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Water-Level-Regulated Ridge-Structured Evaporator for Salt-Resistant Solar Desalination with Radiative Heat Recovery

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ABSTRACT

Solar-driven interfacial evaporation offers a promising route for decentralized freshwater production, yet salt accumulation, inefficient heat utilization, and limited vapor transport continue to restrict long-term operation and scale-up. Here, a ridge-structured evaporator (RSE) was developed by integrating carbon nanotube-loaded carbon felt with a simple 3D-printed double-ridge framework. The opposing inclined surfaces enabled surface-to-surface radiative heat recovery, while the ridge channels promoted water transport, airflow exchange, and vapor removal. More importantly, the salt crystallization pathway could be actively regulated by adjusting the contact height between the evaporator and the water body. Under low-water-level conditions, salt preferentially crystallized at the bottom of the central valley, thereby avoiding extensive coverage of the primary evaporation surfaces. Increasing the water level subsequently shortened the water-supply pathway and enabled complete salt dissolution within 2.5 h. Under one-sun irradiation, the RSE achieved evaporation rates of 1.74 kg m⁻² h⁻¹ in pure water and 1.27 kg m⁻² h⁻¹ in a 20 wt% NaCl solution. Outdoor 9- and 15-unit arrays maintained stable operation for 28 days, with maximum hourly water production rates of 0.196 and 0.341 kg h⁻¹ in pure water and 0.189 and 0.316 kg h⁻¹ in seawater, respectively. These results demonstrate a scalable and low-cost structural strategy for efficient solar desalination.

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1. Introduction

The continuously growing global demand for freshwater has accelerated the development of sustainable seawater desalination technologies. Conventional desalination methods, such as thermal distillation and membrane-based separation [1, 2], can provide a stable freshwater supply but are often associated with high energy consumption, complex system configurations, and substantial maintenance costs [3, 4]. Interfacial solar evaporation directly converts solar energy into localized heat at the water-air interface, offering advantages such as low external energy requirements, simple operation, and suitability for decentralized freshwater production. It is therefore regarded as a promising approach for seawater desalination [5, 6]. In recent years, substantial improvements in solar energy utilization and water evaporation performance have been achieved through the development of broadband photothermal materials, regulation of interfacial water states, and construction of three-dimensional evaporator architectures [7-9].

Nevertheless, salt accumulation remains a major challenge that limits the long-term stable operation of solar evaporators during seawater desalination [10]. As water continuously evaporates, dissolved salts progressively concentrate near the evaporation interface and eventually nucleate to form salt crystals. The deposited salts can cover the photothermal surface, reduce solar absorption, block water-transport pathways, hinder vapor escape, and accelerate the deterioration of evaporation performance. Current salt-management strategies mainly include enhancing ion diffusion, constructing enlarged water-transport channels, inducing localized crystallization, and promoting spontaneous salt redissolution [11-14]. Although these approaches can alleviate surface salt deposition to some extent, the location of salt crystallization is generally determined by fixed material compositions or structural designs [15-17]. When the rate of salt accumulation exceeds the intrinsic diffusion or dissolution capacity of the evaporator, manual cleaning or interruption of the evaporation process is often still required. Therefore, developing a strategy that can guide salt crystallization away from the primary evaporation region and subsequently enable rapid salt redissolution through active regulation is of great significance for the long-term operation of solar-driven seawater desalination systems.

In addition to salt accumulation, inefficient thermal utilization and limited gas-phase mass transfer can also impair the performance of three-dimensional solar evaporators. A portion of the energy absorbed by photothermal materials may dissipate into the surrounding environment through thermal radiation, conduction, and convection [18-20]. Meanwhile, water vapor tends to accumulate near the evaporation interface, resulting in elevated local humidity and increased gas-phase mass-transfer resistance. Three-dimensional architecture can enlarge the effective evaporation interface and provide greater flexibility for regulating water transport, heat redistribution, and vapor diffusion [11, 21]. Radiative exchange between adjacent high-temperature surfaces enables partial reabsorption of emitted thermal radiation, whereas inclined or vertical structural channels can enhance air exchange and facilitate vapor removal [22-24]. However, most existing studies focus on only one or two of these functions, and achieving the synergistic regulation of salt crystallization, heat transfer, water supply, and gas transport within a simple architecture remains challenging [25-27]. Furthermore, complicated fabrication procedures, expensive functional materials, and insufficient structural reproducibility also restrict the large-scale implementation of laboratory-scale solar evaporators.

Based on these considerations, a ridge-structured evaporator (RSE) was developed for scalable solar-driven seawater desalination. The evaporator was assembled by integrating carbon nanotube-loaded carbon felt with a three-dimensional double-ridge framework, and the salt crystallization pathway could be actively regulated by adjusting the contact height between the evaporator and the water body. Under low-water-level conditions, salts preferentially accumulated at the bottom of the central valley, spatially separating the crystallization region from the primary evaporation surfaces on both sides. After substantial salt accumulation, increasing the water level shortened the water-transport pathway and accelerated salt dissolution, thereby establishing a cyclic process involving directional salt crystallization at a low water level and rapid salt removal at a higher water level. Meanwhile, the opposing inclined ridge surfaces enabled partial recovery of radiative heat through surface-to-surface thermal radiation exchange, thereby reducing heat loss and promoting internal heat redistribution. The inclined surfaces and longitudinal ridge channels also guided airflow, enhanced air exchange near the evaporation interface, and facilitated vapor removal. Benefiting from the synergistic regulation of salt crystallization, thermal

management, water transport, and gas-phase mass transfer, the RSE achieved a pure-water evaporation rate of $1.74 \text{ kg m}^{-2} \text{ h}^{-1}$ under one-sun irradiation and maintained an evaporation rate of $1.27 \text{ kg m}^{-2} \text{ h}^{-1}$ in a 20 wt% NaCl solution. After the water level was increased, the salt crystals accumulated in the central valley could dissolve completely and naturally within 2.5 h. Matrix arrays consisting of 9 and 15 RSE units exhibited stable photothermal responses and evaporation performance under outdoor conditions. Together with its simple fabrication process, low material cost, and favorable water-production economics, these results demonstrate the potential of the RSE for large-area and low-cost solar-driven seawater desalination.

2. Experimental Section

2.1. Preparation of RSE

First, single-ridge and double-ridge evaporator substrates were fabricated using three-dimensional printing. The carbon felt was cut into dimensions matching the surface of the evaporator substrates, sequentially ultrasonically cleaned in ethanol and deionized water to remove surface impurities, and then dried at 60°C . Subsequently, carbon nanotubes were added to deionized water containing a small amount of dispersant and ultrasonically dispersed for 2 h to obtain a homogeneous and stable carbon nanotube suspension. The pretreated carbon felt was completely immersed in the suspension, ultrasonicated for an additional 30 min, and then statically soaked for several hours to allow sufficient adsorption of the carbon nanotubes onto the carbon fibers. The carbon felt was subsequently removed and dried at 60°C . This immersion-drying process was repeated three times to obtain a CNTs@CF photothermal layer with uniformly loaded carbon nanotubes. Finally, the CNTs@CF layer was firmly attached to the surface of the 3D-printed substrate using a water-resistant adhesive and fully cured at room temperature, thereby producing single-ridge and double-ridge ridge-structured evaporators (RSE).

2.2. Solar Evaporation Experiments

All solar-driven evaporation and lithium extraction experiments were performed under controlled conditions of $25 \pm 2^\circ\text{C}$ and relative humidity of $52 \pm 2\%$. A solar simulator (Microsolar300 xenon lamp source, Beijing Perfect light) equipped with an AM 1.5 filter was used to provide simulated sunlight, and the irradiation intensity was calibrated using a full-spectrum optical power meter (CEL-NP2000-2, Beijing Education Au light Co., Ltd.). The evaporator was mounted on a high-precision electronic balance to monitor mass loss in real time, from which the evaporation rate was calculated. Surface temperatures were measured by an infrared camera (FLIR E4 Pro, America) and thermocouples (OMEGA, INSP # 33306, 5TC-TT-K-30-197), with data recorded using a data acquisition system (KEYSLIGHT, 34972A).

2.3. Outdoor Solar-driven Evaporation

Solar-driven evaporation tests were conducted outdoors in Wuhan, China, from May to July 2026 for more than one month under natural sunlight, using brine samples collected from the Bohai Sea (China). The RSE device was partially immersed in the brine and exposed to sunlight from 08:00 to 17:00. Solar irradiance was monitored using a full-spectrum power meter, while surface temperatures were measured with an infrared camera and thermocouples. The mass loss of the solution was recorded using a portable electronic balance, and the evaporation rates were calculated accordingly. Brine samples were collected at regular intervals for ion analysis.

2.4. Characterizations

The morphology of the samples was characterized by a field emission scanning electron microscope (FESEM, JSM-7100F, JEOL, Japan). The optical transmittance (T) and reflectance (R) were obtained in the range of 250–2500 nm by a UV-visible-near-infrared spectrophotometer (Shimadzu UV-vis-NIR UN-3600 double beam spectrophotometer) with an integrating sphere. The Raman spectrum was collected by a Raman microscope with an excitation laser of 532 nm (LabRAM HR 800UV, Horiba Jobin Yvon, France). Ion concentrations were determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES, PerkinElmer Optima 8000, USA). DSC measurements were conducted with a differential scanning calorimeter (TA Q200).

3. Results and Discussion

3.1. Fabrication and Characterization of Evaporator

The Ridge Structured Evaporator (RSE) features a unique ridge configuration that enables efficient solar radiation harvesting and precise regulation of water vapor diffusion. By optimizing the contact height between the device and the water body, the crystallization path of salt can be well controlled, which effectively avoids the negative impact of salt scaling on the evaporation process under high-salinity conditions and achieves efficient freshwater recovery in high-salt environments (Fig. 1). In this work, carbon nanotubes (CNTs) were adopted as photothermal functional materials and carbon felt (CF) served as the water-transporting substrate. The CNT-loaded carbon felt was bonded to a 3D-printed double peak ridge shaped substrate, which significantly improved the photothermal conversion efficiency and surface hydrophilicity of the device. The detailed dimensional parameters of the RSE are displayed in Fig. (S1). Meanwhile, a single peak ridge structured evaporator was fabricated as the control sample (Fig. S2) to systematically investigate the effects of heat transfer, vapor transport and water delivery direction on the evaporation performance. Compared with the single peak structure, the double peak ridge evaporator enhances the photothermal absorption performance of the evaporation region through solar radiation reflection between the sidewalls. Moreover, the inclined slope structure optimizes the vapor transport channel and accelerates the vapor escape rate, delivering superior comprehensive evaporation performance. Benefiting from the simple fabrication process and low cost, the proposed evaporator possesses great potential for large scale practical applications.

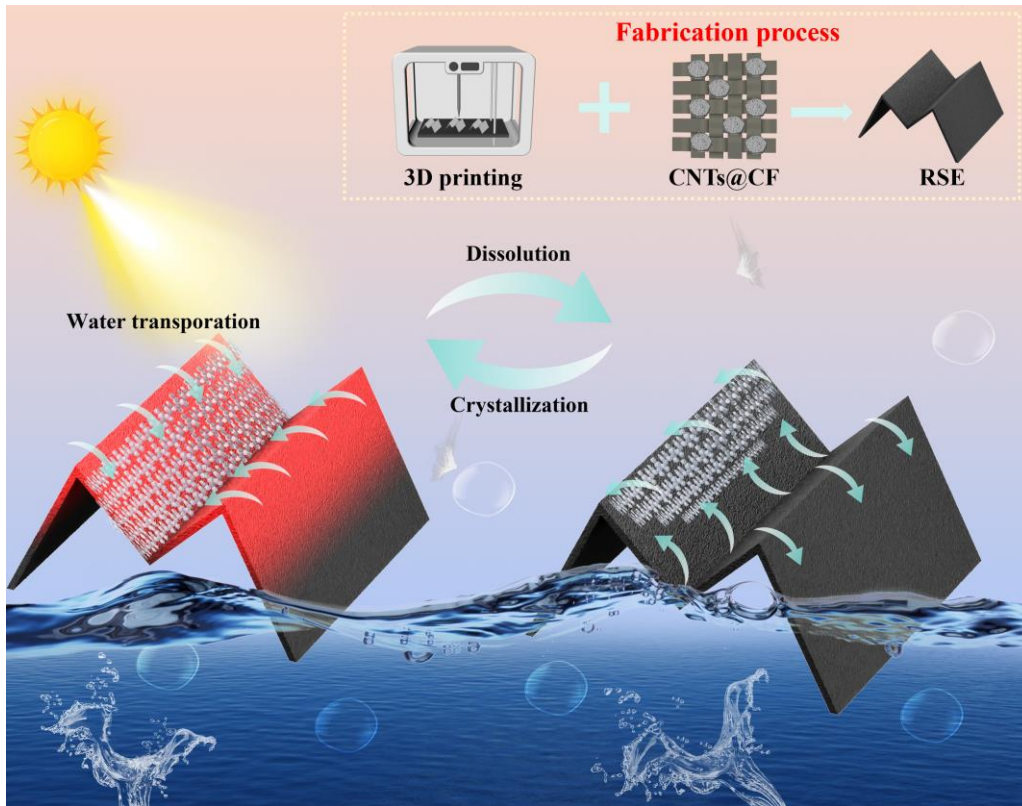


Figure 1: Schematic illustration of the fabrication procedure of the RSE and the cyclic salt crystallization and salt dissolution process during solar evaporation.

Scanning electron microscopy (SEM) was employed to characterize the surface morphologies of CF before and after CNTs loading. As displayed in Fig. (2a) and (2b), CF consists of numerous interwoven carbon felt that form interconnected microscale pores, facilitating water transport and vapor escape. After CNTs loading, the original fibrous framework and porous structure of CF are well preserved, with CNTs uniformly distributed over the

intertwined carbon felt. This structure enhances the multiple scattering and absorption of incident light, thereby improving the photothermal conversion performance. Because the hydrogen-bonding environment of water molecules directly influences the energy barrier for photothermal evaporation, Raman spectroscopy was further employed to investigate the hydrogen-bonding states of water in CNTs@CF and to elucidate its regulation of the relative proportions of intermediate water (IW) and free water (FW). Through peak deconvolution of the Raman spectra, the contents of different water states and their corresponding peak-area ratios were quantitatively determined, as summarized in Table S1. Compared with FW, IW exhibits weaker hydrogen-bonding interactions, and an increased IW fraction is therefore favorable for reducing the energy barrier for water evaporation [23]. The Raman spectrum of CNTs@CF shows characteristic FW peaks at 3229 and 3327 cm^{-1} , whereas the IW-related peaks are located at 3426 and 3601 cm^{-1} (Fig. 2c). Notably, the IW/FW ratio of CNTs@CF reaches 4.91, substantially higher than that of pure water (0.50). This enhancement is mainly attributed to the micro/nanostructures formed by CNTs, which enlarge the water-material interfacial area [28]. The resulting interfacial confinement weakens the original hydrogen-bonding network among water molecules and promotes the conversion of FW into IW, thereby reducing the energy required for evaporation and facilitating the escape of water molecules [29]. Wettability analysis of the RSE evaporation surfaces showed that a water droplet completely spread within 2.2 s, demonstrating its excellent hydrophilicity (Fig. 2d), which facilitates rapid water absorption and continuous transport during photothermal evaporation. Efficient solar absorption and photothermal conversion are essential for achieving high performance interfacial evaporation. After CNTs loading, the CF exhibited an average solar absorptance exceeding 90.5% over the wavelength range of 280–2500 nm, demonstrating excellent broadband light harvesting capability. (Fig. 2e).

Differential scanning calorimetry (DSC) was employed to determine the evaporation enthalpy of water within the evaporator. The heat flow–temperature curves showed that the endothermic peak of water confined in the RSE was substantially lower than that of pure water (Fig. 2f). The equivalent evaporation enthalpy was further calculated to evaluate the vaporization behavior of water within the device. The equivalent evaporation enthalpies of pure water and water in the RSE composite evaporator were 2450 and 1552 J g^{-1} , respectively (Table S2), indicating that the RSE significantly reduced the energy required for water vaporization. This reduction can be attributed to the regulation of the hydrogen bonding network [30]. Conventional bulk water vaporization requires sufficient energy to overcome the strong intermolecular hydrogen bonds and release water molecules from the intact hydrogen bond network [31]. In contrast, the RSE weakens the hydrogen bonding interactions among water molecules, thereby lowering the energy barrier for their escape from the liquid phase. Consistent with the reduced equivalent evaporation enthalpy and enhanced evaporation performance, the calculated photothermal conversion efficiency of the RSE reached 108.75%. The calculation method and relevant parameters are provided in Note S3. It should be noted that efficiencies above 100% have also been reported for three-dimensional solar evaporators, where the enlarged evaporation interface, environmental heat exchange, radiative energy reutilization, and reduced effective evaporation energy of interfacial water can contribute to the calculated efficiency [21, 32–35]. These results are consistent with the Raman analysis and further support the favorable water-state regulation and energy utilization of the RSE.

To investigate the effects of structural geometry and immersion depth on evaporation performance, single-ridge and double-ridge RSEs were evaluated in pure water under one sun irradiation. For the double-ridge RSE, three immersion levels were established by varying its contact height with water and were denoted as DR-H, DR-M, and DR-L for high, medium, and low water levels, respectively. The single-ridge RSE operated at the low water level was denoted as SR. As shown in Fig. (2g), SR exhibited the lowest evaporation rate of $1.36 \text{ kg m}^{-2} \text{ h}^{-1}$. For the double-ridge RSE, the apparent evaporation rate increased with increasing water level, reaching 1.74, 1.79, and $1.89 \text{ kg m}^{-2} \text{ h}^{-1}$ for DR-L, DR-M, and DR-H, respectively. This trend was primarily associated with differences in the effective evaporation area. As the water level increased, the exposed evaporation area decreased from 120 cm^2 for DR-L to 92.8 cm^2 for DR-M and 56 cm^2 for DR-H, resulting in a higher evaporation rate after normalization to the effective area. Notably, despite possessing the largest effective evaporation area, DR-L maintained an area-normalized evaporation rate comparable to those of DR-M and DR-H. This result indicates that the double-ridge configuration promotes evaporation by enhancing radiative energy utilization and airflow transport within the evaporation region.

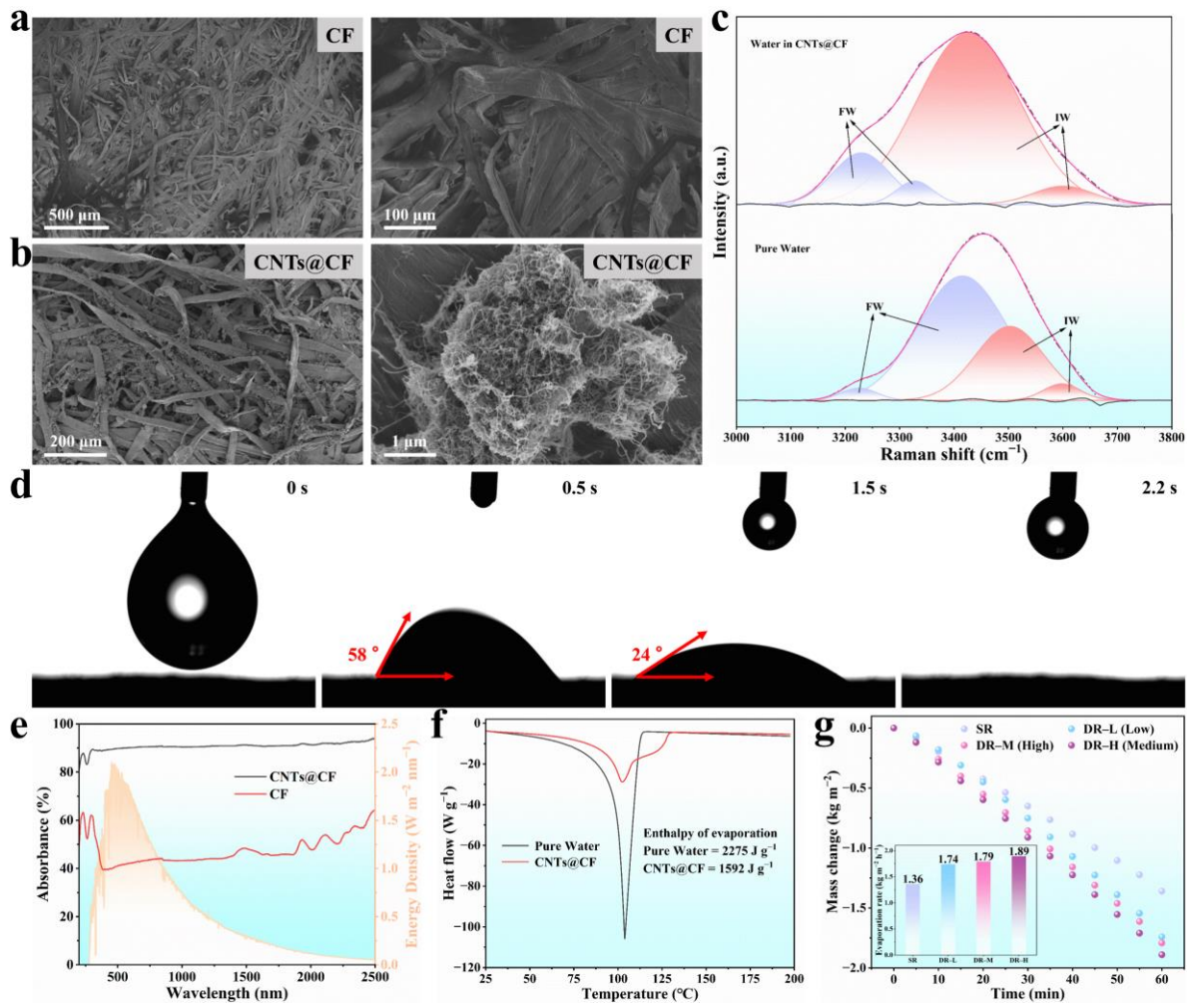


Figure 2: (a, b) SEM images of CF and CNTs@CF. (c) Raman spectra of Pure water and water in CNTs@CF. (d) Water contact angle measured on the RSE surface. (e) UV-vis-NIR absorption spectra of CF and CNTs@CF. (f) DSC thermograms and evaporation enthalpies of pure water and CNTs@CF. (g) Evaporation rates of SR, DR-L, DR-M, and DR-H.

3.2. Surface Thermal Management Mechanism Analysis of RSE

To elucidate the heat-transfer enhancement mechanism of the RSE, COMSOL Multiphysics was employed to simulate its thermal conduction behavior (Note S4). Fig. (3a) presents the transient thermal simulation results of the RSE. As the irradiation time increased from 1 to 10 min, heat gradually propagated from the ridge peaks to the inclined sidewalls and the internal valley regions. Notably, pronounced surface-to-surface thermal radiation occurred between the opposing ridge surfaces. Thermal radiation emitted from one high-temperature surface could be reabsorbed by the opposite surface, thereby enabling radiative heat recovery, reducing heat dissipation to the surroundings, and promoting a higher and more uniform temperature distribution throughout the evaporator. Infrared thermal imaging showed that, under wet conditions, the surface temperature of the RSE rapidly increased from 33.8 $^{\circ}\text{C}$ to 52.4 $^{\circ}\text{C}$ during the first 1-5 min of irradiation, while the high-temperature region progressively expanded toward both inclined ridge surfaces (Fig. 3b). After 10 min of irradiation, the temperature slightly decreased to 50.2 $^{\circ}\text{C}$, primarily because a portion of the absorbed heat was continuously consumed by water vaporization. In contrast, under dry conditions, the surface temperature of the RSE continuously increased from 36.4 $^{\circ}\text{C}$ to 60.3 $^{\circ}\text{C}$, accompanied by the gradual formation of a uniform high-temperature region within the inter-ridge space (Fig. S3). Combined with the COMSOL simulation results, these observations indicate that radiative heat exchanged between the opposing ridge surfaces can be reabsorbed, thereby facilitating heat transfer and accumulation within the structure while minimizing heat loss to the environment. The temperature difference between the dry and wet states further demonstrates that the heat absorbed by the wetted evaporator is effectively utilized for water evaporation.

Fig. (3c) further illustrates the temperature evolution of the RSE under continuous solar irradiation. The surface temperatures under both dry and wet conditions increased rapidly during the initial stage of irradiation, followed by a gradual decrease in the heating rate and eventual stabilization, indicating that a dynamic equilibrium was progressively established between heat absorption and heat dissipation to the surroundings. The steady-state temperature under dry conditions was approximately 58–60 °C, markedly higher than that under wet conditions (50–52 °C), consistent with the infrared thermal imaging results. This temperature difference primarily arises from continuous interfacial evaporation under wet conditions, during which part of the absorbed heat is converted into the latent heat required for water vaporization, thereby producing a pronounced evaporative cooling effect. After the light source was switched off, the temperatures under both conditions rapidly decreased to near ambient temperature, demonstrating the rapid thermal response and low thermal hysteresis of the RSE.

During repeated light on/off cycles, the surface temperature of the RSE increased rapidly upon irradiation and decreased promptly after the light source was switched off. The temperature evolution profiles and peak temperatures remained nearly identical across successive cycles (Fig. 3d). Meanwhile, the peak temperature under wet conditions was consistently lower than that under dry conditions, further confirming the continuous consumption of thermal energy by water evaporation. The stable and reproducible heating-cooling response demonstrates the excellent reversibility of the photothermal conversion process and the robust cycling stability of the RSE. Collectively, the simulation and experimental results indicate that the ridge structure facilitates heat transfer and redistribution within the evaporator through the reabsorption of thermal radiation between opposing surfaces, thereby providing a stable and continuous thermal supply for interfacial water evaporation.

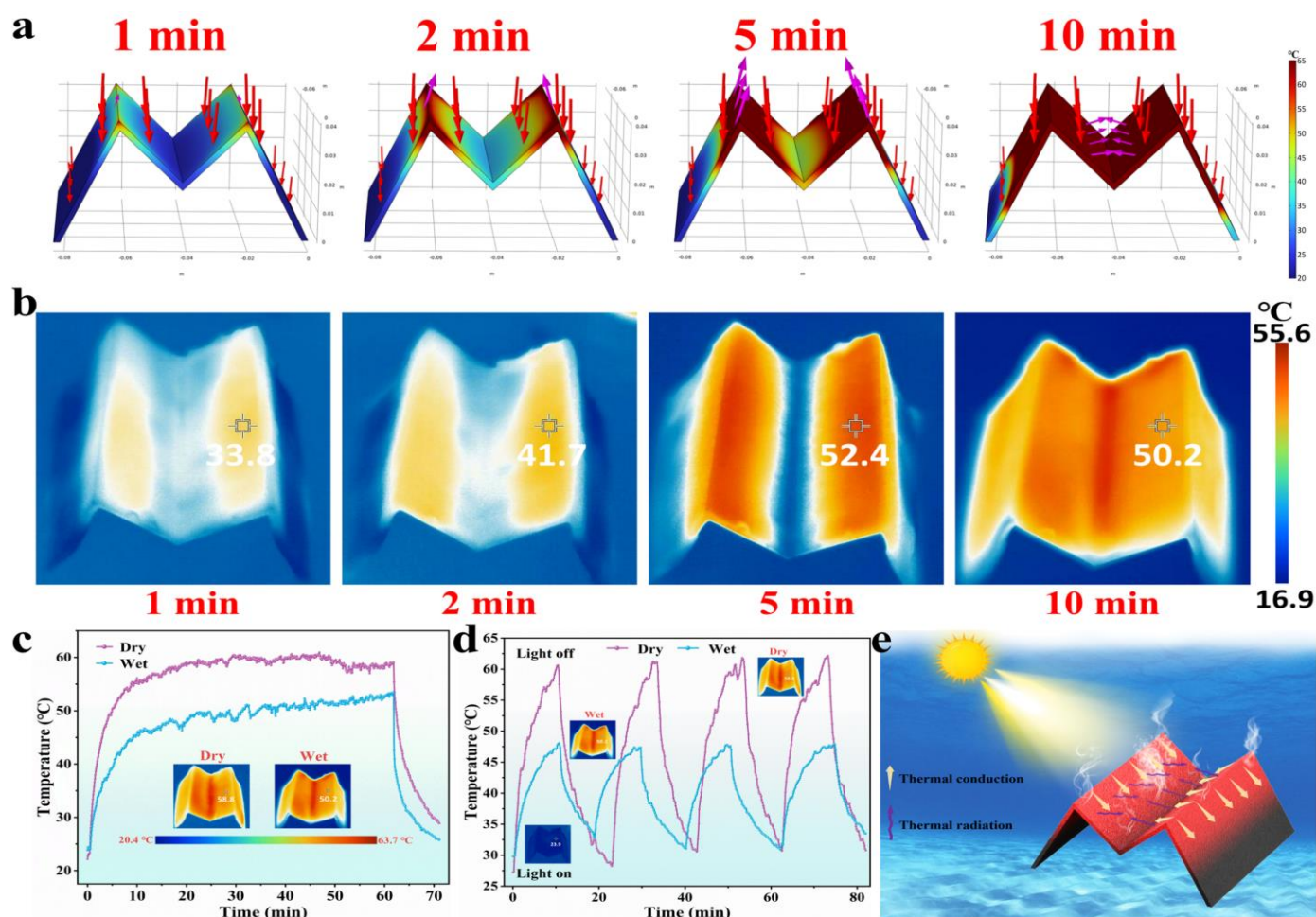


Figure 3: (a) Multiphysics heat transfer simulation for RSE. (b) Infrared thermal images of RSE under 1 kW m⁻² irradiation in wet conditions. (c) Cyclic temperature response of RSE over one hour under dry and wet conditions. (d) Cyclic surface temperature response under short light on-off switching. (e) Schematic illustration of heat transfer mechanism for RSE.

As illustrated in Fig. (3e), the thermal regulation of the RSE arises from the coupling of photothermal conversion, framework-mediated heat conduction, interfacial radiative exchange, and water evaporation. Incident solar energy is absorbed by the ridge peaks and inclined surfaces and converted into thermal energy, which is subsequently redistributed through the continuous framework toward the inclined sidewalls and internal valley regions. Meanwhile, thermal radiation is exchanged between the opposing high-temperature ridge surfaces, allowing part of the emitted radiative energy to be reabsorbed within the inter-ridge region rather than directly dissipated to the surroundings. The combined conduction and radiative exchange promotes heat redistribution throughout the ridge structure and supports a relatively uniform thermal field at the evaporation interfaces. Under wet conditions, part of the accumulated thermal energy is continuously consumed as latent heat for water vaporization, as reflected by the lower steady-state surface temperature of approximately 50–52 °C compared with 58–60 °C under dry conditions. The reproducible heating and cooling responses further indicate stable thermal regulation during repeated irradiation cycles. Therefore, the ridge architecture provides an effective thermal pathway that couples structural heat conduction with radiative energy reutilization to sustain interfacial evaporation. This thermal regulation provides the energetic basis for the coupled water transport and vapor-removal processes discussed in Fig. (4).

3.3. Evaporation Performance of the RSE

To elucidate how the ridge structure regulates airflow transport under different incoming-flow directions and thereby influences evaporation performance, COMSOL Multiphysics was employed to simulate the airflow distributions around the RSE under flows parallel and perpendicular to the ridge direction (Note S5). As shown in Fig. (4a), the airflow distributions under the two flow directions are presented from different viewing angles. The two images on the left correspond to airflow parallel to the ridge direction, where the airflow is transported steadily upward along the longitudinal channels of the ridge structure, forming relatively continuous and symmetric high-velocity regions above the evaporator. The two images on the right correspond to airflow perpendicular to the ridge direction. In this case, the incoming airflow is divided and deflected by the inclined ridge surfaces, subsequently moving upward along the slopes and exiting above the ridge peaks and central region. Under both flow directions, the ridge structure promotes air exchange near the evaporation interface and facilitates vapor removal, demonstrating its effective multidirectional airflow regulation capability.

To elucidate the water-supply behavior of the RSE under low-water-level conditions, COMSOL Multiphysics was employed to simulate the dynamic water transport process within the ridge-structured evaporator (Note S6). As shown in Fig. (4b), water initially enters the RSE through the regions on both sides that are in contact with the bulk water and is subsequently transported upward and inward along the inclined ridge surfaces under capillary action. As the transport process proceeds, the wetting front gradually extends from both sides toward the ridge peaks, inner inclined surfaces, and central valley, forming symmetric and continuous water-transport pathways. The wetting of the central region is relatively delayed because of its greater distance from the water source and longer transport pathway. Ultimately, most of the evaporation interface is effectively supplied with water, demonstrating that the RSE maintains excellent long-distance water transport and interfacial water-replenishment capabilities even under low-water-level conditions.

As shown in Fig. (4c), matrix arrays comprising 9 and 15 RSE units were assembled under a large-area indoor light source, and the water mass loss was continuously recorded using an electronic balance. These experiments were conducted to evaluate the evaporation performance and scalability of the RSE under large-scale assembly conditions. As shown in Fig. (4d), the evaporation rates of DR-H, DR-M, and DR-L in pure water were 1.89, 1.79, and 1.74 kg m⁻² h⁻¹, respectively. This result indicates that increasing the water level shortens the water-supply pathway and enhances interfacial water replenishment, thereby increasing the initial evaporation rate. However, in a 20 wt% NaCl solution, the salt crystallization location and crystallization rate associated with different water levels markedly affected the sustained evaporation performance. Although DR-H exhibited the highest evaporation rate in pure water, its stronger water supply and evaporation promoted rapid salt enrichment at the ridge peaks, where a distinct salt layer formed within approximately 6 h (Fig. S4). As the salt crystals progressively covered the ridge surfaces, the effective evaporation area decreased, while interfacial light absorption, water supply, and vapor escape were simultaneously hindered. DR-M exhibited a similar crystallization behavior, with

salt crystals rapidly depositing along the inclined surfaces on both sides and occupying the primary evaporation interfaces, thereby limiting its long-term evaporation performance.

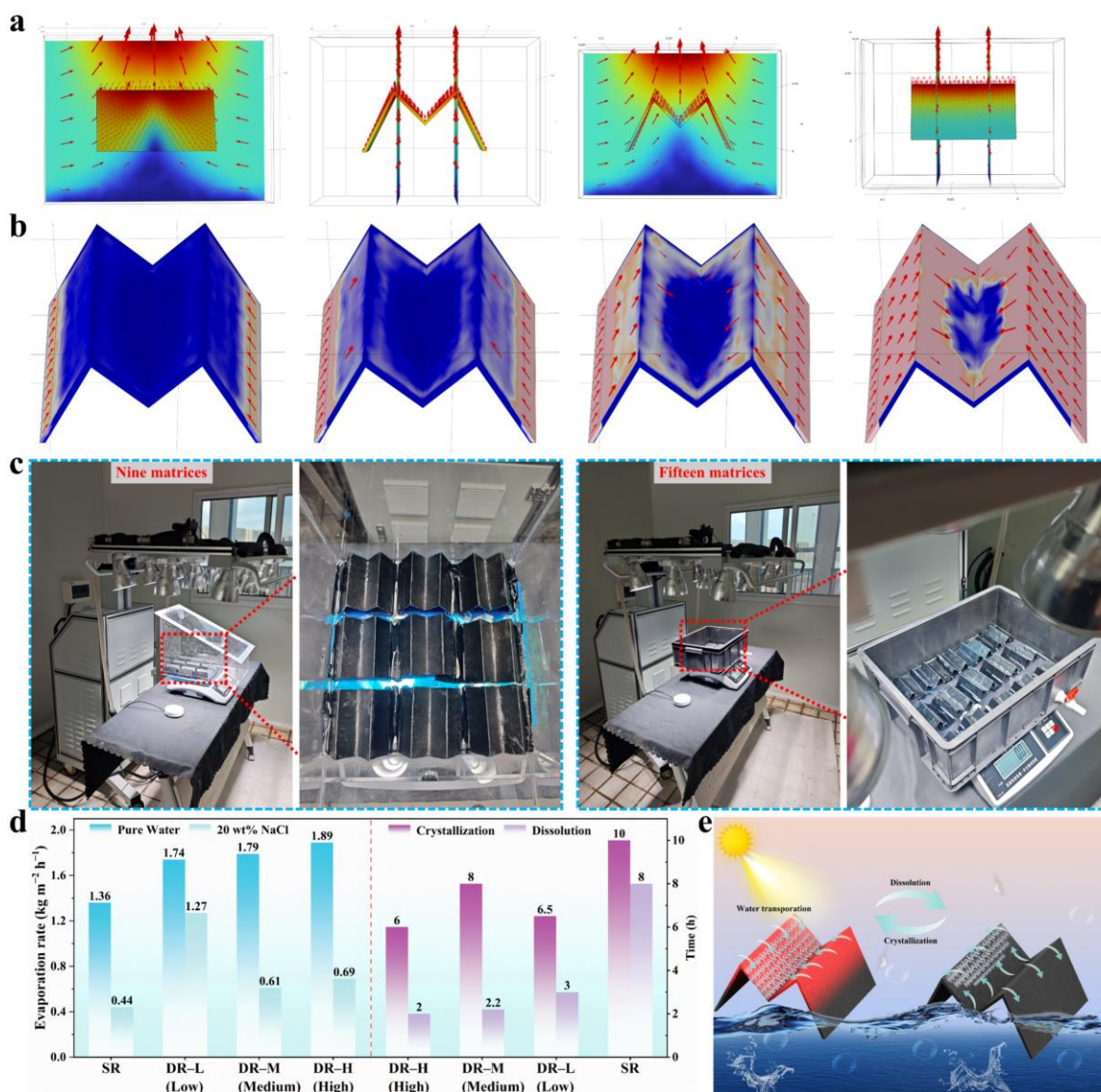


Figure 4: (a) Simulated airflow distributions under two flow directions. (b) Simulated water transport under low-water-level conditions. (c) Scalable evaporation tests using 9- and 15-unit RSE arrays. (d) Evaporation rates and salt crystallization/dissolution times under different water levels. (e) Schematic of the evaporation and salt-regulation mechanism.

In contrast, salt in DR-L preferentially nucleated and accumulated at the bottom of the central valley. This spatially separated the initial crystallization region from the primary photothermal evaporation surfaces on the two inclined ridges. Consequently, the deposited salt neither directly covered the major evaporation interfaces nor immediately disrupted the open space required for radiative exchange and vapor transport during the initial crystallization stage. This behavior reveals an important trade-off associated with water-level regulation. Although the longer water-supply pathway of DR-L resulted in a slightly lower evaporation rate in pure water than those of DR-M and DR-H, localization of salt in the central valley avoided the rapid surface coverage observed at higher water levels and enabled DR-L to maintain an evaporation rate of $1.27 \text{ kg m}^{-2} \text{ h}^{-1}$ in the 20 wt% NaCl solution. Nevertheless, continued salt growth would progressively occupy the central valley and could eventually interfere with radiative exchange and vapor transport. Therefore, the low-water-level strategy delays rather than completely eliminates the adverse effects of salt accumulation. When salt accumulation reaches a certain level, the water level can be temporarily increased from the low to the medium level. The shortened water-supply pathway and

enhanced water replenishment allow water to rapidly reach the crystallization region and promote salt redissolution. Complete salt dissolution was achieved within 2.5 h under both medium- and high-water-level conditions, requiring approximately 2.2 h for DR-M and 2 h for DR-H. After salt removal, the system can return to the low-water-level operating mode. This water-level-mediated regulation therefore balances directional salt crystallization during evaporation with rapid regeneration of the evaporation interface.

Fig. (4e) further illustrates how radiative heat transfer, water transport, airflow regulation, and salt management interact within the RSE rather than functioning as independent processes. Solar irradiation absorbed by the ridge surfaces is converted into thermal energy, while radiative exchange between the opposing inclined surfaces enables partial reabsorption and redistribution of the emitted heat. Capillary water transport continuously replenishes the evaporation interfaces, and the inclined surfaces and longitudinal ridge channels provide open pathways for airflow exchange and vapor removal. Water level governs the balance among these processes. At higher water levels, the shortened water-supply pathway favors rapid interfacial replenishment and a higher initial evaporation rate, but also promotes salt transport toward the ridge surfaces, where salt deposition can simultaneously interfere with light absorption, water transport, and vapor escape. In contrast, low-water-level operation slightly sacrifices the initial evaporation rate but shifts salt crystallization toward the bottom of the central valley. This spatial separation helps preserve the primary evaporation surfaces and delays interference with the opposing radiative surfaces and major vapor-transport pathways. As salt progressively accumulates, these advantages may gradually diminish because the growing crystals occupy the central region. Increasing the water level then accelerates salt dissolution and restores the open evaporation and transport interfaces. Thus, the enhanced performance of the RSE originates from the dynamic balance among water supply, salt localization, radiative heat utilization, and vapor transport, rather than from salt accumulation itself enhancing radiative or airflow transport.

3.4. Outdoor Performance Evaluation

To evaluate the scalability of the RSE and its practical potential for freshwater production, matrix arrays comprising 9 and 15 RSE units were assembled and integrated into an outdoor freshwater collection system, as shown in Fig. (5a). Infrared thermal imaging revealed that both RSE arrays developed large and relatively uniform high-temperature regions under natural sunlight, with a maximum surface temperature of approximately 50.1 °C. The high-temperature regions were primarily concentrated on the ridge surfaces and ridge peaks. Even when the array size was increased from 9 to 15 units, each evaporation unit maintained a stable photothermal response, indicating that matrix assembly did not significantly compromise the photothermal conversion performance of the RSE. These results further demonstrate the feasibility of the RSE for scalable outdoor solar evaporation and freshwater production.

As shown in Fig. (5b) and (5c), the hourly water losses of the 9-unit and 15-unit RSE arrays in both pure water and brine initially increased and subsequently decreased with the variation in solar irradiance. Solar irradiance reached its maximum at midday and then gradually declined, whereas the peak water loss exhibited a slight delay, primarily owing to heat accumulation within the evaporators and the bulk water. In pure water, the maximum hourly water losses of the 15-unit and 9-unit RSE arrays reached 0.341 and 0.196 kg h⁻¹, respectively, while the corresponding values in brine were 0.316 and 0.189 kg h⁻¹. The slightly lower water loss observed in brine was mainly attributed to the reduced water activity of the salt solution, which suppressed interfacial water evaporation [36]. Throughout the outdoor tests, the water loss of the 15-unit RSE array remained consistently higher than that of the 9-unit array, while both arrays exhibited similar responses to variations in solar irradiance. The calculated daily water losses of the 15-unit and 9-unit arrays were approximately 2.81 and 1.59 kg in pure water, respectively, and approximately 2.60 and 1.50 kg in brine, respectively. These results demonstrate that increasing the number of RSE units can effectively enhance the overall evaporation capacity. Moreover, the arrays maintained stable evaporation performance in highly saline water, confirming the feasibility of the RSE for scalable outdoor freshwater production.

As shown in Fig. (5d) and (5e) and the corresponding tabulated data, the 9-unit and 15-unit RSE arrays were subjected to continuous outdoor evaporation tests for 28 days using both pure water and brine (Table S4). Owing to fluctuations in natural solar irradiance, the daily water yields of the arrays varied to some extent. Nevertheless,

no obvious sustained decline was observed throughout the testing period, demonstrating the favorable long-term operational stability of the RSE arrays. In pure water, the maximum daily water yields of the 9-unit and 15-unit arrays reached 1.84 and 3.23 kg, respectively, whereas the corresponding values in brine were 1.72 and 2.97 kg. The 15-unit array consistently produced more water than the 9-unit array in both water systems, confirming that increasing the number of evaporation units can effectively enhance the freshwater production capacity of the system. To further evaluate the practical freshwater-production capability of the RSE arrays, the actual condensate collected during a 10 h outdoor test was quantified separately from the evaporation mass loss. The 9-unit and 15-unit arrays collected 1.595 and 2.624 kg of freshwater, corresponding to average freshwater collection rates of 0.1595 and 0.2624 kg h⁻¹, respectively. Based on the corresponding evaporated-water masses, the freshwater collection efficiencies were approximately 90.5% and 91.5%, respectively (Table S4). These results indicate that the condensation system recovered more than 90% of the generated water vapor, demonstrating effective conversion of solar-driven evaporation into practically collectable freshwater. Collectively, the stable long-term evaporation performance in brine together with freshwater collection efficiencies above 90% demonstrates the practical potential of the RSE arrays for scalable solar-driven seawater desalination and freshwater production.

SEM characterization of the RSE after seawater evaporation revealed that some salt particles were deposited on the CF surface. Nevertheless, the original porous structure was largely preserved, thereby maintaining continuous pathways for water transport (Fig. S5). In addition, the RSE exhibited good cyclic stability during 14 consecutive crystallization–dissolution cycles, with the evaporation rate decreasing only gradually from 1.28 to 1.15 kg m⁻² h⁻¹, corresponding to a retention of approximately 89.8%. Meanwhile, the salt dissolution efficiency remained above 99% throughout all cycles (Fig. S6, Table S5), demonstrating the reproducibility of the water-level-regulated salt removal and interface regeneration process. The collected distilled water was further analyzed by inductively coupled plasma spectroscopy. The concentrations of major metal ions, including Na⁺, Ca²⁺, K⁺, and Mg²⁺, were all below the World Health Organization drinking-water limits (Fig. S5f) [24], indicating that the system effectively retained dissolved salt ions and exhibited excellent desalination and water purification performance.

To further assess the potential economic performance of the RSE for scaled freshwater production, a preliminary levelized cost of water (LCOW) analysis was conducted for projected installation areas of 20, 50, and 100 m² based on the experimentally collected freshwater yield and explicitly defined cost assumptions (Note S9). As shown in Fig. (5g), the projected LCOW of all three systems decreases rapidly during the initial operating period and then gradually approaches a stable value with prolonged operation. This trend is mainly attributed to the progressive distribution of the initial fixed investment, particularly the condensation device, over the increasing cumulative freshwater production, whereas the periodic replacement of the RSE components becomes the dominant cost contribution during long-term operation. After 20 years, the projected LCOW values for the 20, 50, and 100 m² systems are approximately 23.15, 23.15, and 23.16 USD m⁻³, respectively. The nearly overlapping curves arise because the number of RSE units, material consumption, condensation-device area, and freshwater production are assumed to increase approximately linearly with installation scale in the present model, and therefore no additional economy-of-scale benefit is introduced. Under the current material costs, component lifetime, and experimentally measured freshwater yield, the projected LCOW remains above the reference water price of 4.47 USD m⁻³. Accordingly, the present analysis should be regarded as a preliminary economic projection rather than a complete techno-economic assessment. Further extension of the RSE service life, reduction in material and manufacturing costs, and improvement in system-level freshwater collection are expected to be important routes for reducing the long-term LCOW.

Compared with previously reported solar evaporators (Table S9 and S10) [11, 21, 37–51], the RSE exhibited competitive evaporation performance rather than relying on a single high evaporation-rate metric (Fig. 5h). Under one-sun irradiation, the RSE achieves an evaporation rate of 1.74 kg m⁻² h⁻¹ with an energy efficiency of 108.75%. More importantly, its distinguishing feature lies in the integration of thermal management, active salt regulation, and long-term interface regeneration within a simple ridge architecture. The opposing inclined surfaces enable partial reabsorption and redistribution of thermal radiation, while water-level regulation provides direct control over the salt crystallization pathway. Under low-water-level conditions, salt is preferentially localized in the central valley rather than on the primary evaporation surfaces and increasing the water level subsequently promotes rapid salt redissolution. The RSE maintained this regulation capability over 14 consecutive crystallization–

dissolution cycles, with the evaporation rate decreasing gradually from 1.28 to 1.15 kg m⁻² h⁻¹, corresponding to approximately 89.8% retention, while the salt dissolution efficiency remained above 99% throughout all cycles (Fig. S6). In addition, the 9- and 15-unit arrays showed no obvious sustained decline in freshwater production during 28 days of outdoor operation (Fig. 5d and 5e). Therefore, compared with systems evaluated mainly in terms of evaporation rate and energy efficiency, the RSE provides a more balanced combination of competitive evaporation performance, controllable salt management, radiative heat utilization, and extended operational stability. Its simple modular architecture also facilitates scale-up, although further improvements in component lifetime, manufacturing cost, and freshwater collection are still required to reduce the projected LCOW.

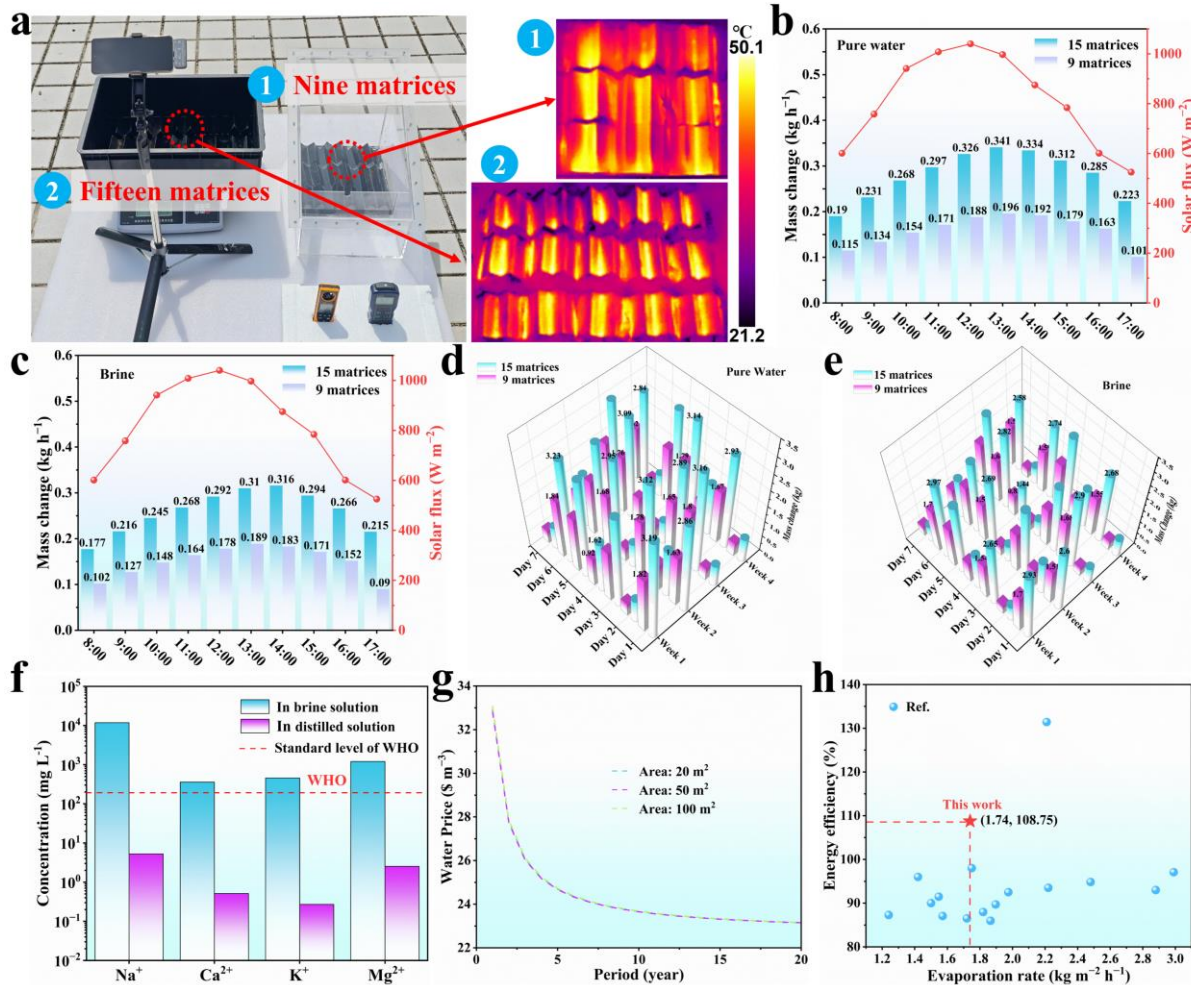


Figure 5: Outdoor freshwater production performance and economic analysis of the RSE arrays. (a) Outdoor water collection systems with 9 and 15 RSE matrices and their infrared thermal images. (b, c) Real-time mass changes in pure water and brine. (d, e) Evaporation performance during continuous operation in pure water and brine. (f) Concentrations of major ions in the feed brine and distilled water. (g) Performance comparison with previously reported solar evaporators. (h) Projected leveled cost of water (LCOW) of the RSE systems with nominal installation areas of 20, 50, and 100 m² as a function of operating period.

4. Conclusion

In summary, a ridge-structured evaporator was developed for efficient and scalable solar-driven desalination. By coupling radiative heat recovery, continuous water transport, airflow regulation, and controllable salt crystallization within a simple double-ridge architecture, the RSE achieved evaporation rates of 1.74 kg m⁻² h⁻¹ in pure water and 1.27 kg m⁻² h⁻¹ in a 20 wt% NaCl solution under one-sun irradiation. During outdoor tests, the maximum hourly water production rates of the 9- and 15-unit arrays reached 0.196 and 0.341 kg h⁻¹ in pure water, respectively, and 0.189 and 0.316 kg h⁻¹ in seawater. The arrays also maintained stable freshwater

production during 28 days of outdoor operation, demonstrating favorable scalability and environmental adaptability. Future work may focus on optimizing array configuration, condensation efficiency, and long-term structural durability to further improve water collection and reduce the cost of large-area solar desalination systems.

Conflicts of Interest

The authors declare no conflict of interest.

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Availability of Data

Data will be made available on request.

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