

Solar-powered photothermal-photocatalytic synergistic platform for simultaneous seawater desalination and antibiotic pollutant degradation

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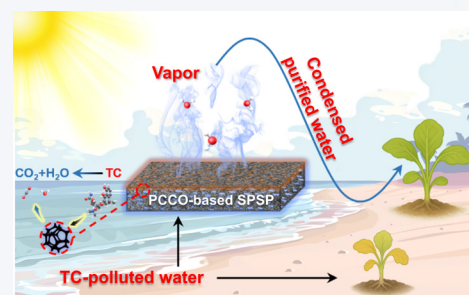
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ABSTRACT: The intensifying global issues of freshwater scarcity and antibiotic contamination, especially in coastal environments, present interconnected threats to both ecosystems and public health. Addressing these issues demands innovative solutions that synergistically enhance energy efficiency, promote sustainability, and deliver multifunctional benefits. In this study, we present a solar-driven photothermal-photocatalytic synergistic platform (SPSP) constructed from a PF/Co₃O₄/CNTs@O-ANF composite (PCCO), engineered to achieve simultaneous seawater desalination and antibiotic degradation. The strategically designed 3D hierarchical architecture combines broadband solar absorption, interfacial hydrophobic regulation, and catalytic heterojunction engineering, enabling an elevated water evaporation rate of 1.75 kg·m⁻²·h⁻¹ and efficient degradation of over 98% of tetracycline (TC) across three operational cycles. Outdoor field tests confirmed the system's operational robustness, producing 6.82 kg·m⁻²·day⁻¹ of purified water. Comprehensive water quality analyses further verified the removal of more than 99% of dissolved salts and organic contaminants, with the collected water exhibiting a neutral pH and complete absence of residual antibiotic activity. More importantly, the purified water facilitated robust growth of *Brassica rapa*, resulting in a 210% increase in biomass relative to plants irrigated with contaminated water, thereby demonstrating both ecological safety and agricultural applicability. Collectively, this SPSP technology represents a substantial advancement in sustainable water treatment, offering an integrated, energy-efficient solution for producing clean water and effectively remedying antibiotics.



KEYWORDS: solar-driven evaporation, photocatalytic, seawater desalination, tetracycline (TC), water remediation

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1 Introduction

Accelerating climate change, coupled with the growing impact of anthropogenic activities, has fundamentally reshaped the global environmental landscape, converging previously isolated challenges into interconnected and multifaceted threats. The concurrent escalation of freshwater scarcity and the proliferation of organic pollutants, particularly antibiotics, has led to a complex ecological

security challenge (Fig. 1(a), Fig. S1 and Table S1 in the Electronic Supplementary Material (ESM)) [1–3]. Remote sensing and geostatistical analyses of global surface water quality reveal that over 40% of coastal and inland watersheds are currently subjected to the combined pressures of rising salinity and contamination by persistent organic pollutants [4–6]. This crisis is especially pronounced in regions such as North Africa, the Middle East, and the western coast of South America [7]. Despite their extensive coastlines and abundant seawater resources, these areas paradoxically suffer from severe freshwater shortages, falling short of meeting the growing demands for drinking water and agricultural irrigation [8].

Concurrently, the unregulated application of antibiotics, such as tetracycline (TC), in intensive offshore aquaculture has led to significant contamination of coastal marine environments [9]. This exacerbates existing water quality challenges while imposing increasingly stringent requirements on seawater treatment technologies. Compounding these challenges is the widespread lack of adequate infrastructure and limited access to energy in affected regions, which collectively hinder efforts to achieve water security and rehabilitate ecological systems.

Conventional water treatment technologies, such as reverse

osmosis [10], multi-stage flash distillation [11], biological processes [12], and advanced oxidation techniques [13], exhibit notable limitations in addressing the multifaceted nature of compromised water quality (Table S2 in the ESM). These limitations can be broadly categorized into three critical challenges: (1) fragmented infrastructure dependence: The compartmentalized nature of the “water extraction-desalination-pollutant removal” workflow, coupled with reliance on extensive infrastructure, limits the effectiveness of conventional approaches in resource-limited settings. (2) Intrinsic technical trade-offs: The effectiveness of conventional treatment systems is compromised by high energy consumption, membrane fouling, labour-intensive maintenance, and the risk of residual pollutants, all of which hinder sustainable long-term operation. (3) Systemic incompatibility: Most current technologies are not inherently designed to address the simultaneous presence of elevated salinity and persistent organic pollutants, resulting in decreased treatment performance and compromised water quality. Overcoming these multifaceted challenges requires the development of a self-sustaining, modular purification platform capable of simultaneously harvesting freshwater and degrading pollutants under ambient conditions. Such a strategy is vital for mitigating the interlinked crises of water

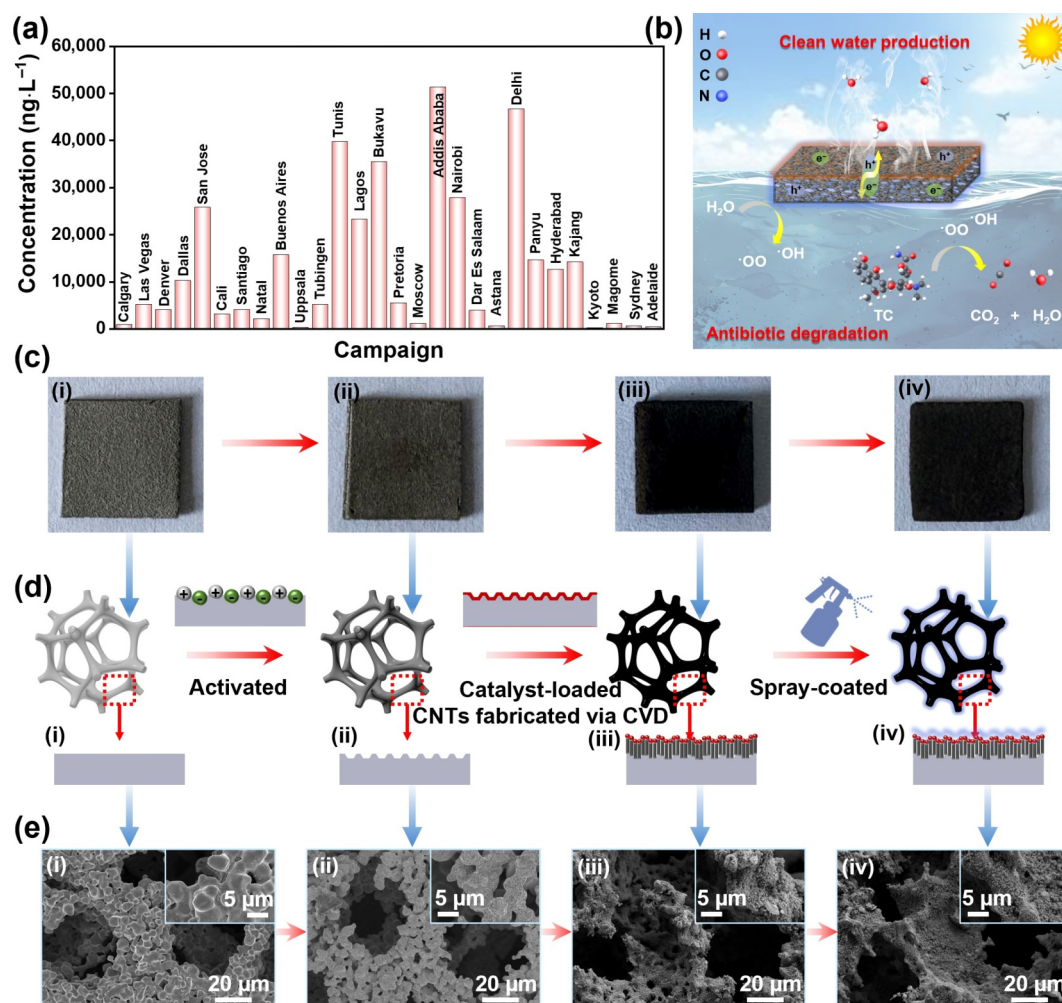


Figure 1 Research context, working principle, and material fabrication of the SPSP system. (a) Spatial distribution of terrestrial water storage and cumulative concentrations of active pharmaceutical ingredients (APIs) in regional river basins. (b) Operational principle of the rationally engineered SPSP. (c) Digital photographs of material evolution: (i) NF, (ii) ANF, (iii) Co₃O₄/CNTs@O-ANF, and (iv) PCCO. (d) Schematic illustrating the stepwise assembly of the PCCO. (e) SEM images of (i) NF, (ii) ANF, (iii) Co₃O₄/CNTs@O-ANF, and (iv) PCCO, showing morphological evolution during synthesis.

scarcity, chemical contamination, and energy insecurity amid intensifying ecological disruptions.

Solar-powered interfacial evaporation (SPIE) has recently gained attention as a promising off-grid water treatment technology [14–16]. Utilising high thermal efficiency, cost-effective scalability, and structural versatility, SPIE systems enable efficient low-temperature water evaporation through the strategic design of photothermal materials [17]. Crucially, the integration of photocatalytic functionality into SPIE systems enables the formation of a synergistic platform capable of simultaneous *in situ* pollutant degradation and high-purity water generation, representing a transformative step toward sustainable and decentralised water treatment solutions [18, 19]. Despite its promising potential, most current research on SPIE remains narrowly focused on optimizing evaporation rates or targeting individual contaminants, with only limited efforts devoted to integrating photocatalytic functionality for comprehensive water purification [20, 21]. Progress remains limited in the development of multifunctional systems capable of effectively treating complex water matrices, especially those simultaneously burdened with high salinity and persistent antibiotic contaminants.

Photothermal materials like carbon nanotubes (CNTs) have been widely employed in interfacial solar evaporation systems due to their broadband solar absorption, high photothermal conversion efficiency, and excellent thermal conductivity—making them ideal candidates for efficient water evaporation [22–24]. Concurrently, photocatalytic materials like cobalt oxide (Co_3O_4), featuring favorable electronic structures, a narrow bandgap, and reversible redox activity between Co^{2+} and Co^{3+} , can generate reactive oxygen species (ROS) under visible light for high-efficiency degradation of organic pollutants in water [25, 26]. While both material classes have demonstrated significant potential in water treatment applications, most, if not all, of the existing studies have focused on either evaporation or degradation individually. Integrated platforms that couple both functionalities within a single system remain largely underexplored. More importantly, the *in-situ* synchronous integration of the two materials—and the resulting synergistic enhancement of photothermal and photocatalytic functionalities—has rarely been investigated in prior research. Within the above context, a single system based on CNTs and Co_3O_4 prepared through a one-step *in-situ* synthesis route, which can enable the simultaneous enhancement of thermal field distribution and charge carrier separation, thus allowing for efficient interfacial water evaporation and photocatalytic degradation of organic contaminants, is highly desirable for real-world applications, yet remains challenging to achieve. Indeed, such a desired dual-functional system is particularly advantageous for treating complex wastewater streams containing both salts as well as organic pollutants.

In this study, we propose a solar-powered photothermal-photocatalytic synergistic platform (SPSP) constructed from a $\text{PF}/\text{Co}_3\text{O}_4/\text{CNTs}@O\text{-ANF}$ (PCCO) composite to address the coupled challenges of water scarcity and pollution in coastal regions. This SPSP system integrates broadband solar absorption, efficient photothermal conversion, and photocatalytic degradation through the rational engineering of a hierarchically structured interface. Specifically, CNTs and cobalt oxide nanoparticles (Co_3O_4) are *in situ* grown on a 3D oxidatively activated nickel foam (O-ANF) under low-temperature conditions, resulting in a hybrid interface that exhibits synergistic photothermal and photocatalytic

functionalities. This synergistic configuration establishes a localised “hot-active” zone that effectively suppresses charge carrier recombination and enhances light-to-energy conversion efficiency (Fig. 1(b)) [9, 19]. Notably, the SPSP strategically integrates hydrophobic-hydrophilic interfacial regulation with a graded pore architecture, enabling multi-level coupling of thermal management, directional water transport, and pollutant diffusion processes. Additionally, the hydrophobic perfluorosilane (PF) coating effectively suppresses salt crystallisation on the evaporation surface and prevents leaching of Co_3O_4 , thereby improving salt resistance and ensuring long-term operational stability. Overall, the SPSP developed in this study, capable of simultaneously harvesting freshwater and eliminating pollutants, represents a paradigm shift in water regeneration and environmental remediation, particularly suited for complex coastal ecosystems where water scarcity and contamination converge.

2 Experimental section

2.1 Preparation of the activated nickel foam (ANF)

The nickel foam (NF, 2.0 cm × 2.0 cm) was sonicated sequentially in high-purity deionized water (DI water) and ethanol (30 min each), then air-dried. Later, the cleaned NF was immersed in a mixed acid solution (acetic, nitric, sulfuric, and phosphoric acid, volume ratio: 5:3:1:1) for 60 s to activate its surface. The resulting acid-treated foam (ANF) was thoroughly rinsed with ultrapure water until neutral and dried at room temperature.

2.2 Synthesis of the $\text{Co}_3\text{O}_4/\text{CNTs}@O\text{-ANF}$

ANF was immersed in a 0.05 mol·L⁻¹ cobalt (II) acetate ethanol solution for 30 min and then air-dried. Later, the sample was transferred to a CVD furnace and treated at 500 °C for 60 min under an ethanol/argon (20 mL·min⁻¹) atmosphere to *in-situ* grow CNTs and Co_3O_4 nanoparticles simultaneously. The as-prepared sample was designated as $\text{Co}_3\text{O}_4/\text{CNTs}@O\text{-ANF}$.

2.3 Construction of the PCCO

A hydrophobic PF coating was applied by spraying a 1:50 (w/w) PF/ethanol solution onto the upper surface of $\text{Co}_3\text{O}_4/\text{CNTs}@O\text{-ANF}$, followed by drying at 60 °C for 1 h to obtain the PCCO.

2.4 Solar-driven evaporation and TC degradation

Simulated solar irradiation was provided by a xenon lamp (CEL-HXUV300H5, Hamamatsu) with an AM 1.5G filter. Evaporation performance was evaluated by measuring the mass loss of water samples using an analytical balance (FA20048, Sunny Hengping). The evaporation structure is depicted in the relevant schematic later. Solar-to-vapor efficiency was calculated using the typical formula [27]. More experimental details can be found in the ESM.

For the photocatalytic TC degradation experiment, 100 mL of TC solution with different concentrations was used. Before the experiment, the PCCO-based SPSP was floated on the surface of the TC solution for 60 min in the dark under stirring (200 rpm) to reach the adsorption equilibrium. During irradiation (1 sun), 2 mL aliquots were collected at selected time points, filtered (0.22 μm), and analyzed via HPLC (Agilent 1260 Infinity II) with a C18 column (4.6 mm × 150 mm, 5 μm). The mobile phase was acetonitrile/0.1% formic acid (20:80, v/v), and detection was performed at 280 nm. Specifically, the degradation ratio (DR) of TC

was calculated as follows [28]

$$DR = \frac{(C_0 - C_t)}{C_0} \times 100\% \quad (1)$$

where C_0 represents the initial concentration of TC, and C_t is the concentration of TC at different time intervals. More experimental details can be found in the ESM.

3 Results and discussion

3.1 Fabrication of the PCCO

Figures 1(c)–1(e) and Fig. S2 in the ESM comprehensively illustrate the fabrication pathway and microstructural evolution of PCCO. Specifically, as shown in Fig. 1(c)(i), the pristine nickel foam (NF) demonstrates a silver-gray metallic luster with uniform 40 μm pores (Fig. 1(e)(i)), providing optimal three-dimensional (3D) mechanical support and fluid transport pathways (Fig. 1(d), step 1). However, the smooth surface and limited active sites constrain its capability for multifunctional integration. To address this, an acid activation step was employed to introduce hierarchical surface roughness, yielding ANF (Fig. 1(c)(ii)), which enhances the specific surface area and hydrophilicity (Figs. 1(e)(ii) and Fig. S3 in the ESM), while also creating stronger interfacial adhesion for subsequent functional deposition.

Building on this, CNTs and Co_3O_4 nanoparticles were *in situ* grown upon the surface of ANF via low-temperature chemical vapor deposition (CVD), yielding $\text{Co}_3\text{O}_4/\text{CNTs}@O\text{-ANF}$ (Fig. 1(c)(iii)). As shown in Fig. 1(e)(iii), CNTs form a thermally conductive network, while Co_3O_4 nanoparticles uniformly decorate both the CNT surfaces and their interstitial voids, thus creating a tightly coupled photothermal-photocatalytic interface. The resulting hierarchical structure not only enhances light absorption and local heat confinement but also integrates high-efficiency charge-transfer pathways with catalytically active sites at the interface, enabling synergistic evaporation and pollutant degradation within a single multifunctional platform [29].

Finally, a hydrophobic layer was formed by spray-coating PF onto the top surface of $\text{Co}_3\text{O}_4/\text{CNTs}@O\text{-ANF}$ (Fig. 1(c)(iv) and Fig. S3 in the ESM), thus obtaining PCCO. Notably, as depicted in Fig. 1(e)(iv), the micro-porous structure of the substrate was preserved without noticeable clogging after the PF loading, thereby sustaining the structural pathways essential for efficient vapor escape. More importantly, this hydrophobic layer not only enhances anti-fouling capability at the interface but also stabilizes the Co_3O_4 nanoparticles by preventing their leaching during service, thereby improving the overall chemical stability of PCCO (detailed analysis will be discussed later).

3.2 Characterizations of the PCCO

Figure 2 and Figs. S4–S7 in the ESM provide a comprehensive characterization of the PCCO from multiple perspectives, revealing its microscopic architecture, elemental distribution, and chemical states. As shown in Fig. 2(a), the SPSP features a typical 3D open porous network. More specifically, it exhibits a hierarchically distributed pore architecture with markedly rough microstructure surfaces. This unique structure offers three critical functional advantages: (1) The hierarchical porosity and increased surface area significantly enhance light absorption and thermal localization through multiple light scattering [30, 31]; (2) the interconnected

macro-/meso-pores facilitate capillary-driven water transport and vapor escape while maintaining structural stability [32]; and (3) the pronounced specific surface area as well as roughness creates abundant active sites for pollutant adsorption and degradation [33]. Together, these structural characteristics can establish an ideal microenvironment for simultaneous high-efficiency solar interfacial evaporation and concentrated pollutant removal.

Figures 2(b)–2(d) and Fig. S4 in the ESM present the spatial distributions and relative contents of F, Co, O, Ni, and C elements in the PCCO. The above elements are homogeneously distributed without notable aggregation or phase segregation, demonstrating a high level of synergistic integration of functional components within the system during the low-temperature assembly process. Specifically, CNTs formed *in situ* upon the surface of the O-ANF substrate are interlaced to create a continuous conductive-thermal network. This network can effectively enhance the material's light absorption and heat transfer capacities. Meanwhile, Co_3O_4 nanoparticles are evenly distributed on the surface and in the interstices of the CNTs, jointly constructing a synergistic reaction interface that couples conductive pathways with catalytically active sites. Overall, this rationally designed interface with "conductive-thermal-catalytic" multi-functional synergistic coupling can significantly boost light absorption and photothermal conversion efficiency, prolong charge carrier lifetimes, and promote the generation of hydroxyl radical, collectively enabling the SPSP's efficient water evaporation and pollutant degradation. Additionally, the uniform distribution of the F element at the interface further confirms successful incorporation of the hydrophobic PF layer, thereby providing direct evidence for the construction of a hydrophobic-hydrophilic gradient structure. This architectural design not only underpins the anti-salt-crystallization capability but also stabilizes the catalytic structure by preventing Co_3O_4 leaching during the prolonged operation, thereby ensuring the long-term performance integrity [34].

Figures 2(e) and 2(f) are the XRD patterns of NF, ANF, and $\text{Co}_3\text{O}_4/\text{CNTs}@O\text{-ANF}$, systematically revealing the structural evolution process of the materials across successive fabrication stages. The pristine NF displays typical characteristic diffraction peaks of the metallic Ni, mainly located at 44.5° , 51.8° , and 76.4° , corresponding to the (111), (200), and (220) crystal planes of Ni, respectively [35]. Upon acid activation, the resulting ANF shows no new crystalline phases, but a noticeable attenuation in peak intensity, indicating that the surface structure is coarsened, which facilitates subsequent deposition of functional components. In the $\text{Co}_3\text{O}_4/\text{CNTs}@O\text{-ANF}$ sample, new peaks emerge at 19.0° , 31.2° , 36.9° , 38.5° , 44.8° , 55.7° , 59.4° , and 65.2° , corresponding to the (111), (220), (311), (222), (400), (422), (511), and (440) crystal planes of Co_3O_4 , thus confirming its successful incorporation. In addition, a broad peak centered around 22.5° is attributed to the (002) plane of graphitic CNTs, further validating their presence. Most notably, additional peaks at 37.2° , 43.3° , 62.8° , and 75.4° match the (101), (012), (110), and (113) crystal planes of NiO, indicating partial oxidation of the Ni scaffold during low-temperature CVD [36]. The introduction of NiO not only does not damage the original support structure but also forms a passivation film to protect the matrix and provides additional photocatalytic active sites at the interface, which is conducive to the synergistic effect with Co_3O_4 in subsequent photocatalytic reactions and jointly helps to improve the electron transfer efficiency and pollutant degradation performance. Moreover, the Raman spectrum in Fig.

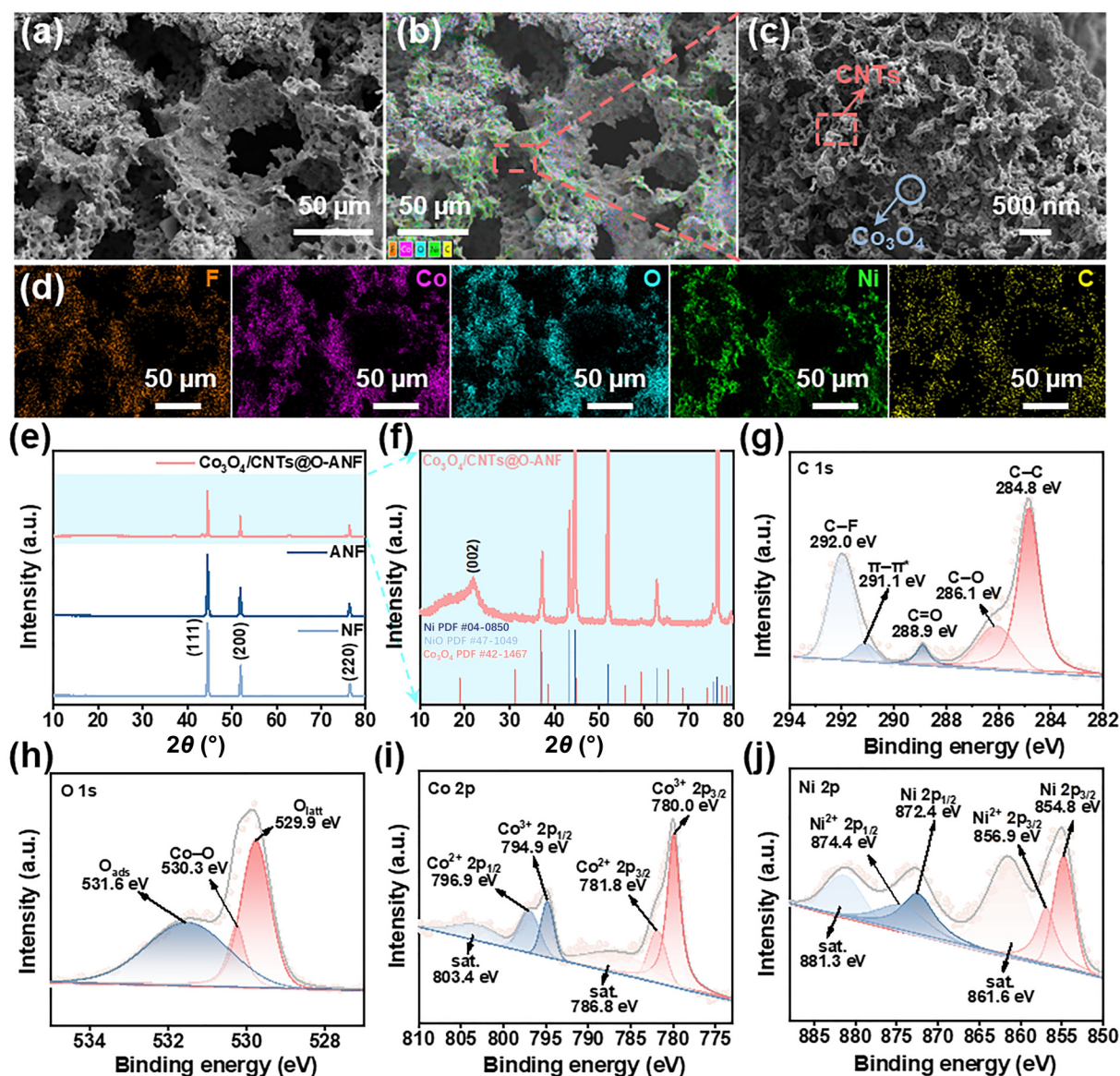


Figure 2 Morphological, compositional, and structural characterizations of the designed PCCO. (a) SEM image showing the hierarchical porous architecture of the PCCO. (b) Elemental mapping of F, Co, O, Ni, and C, indicating homogeneous distribution of components within the PCCO. (c) High-magnification SEM image, revealing surface morphology and nanotexture of the PCCO. (d) The corresponding elemental mapping of the region shown in (b). (e) and (f) XRD patterns of NF, ANF, and the $\text{Co}_3\text{O}_4/\text{CNTs}@O\text{-ANF}$, illustrating structural evolution and phase composition. (g)–(j) High-resolution XPS spectra of C 1s, O 1s, Co 2p, and Ni 2p with peak deconvolution, revealing chemical states and interfacial bonding within the PCCO.

S5 in the ESM elucidates the interaction between the carbon-based structure and the catalytic components. The D band and G band are obvious, and the I_D/I_G ratio is high, indicating that the carbon structure contains many defect sites [37, 38]. These structural defects are helpful for electron separation and provide stable and sufficient anchoring sites for Co_3O_4 . Most specifically, the vibration peaks appearing in the range of $400\text{--}700\text{ cm}^{-1}$ correspond to the characteristic signals of Co_3O_4 , further confirming its composition.

Figures 2(g)–2(j), and Figs. S6 and S7 in the ESM showcase the XPS spectra of the PCCO, further elucidating its surface elemental composition as well as chemical valence states. The C 1s spectrum (Fig. 2(g)) reveals five deconvoluted peaks at 284.8 (C–C), 286.1 (C–O), 288.9 (C=O), 291.1 ($\pi\text{--}\pi^*$), and 292.0 eV (C–F), indicating the presence of diverse oxygen-containing functional groups upon CNTs surface. These functionalities facilitate

interfacial charge transfer and promote surface reaction activity [39]. The O 1s spectrum (Fig 2(h)) consists of peaks at 529.9 eV (lattice oxygen, O_{lat}), 530.3 eV (Co–O bonds), and 531.6 eV (adsorbed oxygen, O_{ads}), thus suggesting an abundance of oxygen vacancies and reactive species, which is conducive to adsorbing reactants and promoting the photocatalytic process [40]. The Co 2p spectrum in Fig. 2(i) exhibits a typical double-peak structure of Co $2p_{3/2}$ (Co^{3+} 780.0 eV and Co^{2+} 781.8 eV) and Co $2p_{1/2}$ (Co^{3+} 794.9 eV and Co^{2+} 796.9 eV), accompanied by obvious satellite peaks (786.8 and 803.4 eV), demonstrating that the Co element exists in a mixed valence state of Co^{2+} and Co^{3+} , further verifying the existence characteristics of Co_3O_4 ($\text{CoO}\cdot\text{Co}_2\text{O}_3$). This dual-valence state helps form a p-n junction interface, enhancing the separation efficiency of photogenerated carriers, and thus effectively improving the photocatalytic degradation performance [41]. In the Ni 2p

spectrum depicted in Fig. 2(j), in addition to metallic Ni $2p_{3/2}$ (854.8 eV) and Ni $2p_{1/2}$ (872.4 eV), characteristic peaks of Ni^{2+} (such as 856.9 and 874.4 eV) and their satellite peaks (861.6 and 881.3 eV) appear, indicating that the surface of part of the Ni foam has been oxidized to form NiO during the fabrication process, which is consistent with the XRD test results [42, 43]. Moreover, Fig. S7 in the ESM presents the high-resolution F 1s XPS spectrum of PCCO, with two primary peaks observed at 688.6 and 689.5 eV, corresponding to $-\text{CF}_3$ and $-\text{CF}_2-$ groups, respectively. The above results further confirm the successful incorporation of hydrophobic PF coating.

3.3 Indoor solar-powered water evaporation

All indoor experiments (Sections 3.3 and 3.4) were performed under controlled laboratory conditions, specifically at a temperature of $25 \pm 1^\circ\text{C}$ and a relative humidity of $45\% \pm 5\%$. Additionally, a calibrated solar simulator emitting an AM 1.5G spectrum with an irradiance of $1000 \text{ W}\cdot\text{m}^{-2}$ was employed, unless otherwise specified.

Initially, the ultraviolet-visible-near infrared (UV-Vis-NIR) spectroscopic analysis (Fig. 3(a)) demonstrated exceptional broadband absorption of PCCO, with absorption efficiencies far exceeding those of the pristine NF (47.78%) and ANF (56.77%). Such a higher optical absorption enabled SPSP to have good light-to-heat conversion capability [34, 44].

Subsequently, deploying the classic evaporation setup (Figs. 3(b) and Fig. S8 in the ESM), the photothermal conversion as well as water evaporation capacities of the PCCO-based SPSP compared to other controls were tested. As shown in Fig. 3(c), the PCCO-based SPSP showcases a rapid photothermal response under 1 sun illumination, reaching thermal equilibrium within 180 s and achieving a surface temperature as high as 50.0°C —significantly higher than those of the control samples, including NF (43.9°C), ANF (38.5°C), and $\text{Co}_3\text{O}_4/\text{CNTs}@O\text{-ANF}$ (40.4°C). The steady-state infrared images under 1 sun and dark conditions (Fig. 3(d) and Fig. S9 in the ESM) further confirm that the PCCO-based SPSP maintains a higher temperature and a more uniform thermal

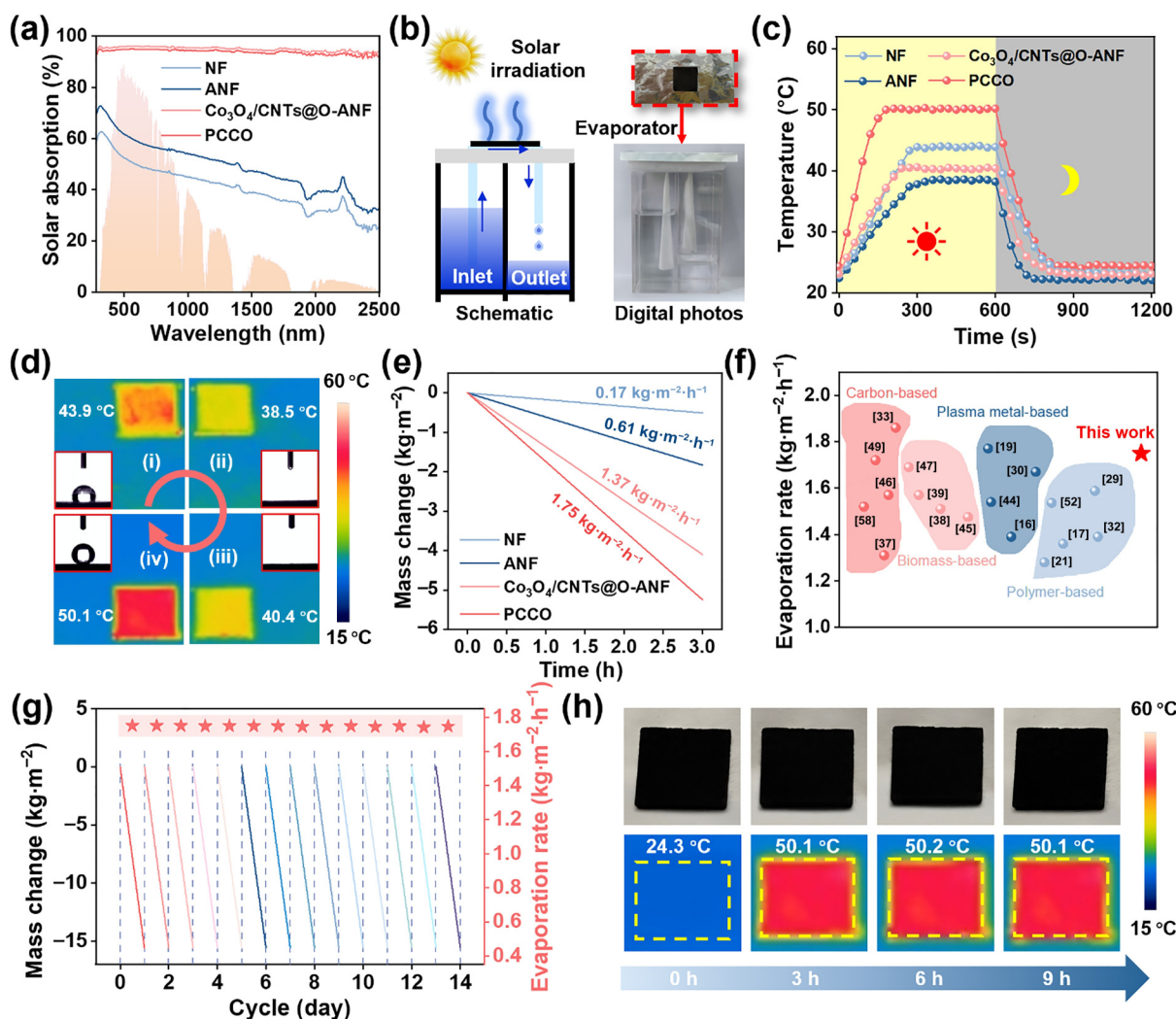


Figure 3 Photothermal performance and solar evaporation behavior of the PCCO-based SPSP under 1 sun. (a) Solar absorption spectra of the different samples (NF, ANF, $\text{Co}_3\text{O}_4/\text{CNTs}@O\text{-ANF}$, and PCCO). (b) Schematic of the typical solar-evaporation design. (c) Temperature-time profiles of the four samples under 1 sun and dark conditions over 20 min. (d) Infrared thermal imaging photos of the four samples when they reach steady state under 1 sun irradiation, insets show the contact angle for the four samples ((i) NF, (ii) ANF, (iii) $\text{Co}_3\text{O}_4/\text{CNTs}@O\text{-ANF}$, and (iv) PCCO). (e) Mass changes of seawater through water evaporation under 1 sun over 3 h. (f) Benchmarking the evaporation rate of the designed PCCO-based SPSP against reported photothermal evaporators under 1 sun. (g) Cyclic stability test of the PCCO-based SPSP showing mass change and evaporation rates through 14 operational cycles (9 h light/15 h dark per cycle). (h) Digital and infrared thermal images of the PCCO-based SPSP's surface during the 14th cycle, confirming salt resistance and thermal uniformity.

distribution at the evaporation interface compared to $\text{Co}_3\text{O}_4/\text{CNTs}@O\text{-ANF}$. This enhancement arises from the balance between capillary-driven water transport and interfacial thermal regulation [45]. Specifically, the rich hydrophilic functional groups on the surface of $\text{Co}_3\text{O}_4/\text{CNTs}@O\text{-ANF}$ and the strong capillary action brought by its 3D porous structure endow it with a superhydrophilic nature [46, 47]. While these characteristics are beneficial for rapid water uptake and continuous replenishment, thereby providing a relatively sufficient water (substance) supply for the evaporation process, they are not conducive to the thermal management at the evaporation interface, which in turn affects the water evaporation performance. Upon the uniform deposition of the PF layer, the surface contact angle reaches up to 140° (Fig. S3 in the ESM), imparting its excellent super hydrophobicity [48, 49]. This tailored surface can effectively synchronize the heat and mass transport while suppressing salt crystallization at the evaporation interface, thus ensuring long-term operational stability under high-salinity conditions. Overall, the synergistic combination of outstanding broadband solar absorption and efficient photothermal conversion of the designed PCCO-based SPSP provides a prerequisite for high-efficiency solar-driven water evaporation.

Afterward, Bohai Seawater was used as the feed to be treated, and the water evaporation performance of the four samples was systematically tested under the illumination intensity of 1 sun. As shown in Fig. 3(e), the evaporation rate of the PCCO-based SPSP is as high as $1.75 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$, representing a 27.7% enhancement over its hydrophilic counterpart without a PF layer. The evaporation rate of PCCO-based SPSP has surpassed most previously reported interfacial evaporation systems (Fig. 3(f) and Table S3 in the ESM). Meanwhile, its photothermal conversion efficiency is as high as 90.87% (Fig. S10 and Table S4 in the ESM, the photothermal conversion efficiency was calculated using the classical energy balance method [50], details can be found in the ESM).

This exceptional performance arises from three synergistic design features: 1) high and broadband solar absorption enhanced by hierarchical porous CNT- Co_3O_4 architecture; 2) high-efficiency thermal confinement via interfacial evaporation and porous insulation; and 3) balanced water-path/vapor-release channels that sustain high interfacial temperatures with limited heat loss [51]. Figure 3(g) further demonstrates the long-term operational stability of the PCCO-based SPSP over 14 consecutive days (08:00–17:00, 9 h light/15 h dark daily). Throughout the 14-day cyclic testing period, the evaporation rate under sunlight remained consistently above $1.73 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ with negligible performance degradation, indicating robust long-term service stability. Additionally, time-resolved optical and infrared thermal images of the SPSP after 9 h of continuous illumination on the 14th day (Fig. 3(h)) revealed no visible salt crystallization upon the evaporation surface, along with uniformly distributed surface temperatures. To verify the long-term optical performance of the designed PCCO-based SPSP, we conducted UV–Vis–NIR absorption tests on PCCO after the above 14 consecutive cycles. As shown in Fig. S11 in the ESM, the absorption spectra remained virtually unchanged across the full 280–2500 nm range, including the visible-NIR regions that most relevant to photothermal conversion. These results confirm the outstanding optical stability of the PCCO material under repeated operation, thus ensuring sustained solar absorption and thermal efficiency for extended usage. Besides, the relevant scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) results in Figs. S12 and S13 in the ESM show that after the 14-

day cyclic test, the pore channels within the PCCO remain intact. Key elements such as Co and F are still stably distributed, with no obvious migration, leaching, or agglomeration. Better yet, there is no obvious salt agglomeration and deposition, highlighting its superb anti-salt ability, thermal response capacity, structural durability, as well as service stability. To further evaluate the anti-fouling performance of the PF-modified top layer, the surface morphologies were then analyzed after 14 consecutive solar desalination cycles using seawater. As presented in Fig. S14 in the ESM, the $\text{Co}_3\text{O}_4/\text{CNTs}@O\text{-ANF}$ surface (without PF coating) exhibited noticeable salt crystallization and surface roughness due to direct exposure to saline water and evaporative flux. In sharp contrast, the PCCO's surface remained clean and smooth (Fig. S12 in the ESM), clearly demonstrating the effectiveness of the PF layer in inhibiting salt accumulation over extended operation.

To further evaluate the hydrophobic durability of the PF top layer during long-term operation, we then conducted water contact angle measurements following each of 30 consecutive desalination-photodegradation cycles. As demonstrated in Fig. S15(a) in the ESM, the contact angle remained consistently above 145.87° , with an initial value of 147.13° , indicating superb retention of water-repellent properties throughout the repeated cycles. Additionally, the representative contact angle images from the 1st, 7th, 14th, and 30th cycles are provided in Fig. S15(b) in the ESM, further confirming the sustained hydrophobicity of the PF top layer without noticeable degradation. Overall, these results demonstrate the robust long-term stability of the PF top layer under prolonged and harsh operational conditions.

In addition, to further and fully verify the structural and chemical stability of the designed PCCO in a high-salinity water environment, UV–Vis absorption spectra were recorded during immersion in a 10 wt.% NaCl solution throughout 0 to 14 days (Fig. S16 in the ESM). The results indicate that with the extension of the immersion time, the corresponding absorption peak of the NaCl solution does not show obvious attenuation, and the color of the solution does not change significantly. This implies that there is no leaching of active components from the PCCO in such a high-salinity water environment, and it has excellent structural stability, thus offering a solid guarantee for long-term operation in practical seawater or high-salinity brine treatment scenarios.

3.4 Indoor solar-powered TC degradation

In this section, a continuous-flow solar-driven organic pollutant degradation and removal device has been designed and constructed. Specifically, this device comprises multiple interconnected water reservoirs coupled with photothermal evaporation/catalysis modules (Fig. 4(a)). Driven by solar energy, the device can achieve continuous water evaporation from tank 1 to tank n , accompanied by stepwise organic pollutants degradation upon the photocatalytic interfaces. Additionally, the condensed water can effectively avoid the risk of pollutant redissolution due to spatial separation.

Afterwards, four different photothermal evaporation/catalysis modules were integrated into the above device, and their performance in degrading TC (concentration: $30 \text{ mg}\cdot\text{L}^{-1}$) was systematically compared and analyzed (Fig. 4(b)). The results show that after a single treatment (from tank 1 to tank 2), the degradation ratio of TC by the PCCO-based SPSP can reach up to 73.4%, significantly outperforming NF (25.7%), ANF (30.5%), and $\text{Co}_3\text{O}_4/\text{CNTs}@O\text{-ANF}$ (58.8%). Such a pronounced enhancement

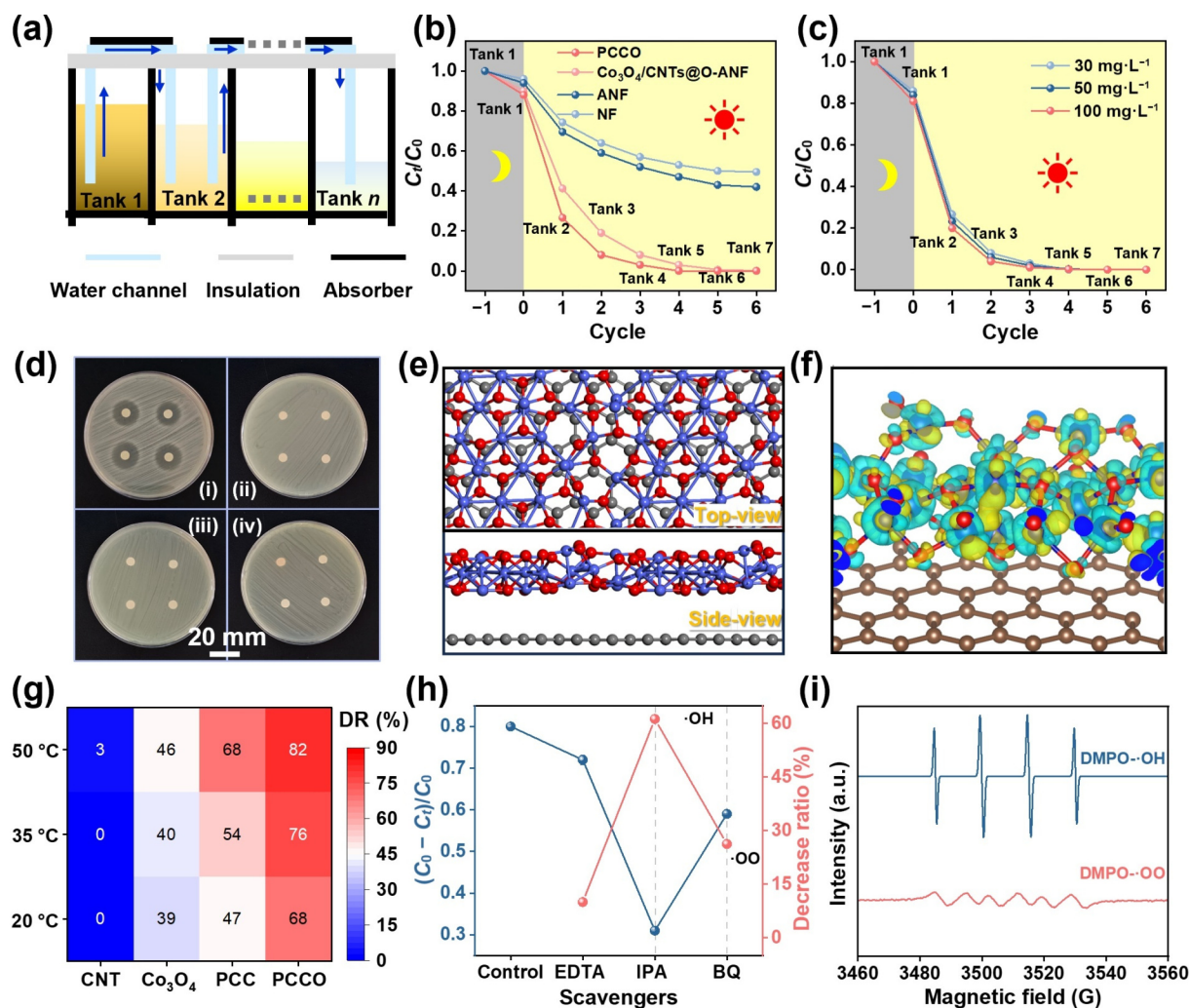


Figure 4 Photocatalytic degradation of TC and mechanistic insights into the SPSP system. (a) Schematic showing the continuous-flow evaporation and degradation device driven by solar energy. (b) TC concentration changes in different SPSP systems using NF, ANF, Co₃O₄/CNTs@O-ANF, and PCCO under 1 sun. (c) TC concentration changes in the PCCO-based SPSP under varying pollutant concentrations under 1 sun. (d) Antibacterial activity assessment via zone inhibition tests: (i) TC-contaminated water, (ii) single-cycle treated water, (iii) purified water, and (iv) DI water control. (e) DFT-optimized interfacial structure of the Co₃O₄/CNTs heterojunction, with crystallographic color coding: blue-violet for Co, red for O, and gray for C. (f) Charge density difference (CDD) analysis of Co₃O₄ before and after loading on CNTs, where the light blue region represents charge depletion and the light-yellow region represents charge accumulation. (g) Temperature-dependent degradation ratios (DR) of TC over different photothermal materials (CNT, Co₃O₄, PCC, and PCCO) at 20, 35, and 50 °C. (h) Effect of various reactive species scavengers (EDTA, IPA, BQ) on the TC degradation ratio, indicating the involvement of ·OH and ·OO radicals. (i) ESR spectra confirming the generation of ·OH and ·OO radicals during the TC degradation process.

is primarily attributed to the synergistic effect of the Co₃O₄/NiO composite catalyst, and the relatively high interfacial temperature provided by the hydrophobic PF layer also facilitates to promote the rapid and efficient progress of the catalytic reaction [52].

Further, to explore the practical application potential of the designed SPSP, its degradation performance for TC at different initial concentrations (30, 50, and 100 mg·L⁻¹) was systematically tested. As shown in Fig. 4(c), even at a high TC concentration of 100 mg·L⁻¹, the device embedded with the SPSP achieves a degradation ratio of 80.2% after a single treatment cycle (from tank 1 to tank 2) and nearly 100% degradation after just three treatment cycles (from tank 1 to tank 4), thereby demonstrating its excellent tolerance to different pollutant loads. Additionally, the results of high-performance liquid chromatography (HPLC) (Fig. S17 in the ESM) confirm that after a single treatment cycle with the SPSP (TC concentration in the feed: 100 mg·L⁻¹), the intensity of the characteristic peak corresponding to TC is significantly reduced,

indicating that its molecular structure has been effectively damage. Notably, no obvious intermediate product peaks are detected in the condensed purified water, and its spectral characteristics are like those of the high-purity deionized water (DI water) produced in the laboratory, thus suggesting high purification quality. Further, to validate the ecological safety of the produced water, antibacterial assays were conducted using the above four types of water samples: (i) TC-polluted water, (ii) one-cycle treated water, (iii) purified water, and (iv) DI water. As shown in Fig. 4(d), only the TC-polluted water sample formed a pronounced antibacterial zone (~17 mm in diameter), whereas the one-cycle treated, purified, and DI water samples all exhibited no inhibitory effect on *Escherichia coli* growth. Such above results confirm that the designed PCCO-based SPSP can effectively degrade and remove TC, and the treated and purified water exhibits favorable biosafety, thus offering promising water sources for ecological restoration and agricultural irrigation. Besides, to verify the long-term service stability of SPSP

in treating high-concentration TC-polluted water (e.g., 100 mg·L⁻¹), a continuous 14-day cycling test was carried out. As depicted in Fig. S18 in the ESM, during the above period, the water evaporation rate has no obvious fluctuations, and the TC degradation ratio after a single treatment (from tank 1 to tank 2) remains at around 80%, thereby confirming its durability and sustained performance under prolonged operation.

Subsequently, the density functional theory (DFT) simulations were employed to elucidate the catalytic degradation mechanism of TC by the PCCO-based SPSP [53]. In Figs. 4(e) and 4(f), and Fig. S19 in the ESM, the carbon nanotube-supported cobalt oxide composite was computationally modeled as a graphene (001)-Co₃O₄ (110) heterojunction configuration, demonstrating an interfacial lattice mismatch below 15%. The simulation result revealed that a stable supported configuration between Co₃O₄ and CNTs can be formed through interfacial charge transfer (Fig. 4(e)). Later, the charge density difference (CDD) plot (Fig. 4(f)) further demonstrated significant electron redistribution regions on the Co₃O₄ surface after CNT loading. Such interfacial electron redistribution facilitates the effective separation of photogenerated electron-hole pairs, thereby enhancing the generation efficiency of reactive oxygen species (ROS) and ultimately improving the photocatalytic degradation performance [54]. These findings confirm the superior photocatalytic degradation activity of the as-prepared Co₃O₄/CNT toward the antibiotic pollutant like TC.

Indeed, in this work, CNTs serve dual roles: (1) photothermal converter that generates localized heating. We prepare CNT-coated ANF (CNT), Co₃O₄-coated ANF (Co₃O₄), and a hydrophobic ANF co-coated with CNT and Co₃O₄ (PCC). Under 1 sun, Co₃O₄ exhibits the slowest temperature rise and the lowest steady-state temperature (Fig. S20 in the ESM). In contrast, the temperature responses of CNT and PCC are similar, and PCCO performs a lower steady-state temperature (Fig. S20 in the ESM). As such, CNTs can significantly enhance the local thermal field. Additionally, the elevated local temperatures can well reduce kinetic barriers for photocatalytic reactions and thus enhance molecular transport, culminating in a synergistic increase in both water evaporation rate and pollutant degradation efficiency [36, 55]. A custom-built temperature-controlled platform (Fig. S21 in the ESM) is employed to investigate the degradation performance under varying interface temperatures at 1 sun illumination. The results demonstrate that, under identical light intensity, the TC degradation ratio exhibits a significant enhancement with increasing interface temperature (Fig. 4(g)). (2) Quasi-metallic electron acceptors that facilitate charge separation. At the heterojunction formed between CNT and p-type Co₃O₄, electron transfer occurs from Co₃O₄ to CNTs, establishing an internal field that hinders recombination. Besides, the CNT network can also ensure uniform dispersion of Co₃O₄ nanoparticles and provide defect-rich catalytic site. As such, CNT does not have photocatalytic degradation performance on TC, and Co₃O₄ shows a weak performance (Fig. 4(g)). In comparison, PCC and PCCO performed a high TC degradation performance (Fig. 4(g)). Note that the performance of PCC is inferior to that of PCCO, likely due to the vapor deposition method producing a more uniform catalytic structure compared to the direct coating approach. In conclusion, PCCO can achieve efficient TC degradation through the coupled photothermal-photocatalytic synergistic process.

Afterward, to further and more precisely elucidate the photocatalytic degradation mechanism of TC by our rationally

designed SPSP, we carry out the quenching experiments and electron spin resonance (ESR) test (Figs. 4(h) and 4(i)). A reduction in degradation ratio with IPA or BQ confirms the huge contribution of ·OH and ·OO·, while minimal inhibition with EDTA-2Na suggests little contributions from holes (Fig. 4(h)). Such above radicals will attack the aromatic rings and amino groups of TC molecules, resulting in ring-opening reactions and eventual mineralization. ESR results confirm the above inference (Fig. 4(i)). These results are consistent with the reported works [9, 56].

Better yet, as showcased in Figs. S22(a) and S23 in the ESM, the SPSP also exhibited excellent catalytic degradation capacity toward volatile organic compounds (VOCs, e.g., phenol) and the typical dye pollutants in textile wastewater, such as methyl orange (MO) and methylene blue (MB). Meanwhile, the condensed water could not detect these pollutants, as shown in Figs. S22(b) in the ESM. The above results highlight the SPSP's broad-spectrum applicability and promising potential for practical wastewater treatment.

3.5 Outdoor experiments and application prospects

Figure 5 systematically evaluates the performance of the PCCO-based SPSP in outdoor environments, highlighting its capacity for simultaneous desalination and photocatalytic degradation of TC-polluted seawater, and the potential application of the purified water obtained through evaporation-condensation in agricultural irrigation.

Figures 5(a) and 5(b) showcase the structural design and physical appearance of the outdoor testing setup. Notably, following about two consecutive hours of operation, water condensation became visibly apparent on the device's upper surface. Figure 5(c) and Fig. S24 in the ESM quantifies the TC degradation ratio and the corresponding water production rate (WPR) achieved by the SPSP over 9 h of continuous outdoor operation using TC-polluted seawater as feed. Despite fluctuations in outdoor solar irradiance (0.45–0.80 kW·m⁻²) during the test period, the system consistently maintained stable photothermal evaporation coupled with efficient photocatalytic degradation, highlighting its operational robustness and practical efficacy under real-world environmental conditions.

Afterward, to further evaluate the desalination and purification capabilities of the designed SPSP, we carried out a comprehensive water quality analysis comparing the collected purified water (obtained via evaporation-condensation processes in Fig. 5(c)) with the original TC-polluted seawater. Key parameters, such as major cation concentration, electrical conductivity, pH, chemical oxygen demand (COD), total organic carbon (TOC), and total dissolved solids (TDS), were systematically examined. As shown in Fig. 5(d), the concentrations of various cations in the purified water decreased by three to four orders of magnitude compared to the original TC-polluted seawater, with removal ratio exceeding 99%. These results well meet the relevant standards for domestic and agricultural usage [57, 58]. From Fig. 5(e), it is evident that the electrical conductivity of the purified water decreased significantly by three orders of magnitude compared to the original TC-polluted seawater, while the pH remained neutral (ranging from 7.23 to 7.60). According to Fig. 5(f), the removal rates of the three key indicators, i.e., COD, TOC, and TDS, in the purified water were 97.39%, 94.11%, and 99.46%, respectively, compared to the original TC-polluted seawater. Collectively, the above results demonstrate the exceptional desalination and purification efficacy of the designed SPSP system.

To visually assess the ecological safety and agricultural

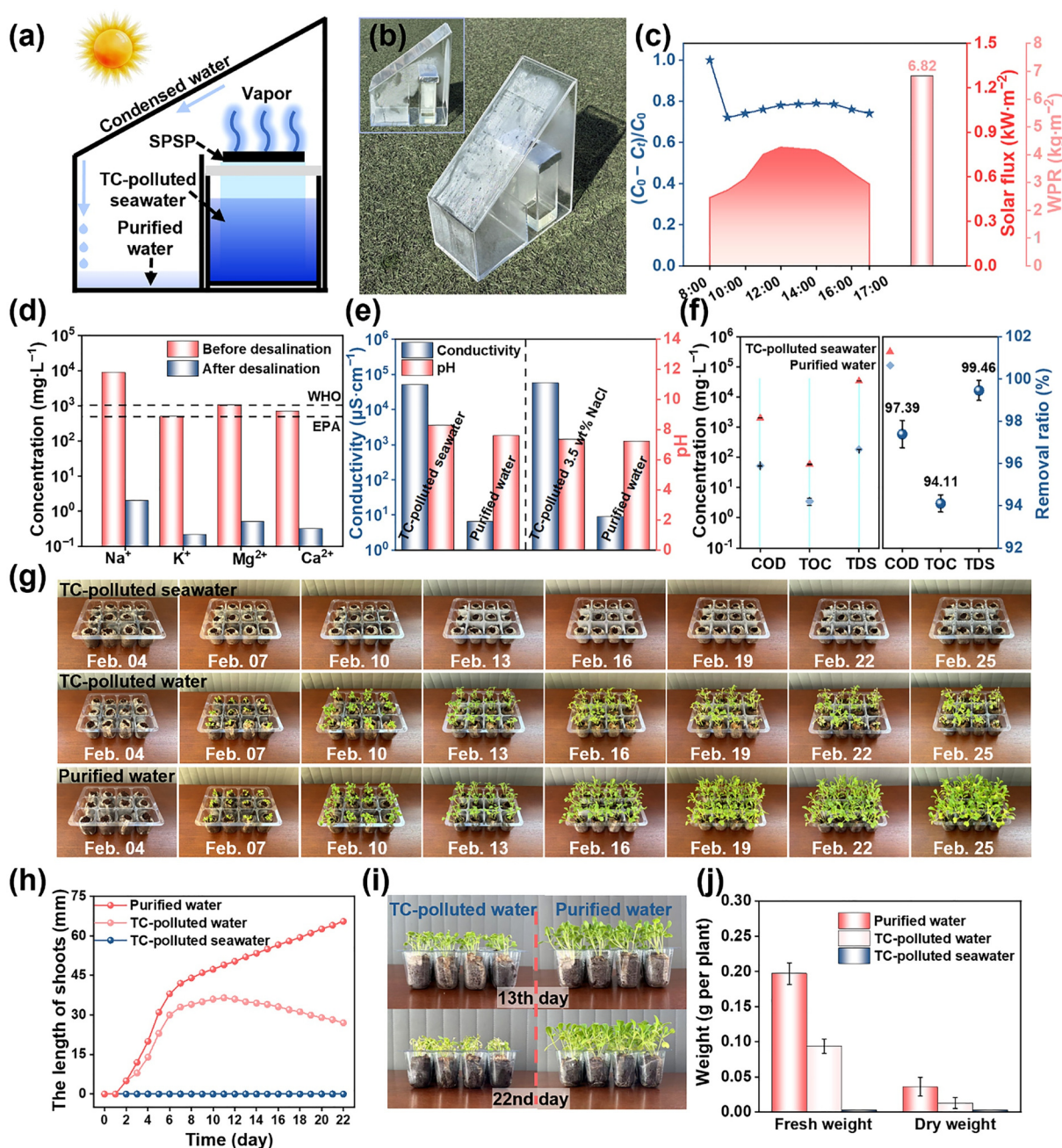


Figure 5 Outdoor performance of the PCCO-based SPSP and agricultural validation of the purified water output: (a) Schematic of the outdoor experimental setup. (b) Photograph of field-testing conditions. (c) Real-time monitoring of solar irradiance, TC degradation ratio, and water production rate (WPR) over a 9-h outdoor cycle. (d) Comparative major ion concentration analysis between TC-polluted seawater and purified water output. (e) Changes in conductivity and pH of both real and artificial TC-polluted seawater before and after the PCCO-based SPSP treatment. (f) Left: COD, TOC, and TDS values of TC-polluted seawater before and after the SPSP treatment. Right: corresponding removal ratio. (g) Time-lapse images of *Brassica rapa* growth from Day 1 to Day 22 under irrigation with TC-polluted seawater, TC-polluted water, and SPSP-purified water. (h) The shoot height changes over 22 days under the three different irrigation conditions. (i) Comparative photos of plant morphology on Days 13 and 22. (j) Fresh and dry biomass of harvested *Brassica rapa*, confirming enhanced agronomic performance with purified water.

applicability of the purified water produced by the SPSP system, a controlled irrigation experiment was conducted using *Brassica rapa* as the model crop. As depicted in Fig. 5(g) and Figs. S25–S27 in the ESM, the growth of *Brassica rapa* was monitored over 22 days under irrigation with three water sources: 1) TC-polluted seawater, 2) TC-polluted water, and 3) the collected purified water. The results clearly show that plants irrigated with the purified water exhibited the most vigorous growth, with germination observed as early as day 2, followed by healthy leaf expansion, vibrant green

coloration, and robust development. In contrast, plants irrigated with the TC-polluted water demonstrated partial germination but suffered from stunted growth, chlorosis, and wilting over time, indicative of antibiotic-induced phytotoxicity. Most notably, no germination was seen in the TC-polluted seawater group throughout the growth period, thus demonstrating synergistic inhibition by combined salt stress and antibiotic toxicity on seedling establishment.

To systematically evaluate the impact of purified water on plant

growth, we then conducted multi-dimensional analyses, including the trend of seedling height growth, actual growth status, as well as biomass accumulation. Through these analyses, the advantages of the purified water obtained by the SPSP system in agricultural irrigation and its positive effect on plant growth are clarified. Figure 5(h) quantitatively tracks the shoot height progression of *Brassica rapa* over the 22-day cultivation period under three irrigation conditions. The group irrigated with purified water achieved an average seedling height as high as 65.5 mm, substantially exceeding that of the TC-polluted water group (~27 mm) and the TC-polluted seawater group (0 mm). This result further highlights the inhibitory effects of high salinity and tetracycline residues on root water uptake and plant metabolic regulation. Notably, from day 11 onward, the seedling height in the TC-polluted water group began to decline, while the purified water group maintained a steady upward growth trajectory, indicating that the purified water provided a more favorable hydraulic environment for plant growth. Figure 5(i) and Fig. S28 in the ESM compare the actual growth status of the two groups of plants on Days 13 and 22. The plants irrigated with purified water demonstrate broad and well-spread leaves, deep green foliage, an upright and robust morphology, and more developed root systems, thus indicating enhanced photosynthetic efficiency and effective nutrient accumulation. In sharp contrast, plants in the TC-polluted water irrigation group show symptoms of phytotoxic stress, including marginal leaf necrosis, yellowing, and stunted growth. This clearly indicates that the presence of antibiotics can lead to obvious physiological disorders in plants and thereby affect their normal growth. Figure 5(j) further compares the biomass accumulation across the three groups.

The average fresh and dry weights of plants irrigated with purified water reached 0.197 and 0.036 g, respectively—more than twice those measured in the TC-polluted water group (0.094 and 0.013 g). No biomass was recorded for the TC-polluted seawater group owing to the germination failure. Together, these results demonstrate that the purified water produced by the SPSP system not only supports healthy plant growth but significantly enhances biomass productivity, thereby confirming its ecological safety and agronomic potential for irrigation applications (Figs. 5(g)–5(j)).

To conclude, this section experimentally validated the designed PCCO-based SPSP system's proficiency in desalinating and purifying the TC-polluted seawater under outdoor real-world conditions. Through a comprehensive plant irrigation experiment, we have conclusively demonstrated the ecological safety and agricultural suitability of the purified water generated by this system. The obtained results indicate the versatility of this SPSP system, thus showcasing its applicability across diverse fields, including sustainable agriculture, water resource regeneration, as well as environmental remediation, and underscoring its strong potential for real-world deployment.

4 Conclusion

In summary, we developed a PCCO-based SPSP that strategically integrates a 3D porous architecture, broadband solar absorption, a conductive catalytic network, and interfacial hydrophobic modulation. This multifunctional design enabled simultaneous and efficient solar-driven seawater desalination and TC degradation, achieving both high evaporation performance and contaminant removal under natural sunlight. During outdoor field trials using TC-contaminated seawater, the SPSP demonstrated a TC degradation ratio exceeding 72% and produced 6.82 kg·m⁻² of

freshwater after 9 h of continuous operation. Comprehensive water quality assessments revealed substantial reductions in key parameters, including major cations, conductivity, COD, TOC, and TDS, with the condensed water maintaining a neutral pH and showing no residual antibiotic activity. Importantly, the purified water directly supported the healthy growth of *Brassica rapa*, resulting in a 210% increase in biomass compared to plants irrigated with untreated contaminated water, thereby validating the ecological safety and agricultural applicability of the system. This study highlights a paradigm shift in sustainable water treatment technologies, introducing a green, low-carbon, and high-efficiency purification strategy that can simultaneously address freshwater scarcity and emerging antibiotic pollutants. The SPSP is particularly suited for vulnerable environments, such as islands, coastal regions, and saline-alkali lands, where access to clean water is limited and contamination risks are high. Overall, the SPSP offers a scalable and modular solution for water regeneration, environmental remediation, and sustainable agriculture, advancing the goal of clean water for all under real-world conditions.

Electronic Supplementary Material: Supplementary material (figures of antibiotic entry routes, material morphologies/spectra, thermal images, pollutant degradation, plant growth, and tables of API concentrations, technology comparisons, and evaporation rates/efficiencies) is available in the online version of this article at <https://doi.org/10.26599/NR.2025.94907971>.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request.

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Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

Author contribution statement

L. Y. Z.: Data curation, formal analysis, writing – original draft. W. W. H.: Data curation, formal analysis, validation. Y. R. D.: Simulation, formal analysis, validation. Z. Y. J.: Visualization. D. C.: Resources, visualization. H. Z.: Formal analysis, investigation. W. S.: Methodology, formal analysis. Y. B.: Resources, visualization. T. S.: Visualization, investigation. L. Z.: Formal analysis, investigation. J. L. K.: Validation. L. H., N. N. C., and Z. Y.: Funding acquisition, project administration, writing – review & editing. All the authors have approved the final manuscript.

Use of AI statement

None.

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