Biomass-based biomimetic-oriented Janus nanoarchitecture for efficient heavy-metal enrichment and interfacial solar water sanitation

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Abstract
Interfacial solar steam generation (ISSG), involving the use of solar energy to evaporate water at the water-to-vapor interface, has presented prospects for the desalination and purification of water due to high energy conversion efficiency and low-cost freshwater generation. Herein, inspired by the aligned nanostructure of plants for efficiently transporting nutrient ions, we optimally design and construct a biomass-based Janus architecture evaporator with an oriented nanostructure for ISSG, using the ice template method, followed by biomimetic mineralization with the resource-abundant and low-cost biomass of the carboxymethyl cellulose and sodium alginate as the raw materials. Taking advantage of the oriented nanostructure allowing efficient transportation of water and coordination capacity of sodium alginate for effective enrichment of heavy-metal ions, the biomass-based Janus architecture shows much lower thermal conductivity and an ultrahigh steam regeneration rate of 2.3 kg m⁻² h⁻¹, considerably surpassing those of previously reported oriented biomass-based evaporators. Moreover, the biomass precursor materials are used for this Janus evaporator, guaranteeing minimum impact on the water ecology and environment during the regeneration process of clean drinking water. This study presents an efficient, green, and sustainable pathway for ISSG to effectively achieve heavy-metal-free drinking water.
1 | INTRODUCTION

Nowadays, the freshwater crisis has become a pervasive issue affecting more than 100 countries worldwide.\(^1\) Since the main difference between freshwater resources and sewage lies in the solutes (or impurities) in water, the complete separation of water and solution is deemed the ultimate goal for water regeneration. It is widely believed that seawater desalination can certainly mitigate the water shortage problem.\(^2\)\(^–\)\(^5\) Although numerous strategies, such as continuous microfiltration and reverse-osmosis technologies, have been used for seawater desalination, it is not omnipotent especially in the non-coastal or energy-scarce areas.\(^6\)\(^–\)\(^10\)

Learning from nature, elaborately designed interfacial solar steam generation (ISSG) systems with black materials have been optimally developed for use in oil/microbe water separation or seawater and sewage treatment that show excellent potential for future industrialization.\(^11\)\(^–\)\(^26\)

Recently, it has been reported that heavy-metal wastewater can be purified to meet the demand for clean water by the ISSG technology using a hydrogel.\(^27\)\(^,\)\(^28\) However, there is still a long way to go toward achieving both efficient heavy-metal enrichment and clean drinking water production simultaneously, because the solar–thermal conversion efficiency and steam generation need to be further boosted. Previous studies have mainly focused on the use of various components instead of nanostructure engineering, which hinders the improvement of photothermal efficiency. Therefore, construction of an ISSG with a rationally designed nanostructure is important to improve solar–thermal conversion efficiency and to also efficiently remove heavy-metal ions as well as produce clean drinking water.

In natural plants, water and nutritional ingredients are transported from the soil to the roots and leaves through oriented nanostructures in the stem during the photosynthesis process; meanwhile, some water is converted into steam through phase transformation by consumption of solar energy.\(^29\) Herein, inspired by the function of oriented nanostructures of enhancing the transportation of water and metal ions in natural plants (Figure 1), we develop a biomass-based Janus architecture with bionic-oriented pore nanostructures as an ISSG evaporator for the production of clean drinking water; the lower part is composed of a calcium-solidified carboxymethyl cellulose/sodium alginate (CCA) nanocomposite and the upper part is composed of CCA blended with a polymeric layer (CCAP). The CCA nanocomposite is prepared using an ice template method, followed by biomimetic mineralization with all biomasses as components, including carboxymethyl cellulose and sodium alginate, in which the oriented pores and functional groups of hydrophilic polyhydroxy not only facilitate water transportation and salt resistance but also promote the exchange and enrichment of heavy-metal ions in the bulk evaporator. Under the synergistic action of the high absorbance of CCA and the efficient convection promoted by oriented pores in this unique biomimetic architecture, the evaporator achieves a remarkable solar absorption of 98% and a low interfacial water vaporization enthalpy of 1475.7 J g\(^{-1}\), thus resulting in a high solar–thermal conversion efficiency of 93% and rapid steam generation of 2.3 kg m\(^{-2}\) h\(^{-1}\). As a whole, this study demonstrates that a biomass-based Janus architecture with bionic-oriented pore nanostructures can be used to construct an evaporator for enrichment of heavy-metal ions during ISSG by mimicking the pore structures in natural trees. This technology can pave the way toward heavy-metal enrichment during sewage regeneration.

2 | EXPERIMENTAL SECTION

2.1 | Preparation of the CAP-CA biomass-based Janus architecture

Liquid nitrogen was poured into an insulated open container. The lower part of the copper block was immersed in liquid nitrogen, and the upper part was exposed to room-temperature air. A polydimethylsiloxane mold was placed on
the surface of a room-temperature copper plate, and then half of the mold was filled with carboxymethyl cellulose/sodium alginate (CA) solution and placed on a low-temperature copper block for orientation freezing. After the CA solution was completely frozen, the CA coated with a polypyrrole layer (CAP) solution was poured and the other half of the mold was filled. After the CAP solution was completely frozen, the CAP-CA Janus nanoarchitecture was obtained by freeze-drying over 4 days.

2.2 Preparation of the CCAP-CCA biomass-based Janus architecture

First, 4.44 g of CaCl₂ powders were dissolved in 200 ml of absolute ethanol. Then, CAP-CA Janus artificial nanoarchitectures were immersed in a CaCl₂ ethanol solution for 2 days. Later, CCAP-CCA Janus nanoarchitectures were collected by drying at 80°C overnight.

2.3 Evaporation performance evaluation

The rate of solar steam generation was recorded using an electronic analytical balance (MTL-MS204, 0.1 mg in accuracy) and real-time communicated to a computer. The surface temperature, the steam temperature, and the temperature distribution of the evaporation system were determined using a thermal imaging camera. The solar steam generation performance was assessed using a Xenon Light Source (PLS-SXE300D/300DUV; PerfectLight) outputting a simulated solar flux of 1 sun at 1000 W m⁻². The solar flux was monitored using a thermopile connected to a power meter (PL-MW2000; PerfectLight). All samples were placed in a hole of 3.80 cm² in the middle of a closed-cell foam, and the upper area of the remaining part was fully covered with a metal foil to reflect the solar irradiation. A long glass tube was placed to restrict the air convection. All the evaporation rates of each sample were determined on the basis of the mass change over 1 h after quiescence in a dark room for 30 min, and the ambient temperature and relative humidity were maintained at 25°C and 30%, respectively. The mass of water evaporated in a dim room was subtracted from the total mass changes when evaluating the energy efficiency. [30]

3 RESULTS AND DISCUSSION

3.1 Material design and fabrication strategy

The biomass-based Janus architecture with a biomimetic-oriented nanostructure is constructed using the orientated ice template method, followed by calcification (Figure 2). First, a mixed solution of carboxymethyl cellulose and sodium alginate (Supporting Information: Figure S1A)
was freeze-cast upon flat copper to prefabricate the framework of this biomimetic architecture with parallel channel structures. Then, the upper part of this Janus architecture was prepared by in situ coating polypyrrole on the top surface of the as-prepared biomimetic architecture framework, while the lower part was fabricated using an ion-exchange method to form a cross-linking network by soaking the prepared framework in an alcohol solution containing calcium ions. Later, the prepared sample was freeze-dried in a cold trap. Using the above methods, a well-defined Janus architecture with a biomimetic-oriented nanostructure was optimally constructed.

For the upper part of this biomimetic architecture, after polymerization of pyrrole using ammonium persulfate for oxidation, the cellulose/sodium alginate/polypyrrole composite appears black in color (Supporting Information: Figure S1A,B). On observing the cross-section of this sample, in terms of the morphology of the interface between CA and CAP, the upper part was coated with polypyrrole because the polypyrrole grew along the orientation of the biomimetic architecture framework (Supporting Information: Figure S1C–E). For the lower part of this biomimetic architecture, to construct a molecular cross-linking network and enhance the stability in water, an ion-exchange strategy was applied and there was exchange of calcium ions in the alcohol solution with sodium ions in sodium alginate, thus forming a cage-like complex. Due to the parallel porous structure of this biomimetic architecture framework (Supporting Information: Figure S2), the ion exchange can be carried out completely through the inner surface of the pores.

X-ray diffraction (XRD) patterns (Figure 3A) further reveal the synthesis process of the biomimetic Janus architecture by the phase composition changes. Compared to the typical wide peak of sodium alginate in CA, the typical peak of Na2SO4 appears in the CAP, which is crystalline salt consisting of the sulfate ions from the reduction product of ammonium persulfate and sodium ions from sodium alginate. Meanwhile, CCA contains NaCl, indicating that a substitution reaction occurs during the calcification process with sodium ions from sodium alginate and calcium ions. Besides, some calcium

**FIGURE 2** Preparation and morphology of the biomass-based Janus architecture. (A) Schematic diagram of the fabrication process of the Janus architecture of CCAP-CCA. (B) Scanning electron microscope images of the cross-section of CCAP-CCA (middle) and magnified images of the bionic porous structure (left for CCAP and right for CCA). Scale bar = 50 μm. CCA, calcium-solidified carboxymethyl cellulose/sodium alginate; CCAP, CCA coated with a polypyrrole layer.
sulfate and Na$_2$Ca$_5$(SO$_4$)$_6$ crystals are formed during the preparation of CCAP owing to their low solubility.

The components of the biomimetic Janus architecture have a huge influence on their anti-solubility behaviors. As shown in Supporting Information: Figure S3, the biomimetic Janus architecture with sodium alginate and carboxymethyl cellulose at a ratio of 1:1 is relatively stable when immersed in an aqueous solution. It is presumed that decreasing the content of sodium alginate will lead to a low degree of cross-linking of the calcium alginate network in the as-prepared architecture, while decreasing the content of carboxymethyl cellulose will weaken the structural strength and stability, resulting in the collapse of the porous structure in the aqueous solution. Due to this well-designed component with a bionic-oriented structure (Supporting Information: Figure S4), the prepared biomimetic Janus architecture still shows a monolithic structure after immersion in an aqueous solution from 5 h to over 10 days, suggesting that this method significantly improves the stability of the composites (Figure 2B and Supporting Information: Figure S5).

3.2 | Structural characterizations and analysis

The functional groups of the as-prepared biomimetic Janus architecture were investigated by Fourier transform infrared spectroscopy (FTIR). In the FTIR spectra (Figure 3B), these peaks at 1726 and 1543 cm$^{-1}$ are assigned to the C–N stretching peak and the ring stretching peak of PPy, revealing the existence of PPy particles in the biomimetic Janus architecture. X-ray photoelectron spectroscopy further confirms the chemical composition and molecular structural features of the architecture (Supporting Information: Figure S6A). The characteristic peak located at 347.7 eV is attributed to Ca$_2$p (Supporting Information: Figure S6B), indicating the existence of calcium in CCA and CCAP and the successful calcification of CA and CAP. The peak of C1s at 286 eV in the scan spectra of the biomimetic Janus architecture (Figure 3C) was fitted and divided into several peaks. Their position, area ratio, and the corresponding bonds are listed in Supporting Information: Table S1. The peaks at 288.1, 286.5, and 284.8 eV were allocated to the carbon in O–C–O (C1S1), O–C–C (C1S2),
and C–C–C (C1S3), respectively. The peaks that appeared at −289.2 eV are assigned to polypyrrole–C in CAP and CCAP, indicating the existence of the PPy component in the biomimetic Janus architecture (Figure 2B), which is further confirmed by the peaks of nitrogen that appeared in CAP and CCAP (Supporting Information: Figure S6C).

To further demonstrate the features of the as-prepared biomimetic Janus architecture, mechanical compression strength tests were conducted. The tangential and radial compressive stress–strain curves (Figure 3D and Supporting Information: Figure S7) show that the structural strength of the architecture after calcification was improved markedly, 10-fold, which is attributed to the crosslinking network of calcium alginate formed in CCA and CCAP. Although CA after doping PPy and calcification shows slightly decreased compressive strength, a stable structure is still maintained.

Thermogravimetry analysis (TGA) in air flow was performed to investigate the thermal stability. TGA curves (Figure 3E) show that the process involves three zones: the hygroscopicity part (removal process of free and intermediate water) marked in blue, the thermo-stability part (removal process of crystal water) marked in white, and the decomposition part (removal process of the hydroxyl group) marked in pink. On comparing these curves in the hygroscopicity part, it is evident that the free and intermediate water in CCA, CCAP, CA, and CAP is ranked from high to low, which suggests that the calcified architecture has much higher moisture absorption, while the doped PPy slightly affects hygroscopicity. These curves in the thermo-stability part demonstrate that the calcifying and PPy doping treatment significantly improved the thermal stability of CA from 140°C to 168°C and 230°C, respectively. The nitrogen physisorption isotherm (Supporting Information: Figure S8A) for the as-prepared biomimetic Janus architecture suggests that its Brunauer-Emmett-Teller surface area changes only slightly compared to CA, CAP, CCA, and CCAP. The pore size distribution (Supporting Information: Figure S8B) also shows that it has many mesopores and macropores, which are useful for mass transport during their application.

3.3 Performance of interfacial solar–thermal conversion steam generation

The biomimetic Janus architecture has the same parallel cross profile structures as natural wood, which can capture sunlight by increasing the optical path and reducing reflection. After doping with pyrrole, CAP and CCAP have high broadband absorption with an absorptance of 95%–98% in a wide wavelength range of 250–2500 nm (Figure 4A and Supporting Information: Figure S9). Compared to natural wood, the as-prepared biomimetic Janus architecture, such as CCAP, has a lower thermal conductivity of 0.0328 W m⁻¹ K⁻¹, which is useful to improve the solar–thermal conversion efficiency (Figure 4B).[31] The equilibrium temperature curves (Figure 4C) of CAP and CCAP show excellent solar–thermal performance and the temperature of their black upper surface can quickly increase to 60°C under 1 sun illumination, which is 22°C higher than that of CA and CCA (38°C; Supporting Information: Figure S10A).

It is noteworthy that we have performed accurate experiments and characterizations to measure the thermal conductivity of the CCA gel, the CCAP gel, and the CCAP aerogel after immersed in water. As shown in Supporting Information: Figure S10B, the thermal conductivity of the CCA gel (606 mW m⁻¹ K⁻¹) and the CCAP gel (619 mW m⁻¹ K⁻¹) is slightly different from that of pure water (683 mW m⁻¹ K⁻¹), whereas the thermal conductivity of the CCAP aerogel (617 mW m⁻¹ K⁻¹) after immersed in water decreased to 550 mW m⁻¹ K⁻¹, which confirms that the CCAP aerogel contributes toward better thermal regulation performance in water than the same materials without a bionic-oriented structure. Furthermore, both CCA and CCAP can absorb water droplets in a very short time (Figure 4D) and have a very high water saturation capacity ratio (about 22.2 and 19.4 times their own weight). This suggests that they are superhydrophilic, with excellent water absorption (Supporting Information: Figure S11), which is owing the increase in the content of saturated water due to the interpenetrating network in the biomimetic Janus architecture.[32]

To estimate the equivalent vaporization enthalpy of water in the bio-inspired Janus architecture, water evaporation rate in the dark were further tested (Supporting Information: Figure S12). The test results (Supporting Information: Figure S13A) indicate that the water evaporation rate in the CCAP with various compositions is much higher than that in the CCA with only the hydrophilic component. Since the energy sources in the dark room, including mainly thermal convection and conduction at the gas–liquid interface, are equivalent, the equivalent vaporization enthalpy is represented by the equation given below:

\[ E_v = \frac{m_w E_w}{m_e}, \]  

where \( m_e, m_w, \) and \( E_w \) are the vaporization enthalpy, the mass change of bulk water, and the mass change
of water due to the presence of the bio-inspired architecture, respectively. Considering the vaporization enthalpy of water to be 2444 J g$^{-1}$, the calculated $E_e$ values of water with CCA and CCAP are 1696 and 1475 J g$^{-1}$ (Supporting Information: Figure S13B), respectively, suggesting that the hydrophilic networks of the bio-inspired Janus architectures facilitate the evaporation of water. To investigate the effect of the bio-inspired Janus architecture on the phase-change behavior of water, we studied the melting behavior of the bio-inspired architecture using differential scanning calorimetry (DSC) analysis. DSC curves (Supporting Information: Figure S14) show that all the endothermic peaks of CCAP and CCA have two parts, representing the desorption process of free water and the melting process of the intermediate. Since the water interacts strongly with polar molecule chains and is nonfreezable, it is unnecessary to divide the peak of bound water. The weight fraction of intermediate water ($\omega_i$) in bio-inspired architectures can be determined from the split intermediate peak area. Also, the melting enthalpy of intermediate water ($\Delta H_i$) in bio-inspired architectures can be estimated using the following equation:

$$\Delta H_i = \frac{\Delta H_w \times \omega_w - \Delta H_f \times \omega_f}{\omega_i},$$

in which the $\Delta H_w$ and $\Delta H_f$ are the measured melting enthalpy values of the biomass-based Janus architecture and subcooled pure water, respectively. Also, the weight fraction of free water ($\omega_f$) has the formula: $\omega_f = \omega_w - \omega_i$. All of the measured and estimated results (Supporting Information: Table S2) indicate that the melting enthalpy values of intermediate water in CCA ($-190.5$ J g$^{-1}$) and CCAP ($-164.3$ J g$^{-1}$) decrease significantly, and the CCA doped with PPy (CCAP) has a strong influence on the phase-change process of water.

The surface temperature of samples in water under 1 sun illumination is recorded using a thermal infrared camera. The equilibrium temperature of CCAP is 10°C higher than the ambient temperature (Supporting Information: Figure S15), while the surface temperature of water and CCA only increases 1.5°C and 2.7°C,
respectively. Due to the excellent solar–thermal conversion performance, water absorption property, thermal management, and low evaporation enthalpy, the biomimetic Janus architecture (CCAP) presents a high water evaporation rate of up to 2.3 kg m$^{-2}$ h$^{-1}$ under 1 sun irradiation (Figure 4E), 4.4 times higher than the evaporation rate of bulk water (0.52 kg m$^{-2}$ h$^{-1}$), and 2.0 times that of water in CCA (1.17 kg m$^{-2}$ h$^{-1}$), respectively. The energy efficiency ($\eta$) is further calculated using the following formula:

$$\eta = \frac{m \times E_\text{v}}{C \times P_{\text{Solar}}},$$  \hspace{1cm} (3)$$

in which $m$ is the mass change within 1 h (all the experimental data were calibrated with dark evaporation data), $P_{\text{Solar}}$ is the solar irradiation power of 1 sun, and $C$ is the optical concentration (1 sun) on the evaporator surface. The biomimetic Janus architecture (CCAP) shows a high energy efficiency of 85.8%, much larger than that of bulk water (27.3%) and CCA (46.6%).

The long-term ISSG test under 1 sun irradiation demonstrates that CCAP shows good cyclic stability performance (Supporting Information: Figure S16). These results indicate that the outstanding ISSG performance of CCAP mainly relies on the high solar absorption, low thermal conductivity, and small vaporization enthalpy, which originate from the well-designed cross-linked networks in the biomimetic Janus architecture. Compared with previously reported materials, this biomimetic Janus architecture has significant advantages of both thermal management and a high water evaporation rate (Figure 4F and Supporting Information: Table S3), further demonstrating its potential for practical ISSG.

### 3.4 Performance of solar desalination and metal–ion enrichment

To demonstrate the practical solar desalination performance of the biomimetic Janus architectures, we conducted ISSG tests under 1 sun irradiation. The water evaporation rate of CCA-CCAP in various solutions can be maintained above 2.0 kg m$^{-2}$ h$^{-1}$ (Figure 5A), which is similar to that in pure water, indicating the structural stability of the biomimetic Janus architectures during wastewater purification. In addition, we find that CCAP-CCA without an orientation structure does not significantly impact the evaporation rate. This is mainly attributed to the fact that the orientation structures do not have much obvious difference in water transport, heat management, and solar absorption. When using this biomimetic Janus architecture for ISSG desalination in seawater, lake water, and sewage containing various metal ions, such as Na$^+$, K$^+$, Mg$^{2+}$, and Ca$^{2+}$, the metal–ion concentrations are significantly reduced by 2–4 orders (Figure 5B), which fulfills the drinking water standards defined by the US Environmental Protection Agency and the World Health Organization.

There are abundant hydroxyl/carboxyl groups in the biomimetic Janus architectures, especially CCA, which can be used for enriching toxic metal ions, such as Pb$^{2+}$, Cu$^{2+}$, and Cd$^{2+}$, in wastewater. Because of the strong combination of metal ions and hydroxyl/carboxyl groups (Figure 5C), these toxic metal ions are enriched in biomimetic Janus architectures, thus forming a more stable network structure for long-term desalination. To further explore their feasibility in the practical applications of metal–ion enrichments, the ISSG process is carried out for wastewater treatments with more than two kinds of metal–ion mixtures. The neutral solution marked Metal 1, including Cu$^{2+}$/Cr$^{3+}$/Cd$^{2+}$/Pb$^{2+}$/Ni$^{2+}$/Co$^{2+}$/Mn$^{2+}$, and the acid solution marked Metal 2, including Ba$^{2+}$/Fe$^{3+}$/Zn$^{2+}$/Mg$^{2+}$/Al$^{3+}$/Hg$^{2+}$ (Supporting Information: Figure S17), are prepared for testing wastewater treatment performances. When the biomimetic Janus architectures are soaked in the wastewater used for solar desalination, most of these metal ions are absorbed and enriched into them, thus resulting in lighter colors of these solutions. After the ISSG desalination treatment, the biomimetic Janus architectures show the colors of these metal ions (Figure 5C) and the water collected in the beaker becomes transparent. Inductively coupled plasmaatomic emission spectrometry (ICP-AES) results (Figure 5D) show that all the compositions of the 14 typical metal ions in the collected water are considerably lower than the drinking water standards defined by the World Health Organization (2008, indicated by the red lines), which reveals that healthy drinking water is regenerated by the biomimetic Janus architectures, further indicating that the biomimetic Janus architectures can be used for the regeneration of pure water. Moreover, scanning electron microscope-energy dispersive X-ray detector results of the metal–ion-enriched biomimetic Janus architectures (Supporting Information: Figure S18) show that all metal ions are detected on their skeletons. XRD patterns (Supporting Information: Figure S19) demonstrate that all enriched metals in the Janus architecture are amorphous; it can be speculated that the metal ions exist in the form of complexes with alginate (Supporting Information: Figure S20). The above results show that the biomass-based Janus architecture in the ISSG process works on a principle similar to that of water transportation in
plants during photosynthesis. On the one hand, salt and metal ions are transported to the evaporation interface and the phase transformation process occurs via solar energy. On the other hand, metal ions in water are enriched into the CCA layer of the biomass-based Janus architecture.

4 | CONCLUSION

Inspired by natural plants with oriented pore structures for transporting nutrient ions from soil in the photosynthesis, we develop a biomimetic Janus architecture using all biomass-regenerated precursors to obtain clean drinking water and simultaneously remove heavy-metal ions with high efficiency. With high light absorbance (98%), outstanding thermal management (λ = 32.8 mW m⁻¹ K⁻¹), and low vaporization enthalpy (1475 J g⁻¹), the prepared biomimetic Janus architecture of CCAP-CCA presents a high-rate steam regeneration rate of 2.3 kg m⁻² h⁻¹ under 1 sun illumination. Furthermore, because the superhydrophilicity and macroporous skeleton enable transport of sufficient water and salt, CCAP-CCA shows long-term evaporation stability and a high water evaporation rate (2.0 kg m⁻² h⁻¹) in metal-ion solutions. This study provides a pathway for heavy-metal ion enrichment during the construction of high-performance solar desalination evaporators. This method is important for various practical applications, including sewage reclamation and heavy-metal wastewater reduction.

AUTHOR CONTRIBUTIONS

Shu-Hong Yu, Li-Feng Chen, and Hao-Yu Zhao conceived the idea of the study and designed the research project. Hao-Yu Zhao, Wei-Xu Dong, Yu Deng, Chen-Fan Zhao, Chen-Fan Zhao, Chuan-Ling Zhang, Jie Zhou, Yan-Song Li, and Dong-Jun Li performed the experiments, and collected and analyzed the data. Hao-Yu Zhao, Li-Feng Chen, and Shu-Hong Yu wrote the manuscript. Shu-Hong Yu supervised the project. All authors discussed the results and commented on the manuscript.

FIGURE 5 Solar desalination and metal enrichment performance of the biomass-based Janus architecture. (A) Mass changes of deionized water (DIW), seawater, lake water, sewage solution, and metallic wastewater in the biomass-based Janus architecture of CCAP-CCA with or without orientation structures as a function of time under 1 sun illumination. (B) Concentrations of four primary ions in various solutions before and after ISSG desalination. (C) Photographs of the CCA layer of the biomass-based Janus architecture of CCAP-CCA after solar metal enrichment. (D) Overall metal removal performance of the biomass-based Janus architecture before and after solar distillation. CCA, calcium-solidified carboxymethyl cellulose/sodium alginate; CCAP, CCA coated with a polypyrrole layer; ISSG, interfacial solar steam generation.
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CONFLICT OF INTEREST
The authors declare no conflict of interest.

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REFERENCES
[1] He C, Liu Z, Wu J, et al. Future global urban water scarcity and potential solutions. Nat Commun. 2021;12(1):4667.
[2] Min XZ, Zhu B, Li B, Li JL, Zhu J. Interfacial solar vapor generation: materials and structural design. Acc Mater Res. 2021;2(4):198-209.
[3] Zhao F, Guo YH, Zhou XY, Shi W, Yu GH. Materials for solar-powered water evaporation. Nat Rev Mater. 2020;5(5):388-401.
[4] Zhou X, Guo Y, Zhao F, Yu G. Hydrogels as an emerging material platform for solar water purification. Acc Chem Res. 2019;52(11):3244-3253.
[5] Zhu L, Sun L, Zhang H, et al. A solution to break the salt barrier for high-rate sustainable solar desalination dagger. Energy Environ Sci. 2021;14(4):2451-2459.
[6] Elimelech M, Phillip WA. The future of seawater desalination: energy, technology, and the environment. Science. 2011;333(6043):712-717.
[7] Greve P, Kahil T, Mochizuki J, et al. Global assessment of water challenges under uncertainty in water scarcity projections. Nat Sustain. 2018;1(9):486-494.
[8] Lord J, Thomas A, Treat N, et al. Global potential for harvesting drinking water from air using solar energy. Nature. 2021;598(7882):611-617.
[9] Chen W, Chen S, Liang T, et al. High-flux water desalination with interfacial salt sieving effect in nanoporous carbon composite membranes. Nat Nanotechnol. 2018;13(4):345-350.
[10] Wang J, Li Y, Deng L, et al. High-performance photothermal conversion of narrow-bandgap Ti2O3 nanoparticles. Adv Mater. 2017;29(3):1603730.
[11] Xu X, Ozden S, Bizmark N, Arnold CB, Datta SS, Priestley RD. A bioinspired elastic hydrogel for solar-driven water purification. Adv Mater. 2021;33(18):e2007833.
[12] Li X, Min X, Li J, et al. Storage and recycling of interfacial solar steam enthalpy. Joule. 2018;2(11):2477-2484.
[13] Yang P, Liu K, Chen Q, et al. Solar-driven simultaneous steam production and electricity generation from salinity. Energy Environ Sci. 2017;10(9):1923-1927.
[14] He S, Chen C, Kuang Y, et al. Nature-inspired salt resistant bimodal porous solar evaporator for efficient and stable water desalination. Energy Environ Sci. 2019;12(5):1558-1567.
[15] Ma Q, Yin P, Zhao M, et al. MOF-based hierarchical structures for solar-thermal clean water production. Adv Mater. 2019;31(17):e1808249.
[16] Zhao W, Gong H, Song Y, et al. Hierarchically designed salt-resistant solar evaporator based on Donnan effect for stable and high-performance brine treatment. Adv Funct Mater. 2021;31(23):2100025.
[17] Li Z, Ma X, Chen D, et al. Polyaniline-coated MOFs nanorod arrays for efficient evaporation-driven electricity generation and solar steam desalination. Adv Sci. 2021;8(7):2004552.
[18] Ni G, Zandavi SH, Javid SM, Boriskina SV, Cooper TA, Chen G. A salt-rejecting floating solar still for low-cost desalination. Energy Environ Sci. 2018;11(6):1510-1519.
[19] Chen J, Yin JL, Li B, et al. Janus evaporators with self-recovering hydrophobicity for salt-rejecting interfacial solar desalination. ACS Nano. 2020;14(17):17419-17427.
[20] Zhou X, Zhao F, Guo Y, Rosenberger B, Yu G. Architecting highly hydratable polymer networks to tune the water state for solar water purification. Adv Sci. 2019;5(6):eaaw5484.
[21] Shi Y, Ilic O, Atwater HA, Greer JR. All-day fresh water harvesting by microstructured hydrogel membranes. Nat Commun. 2021;12(1):2797.
[22] Liu X, Tian Y, Chen F, et al. An easy-to-fabricate 2.5D evaporator for efficient solar desalination. Adv Funct Mater. 2021;31(27):2100911.
[23] Wang H, Zhang C, Zhang Z, Zhou B, Shen J, Du A. Artificial trees inspired by Monstera for highly efficient solar steam generation in both normal and weak light environments. Adv Funct Mater. 2020;30(48):2005513.
[24] Xu N, Li J, Wang Y, et al. A water lily-inspired hierarchical design for stable and efficient solar evaporation of high-salinity brine. Sci Adv. 2019;5(7):eaaw7013.
[25] Zou M, Zhang Y, Cai Z, et al. 3D printing a biomimetic bridge-arch solar evaporator for eliminating salt accumulation with desalination and agricultural applications. Adv Mater. 2021;33(34):e2102443.
[26] Tao P, Ni G, Song C, et al. Solar-driven interfacial evaporation. Nat Energy. 2018;3(12):1031-1041.
[27] Guo Y, Lu H, Zhao F, Zhou X, Shi W, Yu G. Biomass-derived hybrid hydrogel evaporators for cost-effective solar water purification. Adv Mater. 2020;32(11):e1907061.
[28] Li H, Zhu W, Li M, et al. Side area-assisted 3D evaporator with antibiofouling function for ultra-efficient solar steam generation. *Adv Mater*. 2021;33(36):e2102258.

[29] Yu ZL, Yang N, Zhou LC, et al. Bioinspired polymeric woods. *Sci Adv*. 2018;4(8):eaat7223.

[30] Zhao H-Y, Zhou J, Yu Z-L, et al. Lotus-inspired evaporator with Janus wettability and bimodal pores for solar steam generation. *Cell Rep Phys Sci*. 2020;1(6):100074.

[31] Zhao HY, Huang J, Zhou J, et al. Biomimetic design of macroporous 3D truss materials for efficient interfacial solar steam generation. *ACS Nano*. 2022;16(3):3554-3562.

[32] Zhou X, Guo Y, Zhao F, Shi W, Yu G. Topology-controlled hydration of polymer network in hydrogels for solar-driven wastewater treatment. *Adv Mater*. 2020;32(52):e2007012.

**SUPPORTING INFORMATION**

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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