u)^T)$

$0 = \nabla[-pI + K] + F + \rho g$

In the equation, ρ represents density, **u** is the velocity vector, p is the relative water pressure, I is the second-order unit tensor, **K** is the viscous stress tensor, F is the gravity of water, μ is the viscosity of water, and T is the water temperature.

COMSOL simulation of salinity in the 3D SCS

In order to simulate the diffusion and convection of salt ions within the microstructure of 3D SCS and observe the distribution of salt concentration in different parts of the SCS,

we simulated the internal mass transfer process of the 3D SCS, which can be described by the following equation:[5]

$$\nabla \cdot J_j + u \cdot \nabla c_j = R_j$$

$$J_j = - D_j \nabla c_j$$

In the equation, $\mathbf{J}_j$ represents the mass flux relative to the mass-averaged velocity, $\mathbf{u}$ is the mass-averaged velocity vector, c_j is the concentration of the substance, R_j is the reaction rate expression for the substance, and D_j is the diffusion coefficient. The salt concentration in the water below is set to 15 wt%.

Performance testing of thermoelectric power generation:

Select the thermoelectric (TE) module (TEP1-097T200, 20X40mm) as the power generation device. Cut a curved 3D SCS with a height of approximately 1.0 cm and assemble it onto the upper surface of the TE module, with its two walls connected to a large amount of seawater (3.5% NaCl). The 3D SCS covers the upper side of the TE module in an arched shape. With the aid of the foam frame, the lower side of the TE module is just immersed in a large volume of water (3.5 wt% NaCl), where the two walls of the 3D SCS are in contact with a large amount of water (Figure 6a). A digital multimeter (VC890C) was used to measure the open circuit voltage and load current of the thermoelectric. To estimate the theoretical maximum output power of the TE-evaporator, its output current was measured using a multimeter with an external load resistance of 2 Ω. Then, according to the formula P = I^2 * R, the output power is obtained. All tests were carried out under consistent environmental conditions, with an environmental temperature of 25 °C and a relative humidity of 45%.
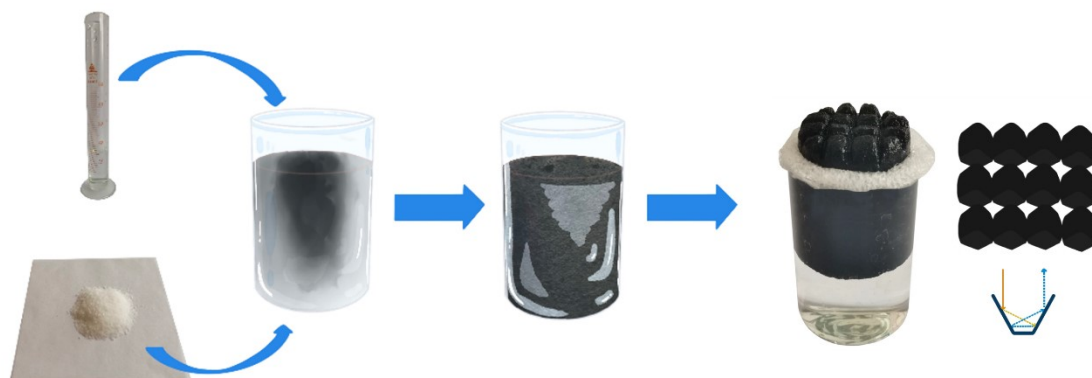
2. Supplementary Figures

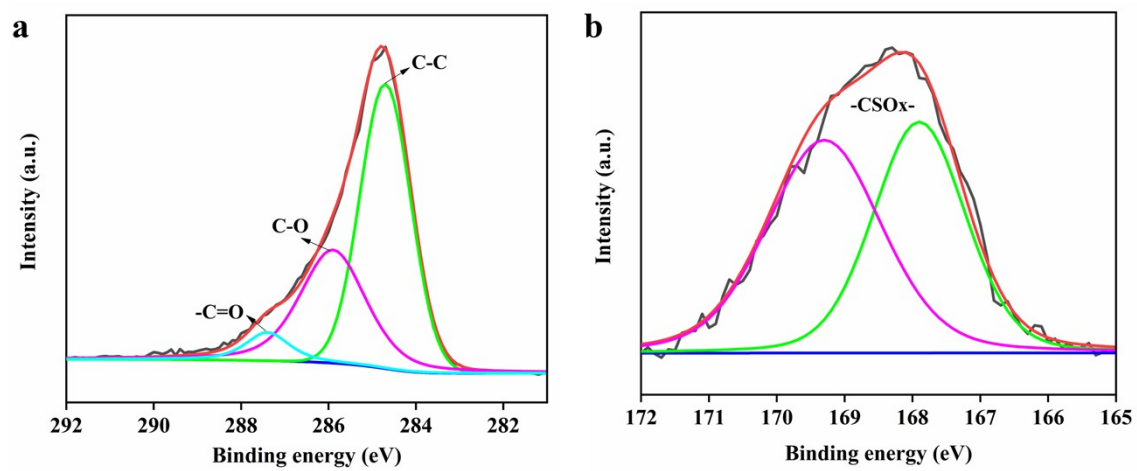**Figure S1** Preparation process diagram of 3D SCS evaporator.

Figure S2 High-resolution XPS spectra of a) C1s and b) S2p spectra for 3D SCS.
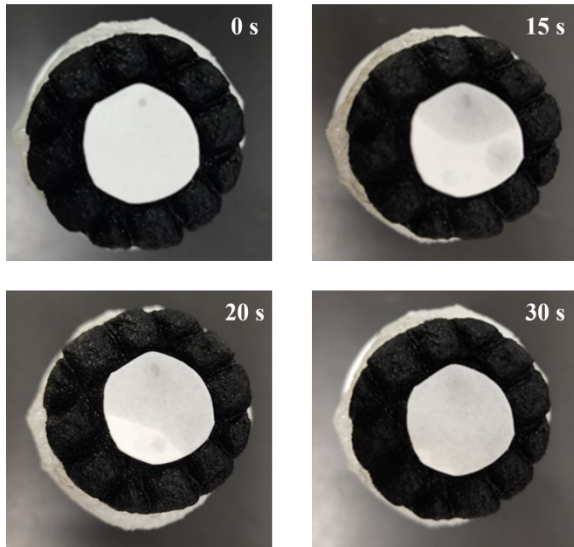
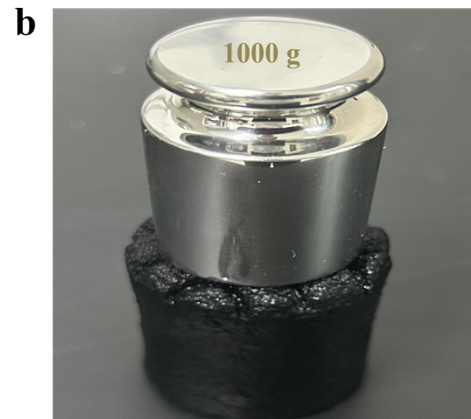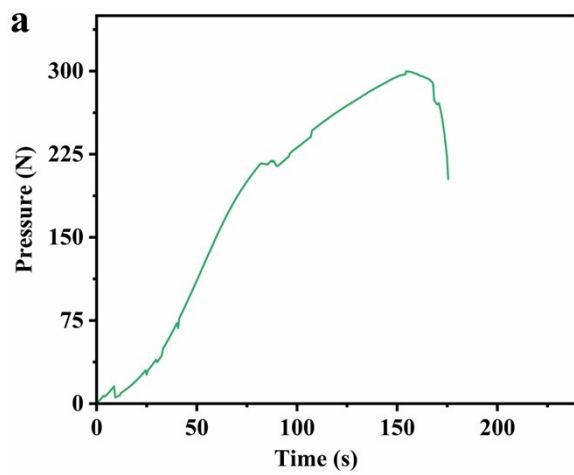**Figure S3** The optical photographs of the wetting process for 3D SCS.

Figure S4 a) Pressure versus time curve for 3D SCS and b) Photos of 3D SCS supporting a load of 1000 g for 1 h.
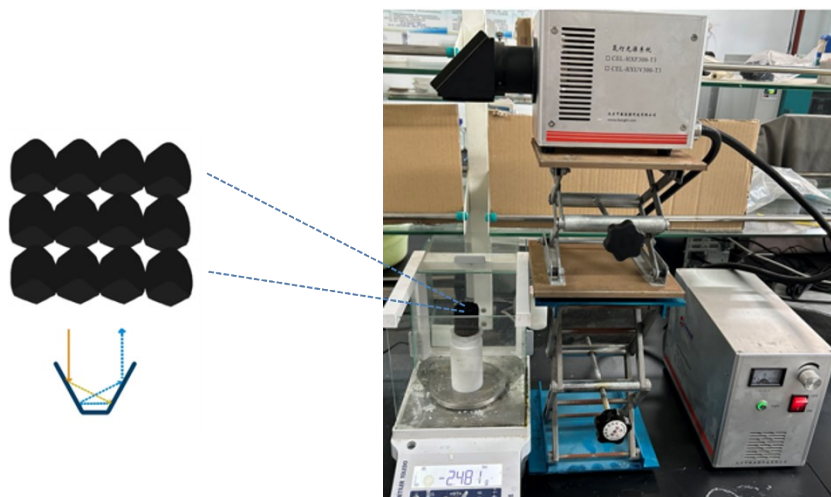
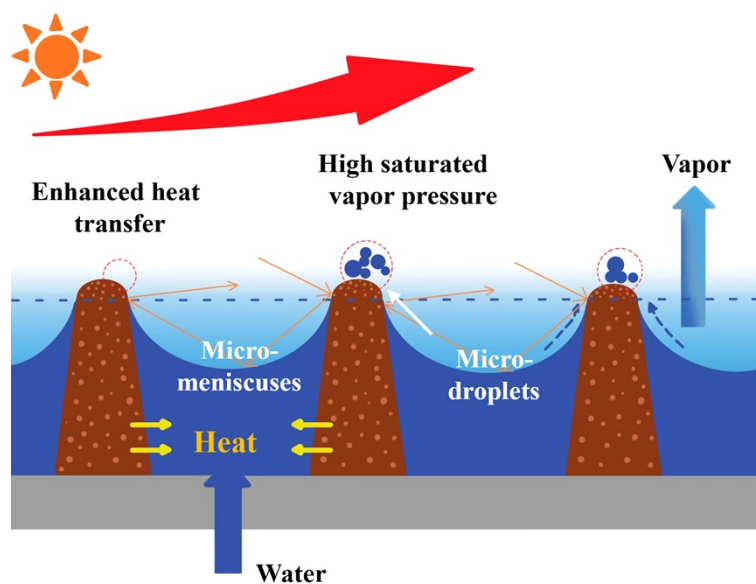**Figure S5** Schematic diagram of indoor evaporative water driven by solar energy.

Figure S6 The structure of the solar evaporator based on 3D SCS array, in which porous dome array greatly enhanced the evaporation performance.
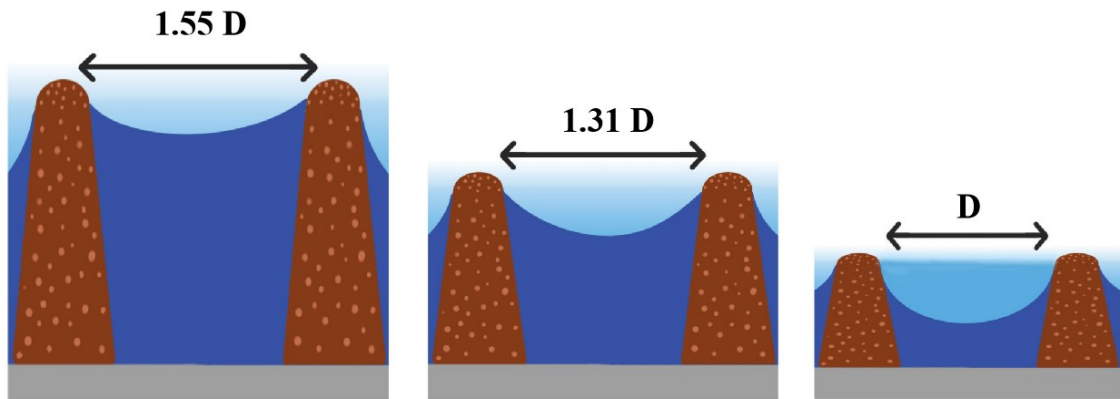
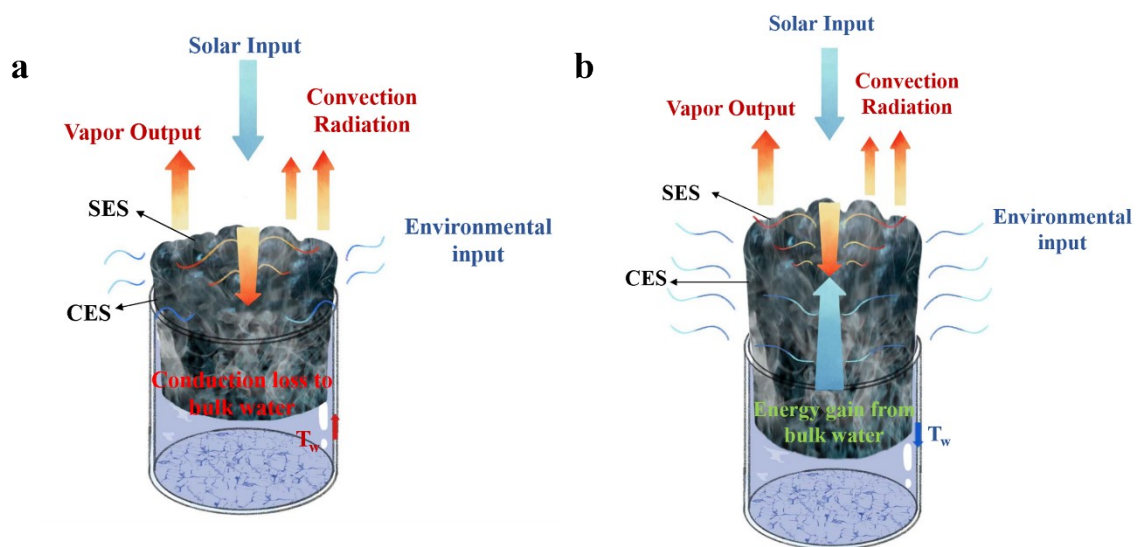**Figure S7** Schematic diagram of the variation of meniscus diameter with the height of 3D SCS array.

Figure S8 Schematic illustration of the heat conduction between the SES, CES and bulk water of cylinder evaporator with a small and large CES.
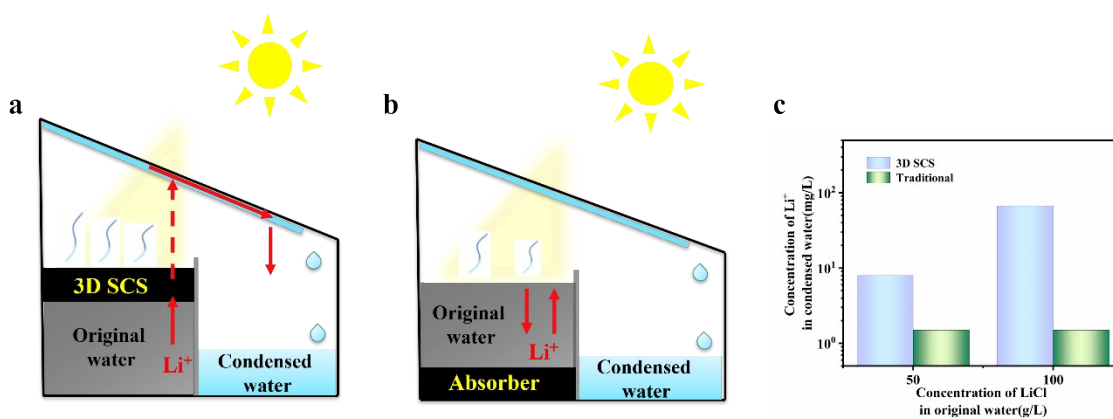
Figure S9 The experimental setup of a) 3D SCS-based evaporation and b) traditional evaporation. c) The concentration of Li^+ in condensed water from different LiCl solutions 3D SCS-based evaporation and traditional evaporation.
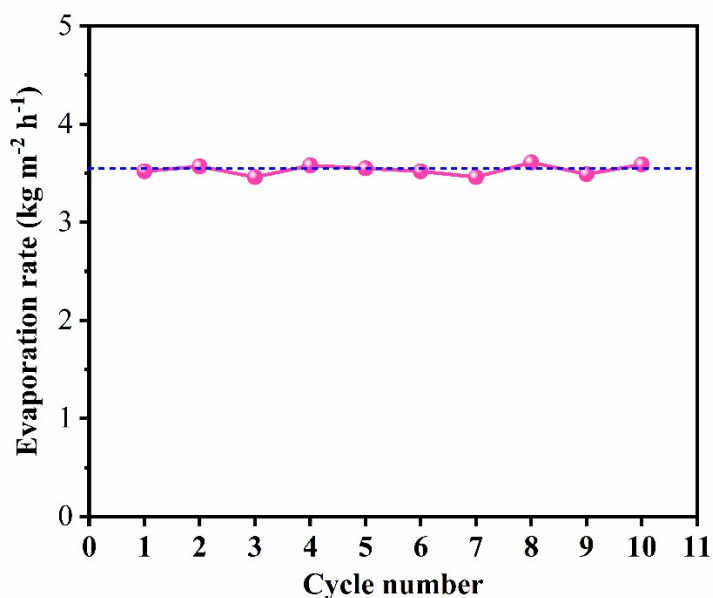

Figure S10 Repeated evaporation performance of 3D SCS for 10 cycles in 1 h under one sun illumination.

Note: After each cycle test is completed, deionized water is injected into the evaporator to fully wet the entire surface. Then, using a spraying method, deionized water is circulated inside the evaporator for half an hour to thoroughly clean the surface and interior of the evaporator.
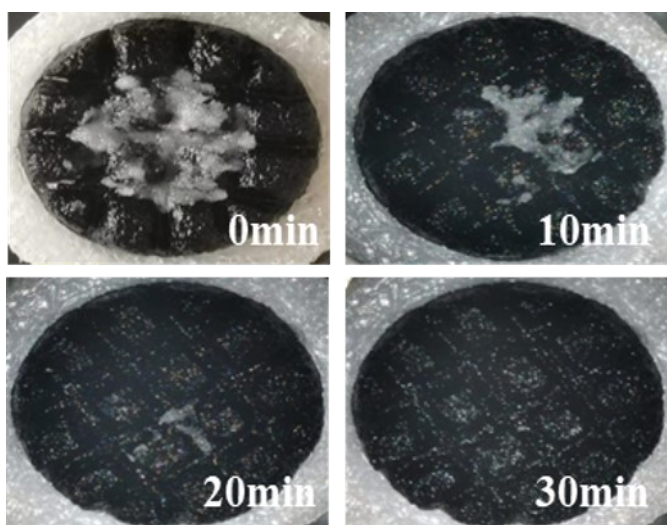
Figure S11 The self-desalination ability of 3D SCS with the presence of 0.5 g NaCl under one sun.
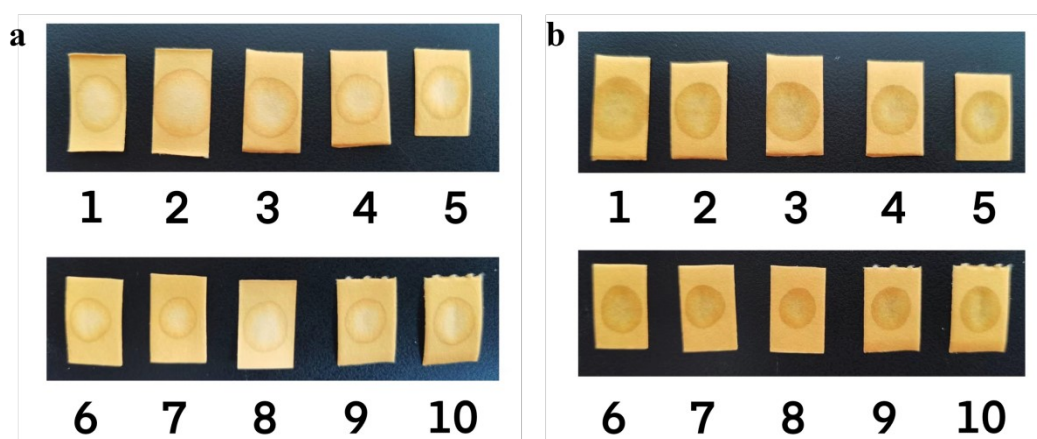

Figure S12 The pH value of 3D SCS evaporated water was repeatedly evaporated for 10 cycles in 1 M HCl a) and 1 M NaOH solutions under one sunlight exposure.

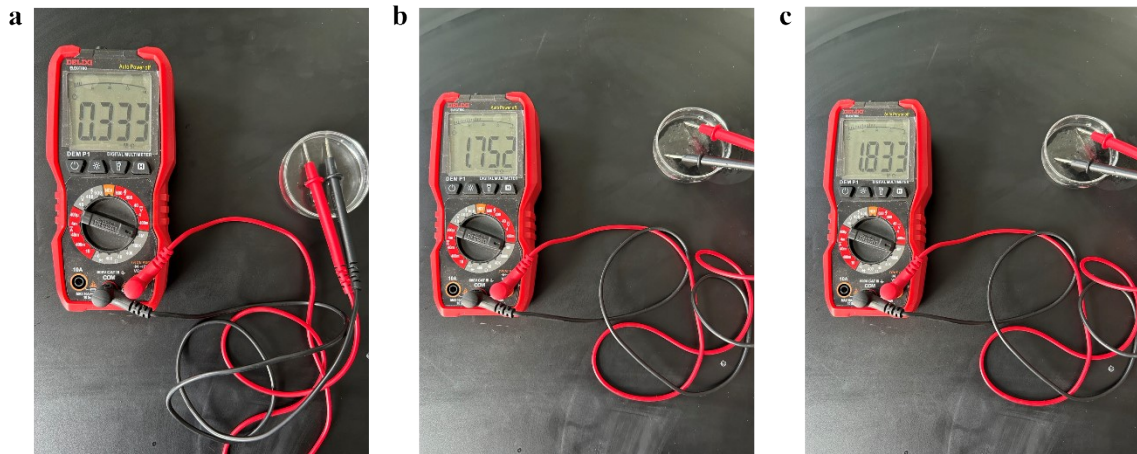**Figure S13** The resistance values of a) simulated seawater, b) domestic water, and c) condensed water.
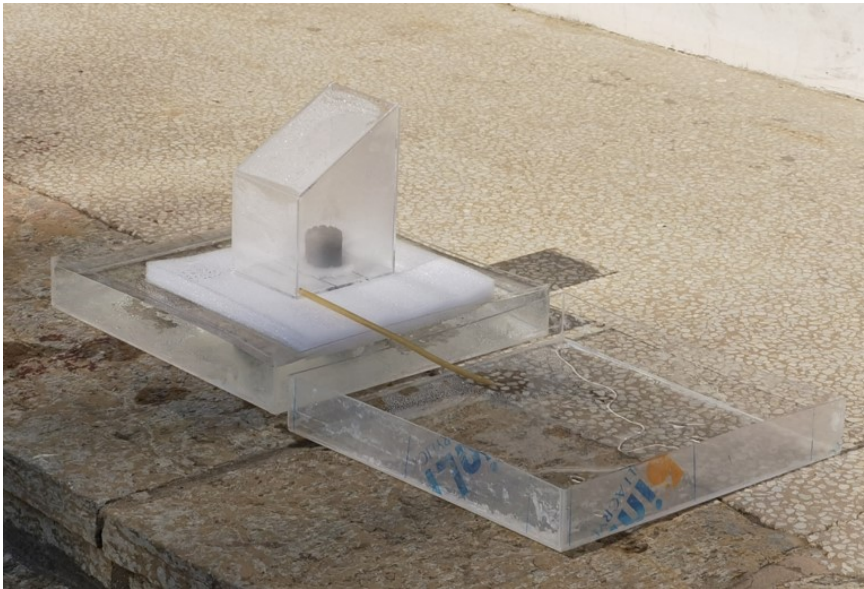

Figure S14 The outdoor desalination test based on 3D SCS.
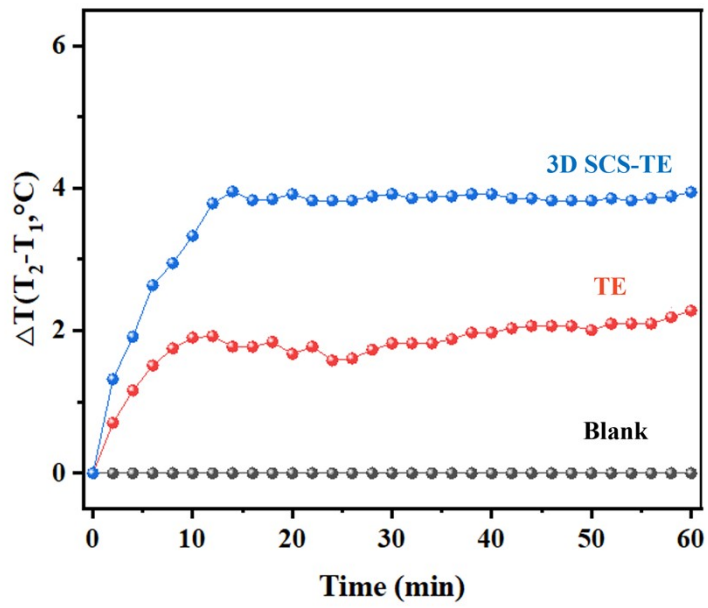
Figure S15 The temperature difference change between the top and bottom of the TE module.
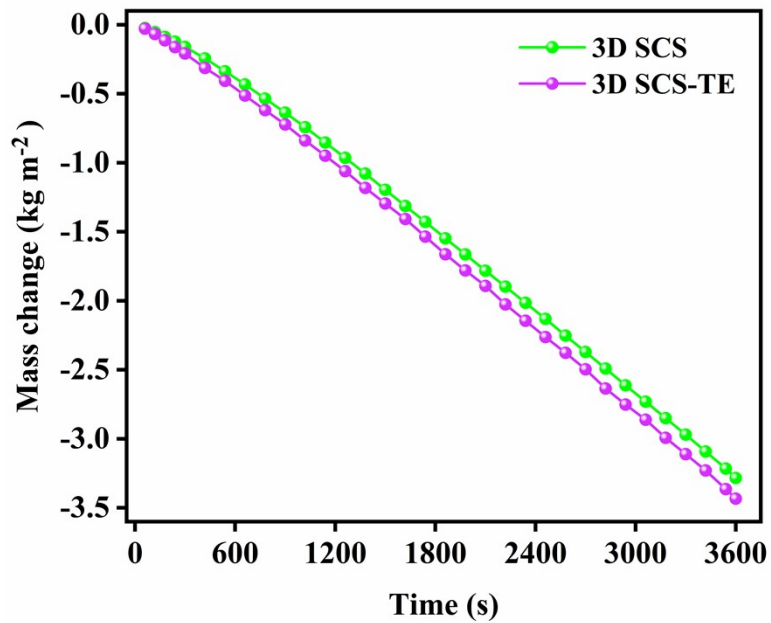
Figure S16 Water mass variation with time for 3D SCS evaporators with and without TE modules under one light intensity and simulated sea water.

Table S1 The evaporation rate of 3D SCS under different number of arrays.

Number of arrays	1*1	2*2	3*3	3*4
Evaporation rate (kg m^{-2} h^{-1})	2.21	2.38	2.56	2.75

Table S2 The evaporation rate of 3D SCS under different height of arrays (3*4 array).

Number of arrays	0.1 cm	0.2 cm	0.3 cm	0.4 cm	0.5 cm
Evaporation rate (kg m^{-2} h^{-1})	2.45	2.55	2.69	2.75	2.72

Table S3 The evaporation rate of 3D SCS under different spacing of arrays (3*4 array; 0.4 cm height).

Number of arrays	1 mm	2 mm	3 mm	4 mm	5 mm
Evaporation rate (kg m^{-2} h^{-1})	2.72	2.75	2.71	2.65	2.58

Table S4 The calculated conduction flux between 3D SCS and bulk water.

Evaporator height (cm)	0.5	1	2	3	4	5
Initial T_W (°C)	23.5	23.4	23.5	23.4	23.4	23.5
Stable T_W (°C)	24.6	24.3	23.9	23.5	23.3	23.3
Initial water weight (g)	59.586	59.108	58.927	59.207	59.394	59.612
Stable water weight (g)	56.468	55.695	55.276	55.363	55.391	55.643
Conduction flux (W)	-0.074	-0.060	-0.027	-0.007	0.007	0.013

Calculation of heat conduction:

The conductive heat was calculated by the following formula

$$Q = Cm\Delta T \tag{3}$$

Q is the heat exchange between the bulk water and the evaporator;

C is the specific heat of the bulk water (4.2 J g^{-1} K^{-1});

m is the average mass of the bulk water before and after evaporation;

ΔT is the temperature change of the bulk water during evaporation.

Table S5 Convection and radiation loss of SES during solar evaporation under 1.0 sun.

3D SCS height (cm)	0.5	1	2	3	4	5
Ambient temperature (℃)	25.0	25.0	25.0	25.0	25.0	25.0
Area of SES (10^{-3} m²)	1.134	1.134	1.134	1.134	1.134	1.134
Stable T_{SES} (℃)	57.8	52.0	48.5	45.7	42.5	42.3
Convection flux of SES (W)	0.186	0.153	0.133	0.117	0.099	0.098
Radiation flux of SES (W)	0.243	0.195	0.166	0.145	0.120	0.119

The convection and radiation flux were calculated by the following formulas:

$$q_{con} = Ah(T_{SES} - T_E) \tag{4}$$

$$q_{rad} = A\sigma\epsilon(T_{SES}^4 - T_E^4) \tag{5}$$

A is the area of the SES in m^{-2};

h is the convection heat transfer coefficient in W m^{-2} K^{-1}; In this study, $h = 5$ W m^{-2} K^{-1};

σ is the Stefan-Boltzmann constant i.e. $5.67 * 10^{-8}$ W m^{-2} K^{-4};

ϵ is the emissivity of material; In this study, $\epsilon = 0.924$;

T_{SES} is the average stable temperature of the SES;

T_E is the ambient temperature (25 °C).

Table S6 Convection and radiation energy gain of CES from the environment during solar evaporation under 1.0 sun.

3D SCS height (cm)	1	2	3	4	5
Ambient temperature (°C)	25.0	25.0	25.0	25.0	25.0
Area of CES (10^{-3} m²)	1.193	2.386	3.580	4.773	5.966
Stable T_{CES} (°C)	23.6	22.8	21.9	21.2	21.1
Convection flux of CES (W)	-0.008	-0.026	-0.055	-0.091	-0.116
Radiation flux of CES (W)	-0.009	-0.029	-0.061	-0.099	-0.127

$T_{CES} = 1/3\ (T_{top} + T_{middle} + T_{bottom})$

T_{top}, T_{middle} and T_{bottom} represent the average surface temperature of top, middle and bottom of the CES during solar evaporation.

Table S7 Evaporation enthalpy results from dark experiment.

	Pure water	3D SCS 1 cm	3D SCS 2 cm	3D SCS 3 cm	3D SCS 4 cm	3D SCS 5 cm
Evaporation rate (g m^{-2} h^{-1})	130	289.2	304.3	316.7	326.7	323.3
Enthalpy (J g^{-1})	2450	1101.3	1046.7	1005.7	974.9	985.2

The ΔH_{equ} of water in 3D SCS can be estimated by evaporating water under dark condition assuming identical power input (U_{in}):

$$U_{in} = \Delta H_{vap} m_o = \Delta H_{equ} m_g$$

where ΔH_{vap} and m_o are the evaporation enthalpy and evaporation rate of water under the dark condition, m_g is the evaporation rate of 3D SCS within the same environmental condition. In this study, the values of ΔH_{vap} and m_o are 2450 kJ kg^{-1} and 0.130 kg m^{-2} h^{-1} respectively.

References

[1] X. Liu, Z. Liu, D. D. Mishra, Z. Chen, J. Zhao, C. Hu, *Chem. Eng. J.* **2022**, *429*, 132335.

[2] F. Zhao, X. Zhou, Y. Shi, X. Qian, M. Alexander, X. Zhao, S. Mendez, R. Yang, L. Qu, G. Yu, *Nat. Nanotechnol.* **2018**, *13*, 489.

[3] Y. Guo, H. Lu, F. Zhao, X. Zhou, W. Shi, G. Yu, *Adv. Mater.* **2020**, *32*, 1907061.

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