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**Metal Sulfides Functionalized Carbon Foam from Waste PET: An Advanced Photothermal Material
Enabling Circular Economy for Interfacial Solar Desalination**

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DEDICATION

TO MY PARENTS, WHO TAUGHT ME
PERSEVERANCE AND GAVE ME THE SPACE TO
DREAM

Everything Broke to Evolve: So Value Experience Over Possession,
Because Memories are a Real Treasure of Life
(Muzammil Hussain)

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Abstract

Water scarcity is an increasingly pressing issue and, for this reason, developing clean water production technologies is crucial. Interfacial solar desalination is a promising technology that produces clean water from bulk available seawater using renewable solar energy. However, finding a novel photothermal material is challenging. To operate this advanced technology efficiently, the material should be capable of capturing the maximum solar spectrum from UV/Vis to Near-IR to gain maximum photothermal efficiency, making the process more sustainable. An advanced photothermal material demands a rational design that meets the environmental, technological and economic needs of a sustainable process. In this framework, developing advanced materials from waste offers a win-win solution that advances the circular economy. In addition to water scarcity, plastic pollution is another challenge for researchers, the environment, and the industrial sector. In this study, we upcycled waste PET (Polyethylene Terephthalate) into carbon foam (CF) using eutectic salt (NaCl/ZnCl₂) at low-temperature carbonization (340 °C), compared to Flash Joule Heating carbonization (2000-3000 °C). To enhance the optical activity and photothermal effect of CF, we further functionalized the CF with various metal sulfide nanostructures such as CuS, CuCo₂S₄, and Cu₃SbS₄-Sb₂S₃ via conventional hydrothermal synthesis, and Co_xBi₂S₃ using microwave synthesis technology. The synthesized solar evaporators were characterized through a multi-technique approach using XRD (X-ray Diffraction), SEM (Scanning Electron Microscopy), XPS (X-ray Photoelectron Spectroscopy), and UV/Vis-NIR (Ultraviolet/Visible to Near-Infrared) spectroscopy.

The metal sulfides-functionalized CF demonstrated a significant enhancement in average absorption, above 95%, compared to bare CF (68%) in the IR region. An interfacial solar desalination experiments were conducted under one-sun solar irradiation (1000 W/m²). The obtained results demonstrated an excellent evaporation rate of CuS/CF (1.92 kg m⁻² h⁻¹), CuCo₂S₄/CF (2.40 kg m⁻² h⁻¹), Co_xBi₂S₃/CF (2.35 kg m⁻² h⁻¹), and Cu₃SbS₄-Sb₂S₃/CF (2.82 kg m⁻² h⁻¹) compared to the benchmark CF (1.58 kg m⁻² h⁻¹). These remarkable outperforming results were achieved due to excellent photo-to-thermal conversion and the crucial role of morphology, both in CF and in metal sulfides. To emphasize the role of hydrophilicity, contact angle analysis was systematically applied, demonstrating the excellent wettability of the photothermal material. ICP-AES (Inductively Coupled Plasma Atomic Emission Spectroscopy) was applied to the evaporated water by collecting water vapors, demonstrating a 99% reduction in salt concentration. These results reflect the rational design of metal

sulfide-decorated CF as a potential nano-enhanced photothermal material for interfacial solar desalination. Moreover, the outcomes of the work underscore the integral role of the circular economy in achieving sustainability goals, specifically focusing on SDG-6, SDG-7, and SDG-13, to address global plastic pollution and water scarcity in an eco-friendly and economically attractive manner.

List of Abbreviations

XRD	X-ray diffraction
XPS	X-ray photoelectron spectroscopy
SEM	Scanning electron microscopy
EDS	Energy dispersive spectroscopy
HRTEM	High-Resolution transmission electron microscopy
TEM	Transmission electron microscopy
DSC	Differential scanning calorimetry
HAADF-STEM	High-angle annular dark-field scanning transmission electron microscopy
UV-vis-IR	Ultraviolet-visible-infrared spectroscopy
IR	Infrared
NIR	Near Infrared
ICP-AES	Inductively coupled plasma-atomic emission spectroscopy
STG	Solar steam generator
ISD	Interfacial solar desalination
PET	Polyethylene terephthalate
PU	Polyurethane
PS	Polystyrene
PP	Polypropylene
PTFE	Polytetrafluoroethylene
PVDF	Polyvinylidene fluoride
MW	Microwave
SCP	Single country publication
MCP	Multi-country publication
SDG	Sustainable development goals
IWRM	Integrated water resources management
RO	Reverse osmosis
ED	Electrodialysis
EDR	Electrodialysis reverse
CAGR	Compound annual growth rate
LSPRs	Local surface plasmonic resonance
rGo	Reduce graphene oxide
3DTPS	3-dimensional porous sponge

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1 Introduction and Review of Literature

Water is an essential compound originating in nature, with its structure and unique chemical properties, acting as a key player in biological, environmental, and societal systems. The unique molecular structure of water is based on hydrogen bonding, which gives rise to its polarity, solvent properties, cohesive behavior, and high specific heat, reflecting its critical importance to sustaining life. There is no argument or debate about saying ‘no known biological process could proceed without water and ecosystems would collapse’. Beyond its biological importance, it plays crucial roles in industrial manufacturing, agricultural productivity, and urban development. According to Gleick (2003), freshwater resources are irregularly distributed worldwide, with variable chemical and physical properties; only 2.5% of Earth’s total water is freshwater, and less than 1% of that is readily accessible for human use. This limited access to freshwater across regions and cultures demands urgent, sustainable water management. Water scarcity pressure is increasing day by day due to a combination of factors such as industrial expansion, population growth, urbanization, and climate change (Gleick, 2003).

According to the United Nations report, by 2050, the universal water requirement is expected to surge by up to 55% (UNESCO, 2018). The demand will mainly be driven by increases in manufacturing (400%), electricity generation (140%), and domestic use (130%). In addition, around 40% of the world population is estimated to face water stress by mid-century (WWAP, 2018). Moreover, the World Health Organization (2021) stated that even today, over two billion people face a lack of access to pure drinking water, which openly impacts public health and economic development (WHO, 2021). Water scarcity is one of the significant challenges of the 21st century, as water is essential to sustaining life and development. To overcome these challenges, several vital steps are required, such as the need for integrated water resource management (IWRM), innovation in water-saving technologies, including novel material development, and policy reforms to promote sustainable access to freshwater.

In this context, the widespread research and development of wastewater treatment processes, including activated sludge, advanced oxidation, nutrient removal, membrane bioreactors, and even direct potable reuse, has resulted in an overall treatment capacity that remains insufficient to meet agricultural, growing urban, and industrial demands worldwide. In addition to clean water production from industrial wastewater, the conceptualization of alternative water resources and reusability/upcycling could be excellent candidates. Seawater

corresponds to a vast, ever-renewing resource that covers approximately 70% of Earth's surface and offers an enormous volume and global connectivity.

1.1 Desalination and the global market view

Desalination is one of the crucial methods of freshwater production from seawater by separating salt, and it is becoming an increasingly vital part of integrated water resource strategies (Angelakis et al., 2021). Essentially, desalination can be obtained through two primary processes: thermal desalination or membrane desalination. Thermal desalination works on the utilization of thermal energy to evaporate the water and condense in an additional step; on the other hand, the membrane process produces freshwater based on selectivity pressure, electrical potential, or vapor pressure gradients (J. Wang & Huo, 2022). Membrane desalination includes several technologies, such as reverse osmosis (RO), electrodialysis (ED), electrodialysis reversal (EDR), and forward osmosis. The reverse osmosis supports 80% of the world's freshwater production from seawater, and at the end of 2020, the international desalination capacity was around 115 Mm³/day (42 billion m³/year) (Dhakal et al., 2022). Sea water reverse osmosis desalination operates at a higher pressure than the osmotic pressure by exposing saline water to a selectively permeable membrane. During this process, the water passes through the membrane, and the membrane's selective properties reject salt. The complete desalination process comprises several steps: a saline water intake system and pretreatment; a desalination separation system; energy recovery devices; post-treatment of treated water; and salt management. In seawater reverse osmosis, the recovery ratio of water is lower (35-50% at 40-80 bars). Apart from its performance, over time, with advancements in technology, various factors have been considered to reduce the cost of this process, from material development to plant operation. According to a recent report, the global water desalination market size is estimated to be USD 18.36 billion in 2024. It is projected to reach USD 31.69 billion by 2030, growing at a CAGR (Compound Annual Growth Rate) of 9.6% from 2025 to 2030, as shown in Figure 1.1. This surge in market value ultimately reflects the need for such technology to fill the gap of water scarcity, especially in regions with low river and natural lake resources (Shemer et al., 2023).

The energy consumption and environmental aspects of membrane technology are one of the major rising concerns. Figure 1.2 shows the estimated unit costs of saline water reverse osmosis desalination from 2015 to 2050, categorized into three cost components: energy, capital, and a combined production cost. Two scenarios are compared: one under a standard production scenario (black dashed line) and another under a stringent energy-climate policy

scenario (green dashed line). Over time, capital costs (represented by the gray bars) decline steadily, from approximately \$0.75/m³ in 2015 to around \$0.40/m³ by 2050. Energy costs (red bars) remain relatively stable, slightly below \$0.35/m³ throughout the period. Under the energy-climate policy (blue bars), energy costs are higher than in the standard scenario due to the likely implementation of more sustainable energy sources, peaking around 2035 and then gradually decreasing. Total production costs decline in both scenarios, but the energy-climate policy scenario consistently projects higher overall costs than the standard production scenario. The energy cost is estimated to remain unchanged for plant operation based on conventional fossil fuel processes; energy costs are projected to remain unchanged, while they will increase primarily due to elevated electricity rates driven by climate policies (L. Gao et al., 2017). Environmental concerns about the desalination process are essential, particularly how it affects marine life and contributes to global warming. Fossil fuels are the bottom line for energy production to operate desalination processes; these energy-producing units are directly correlated with emissions of greenhouse gases and air pollution. The emission of CO₂ in RO desalination is estimated at 0.6-4.3 kg CO₂/m³ with a maximum value of 8.6 kg CO₂/m³ (Shemer et al., 2023).

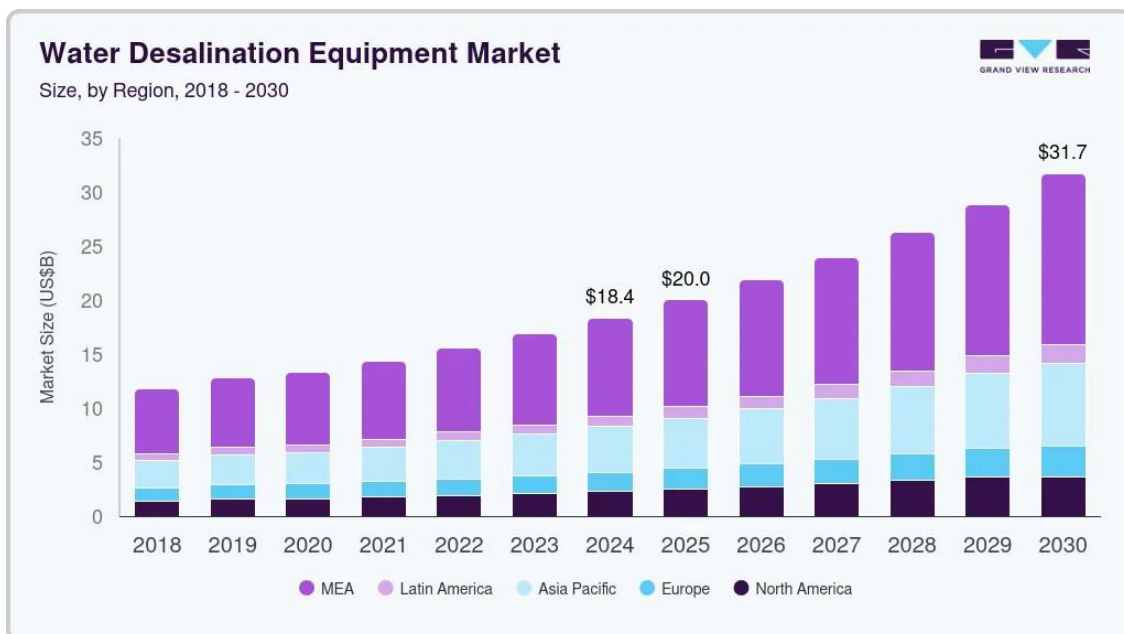


Figure 1.1: Water desalination equipment market cost analysis from 2018 to 2030 for MEA (Middle East and Africa), Latin America, Asia Pacific, Europe, and North America (data taken from <https://www.grandviewresearch.com/industry-analysis/water-desalination-equipment-market>).

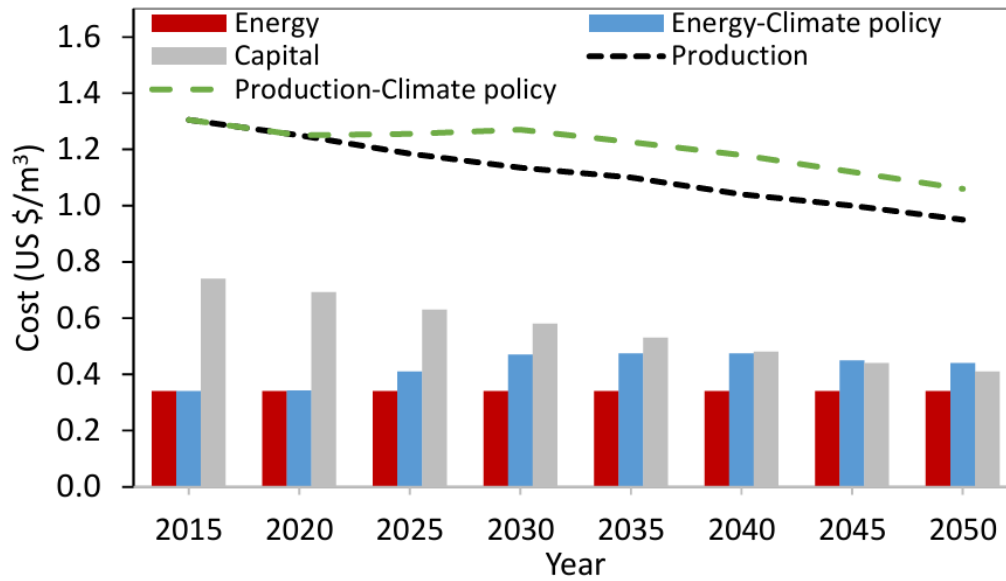


Figure 1.2: Averaged predicted unit production, capital, and energy costs of SWRO desalination. Climate policy assumed stringent policies to constrain global warming; Copyright Open Access (Shemer et al., 2023).

The sustainable development and management of water require highly cost-effective and robust technologies to reuse water, and achieving these goals demands consideration of the economic and societal factors that can lead to success. The number of problems, such as the long lifespan of surviving infrastructure, high initial costs, and limited flexibility for rapid integration of newer technologies, can limit innovation within the water industry. Several innovative technologies at lab scale are facing diverse issues, including poor infrastructure, limited engineering expertise, low process efficiency, high energy requirements, and limited economic benefits, with scaling-up challenges. There is a vast gap in conceptualization, and a lack of novel technologies adaptation for scaling up. To overcome all these issues, it is imperative to broaden critical thinking, accelerate funding support for research and development bodies, and adapt towards novel solutions (Ahmed et al., 2023; Söderholm, 2020).

In light of the above discussion, it is an urgent requirement to consider renewable energy-based resources for desalination. In this context, solar desalination represents a significant advancement over conventional desalination approaches, offering a sustainable, energy-efficient, and environmentally friendly solution to freshwater scarcity.

1.2 Solar Desalination

Solar energy is one of the most significant sources of renewable energy with a broad spectrum that offers the highest potential to achieve sustainable high-intensity energy output

(Dalvi et al., 2015). Sunlight comprises a broad wavelength spectrum with the zenith angle of 48.2° that covers a significant region of the world, which includes the ultraviolet (UV) region (300-380 nm), visible light region (380-760 nm), and near infrared region (760-2500 nm) at the standard solar spectrum (AM 1.5). The energy distribution within the solar spectrum is accounted for as the UV region (3%), visible light (45%), and the near-infrared region (52%) (Taranova et al., 2024). Figure 1.5(a) shows the global distribution of solar energy, indicating the enormous and widespread availability of these renewable energy resources. These observations open a new door for implementing renewable solar energy technologies to meet sustainability goals. With advances in related technologies, solar-to-thermal conversion has advanced significantly, ushering in a new era of solar steam generation (Ni et al., 2015a).

At the moment, the solar-based technologies such as photo-electric, photo-thermal, photo-catalytic, and photo-biological are progressing very efficiently, but to date, the most excellent direct utilisation method for solar energy harvesting is solar-thermal conversion and steam generation, which includes application in photo-thermal power generation, photo-thermal energy storage, and seawater desalination (Shi et al., 2020). The urgency of this technology has led to an entirely innovative approach to novel materials that act as solar absorbers. The solar absorber should encompass the following characteristics: a broad absorption spectrum, high photo-to-thermal conversion efficiency, low cost, high surface hydrophilicity, and a multi-pore structure (Sheng et al., 2020). Table 1.1 summarizes the limitations of conventional desalination processes and highlights the advantages of solar desalination as an alternative. By harnessing renewable solar energy, solar desalination offers a pathway to overcome the drawbacks of traditional methods and advance beyond conventional desalination technologies.

Table 1: Comparison of solar desalination vs the conventional desalination process

Conventional Desalination (Disadvantages)	Solar Desalination (Advantages / Solutions)
High energy consumption (usually fossil fuels)	Uses free, renewable solar energy (drastically reducing operating energy costs)
High C-emission & environmental impact	Solar-based systems produce little to no greenhouse gases
Costly operation and maintenance	Lower operational costs over time, especially in off-grid or sunny regions
Brine discharge harms marine ecosystems	Small-scale solar systems can be designed with integrated brine management or lower brine volumes
Infrastructure costs for remote areas	Solar stills and small modular units are more suitable for decentralized or remote locations
Reliance on centralized water infrastructure	community-based water solutions (enhances water security)

1.2.1 Types of solar desalination

Based on the working principle of a solar steam generator, mainly focusing on how the solar absorber is implemented to derive this phenomenon and the mechanism behind solar energy capturing, the solar desalination can be categorized into three different types as shown in Figure 1.3:

- I. Bottom Heating
- II. Bulk Heating
- III. Interfacial Heating

In the bottom-heating technique, water evaporates as a solar absorber at the base of the assembly is heated. Generally, heating occurs at the bottom of the bulk water without the aid of a solar concentrator or a solar still. However, during this process, evaporation may also occur at other regions, leading to inconsistent results of evaporation efficiency. This is because solar radiation comes into direct contact with the cold bulk water (typically saline), which significantly lowers efficiency. As a result, the method fails to achieve the efficiency required for effective solar evaporation. (Kabeel & El-Agouz, 2011). The second type of solar desalination, bulk heating, involves the direct addition of a solar absorber (typically responsible for capturing solar energy and generating heat) into the bulk mass. In this system, the solar absorber generates localized heat within the water mass. As a result, the bulk temperature increases, enhancing water evaporation compared to bottom-heating techniques. This volumetric approach achieves minimal evaporation efficiency due to several drawbacks,

such as prolonged exposure of the solar absorber to harsh saline water, which directly challenges the material's stability, and significant loss of the solar absorber, especially since it does not allow direct application in seaside water desalination. Considering the high solar-to-thermal conversion efficiency, one of the biggest drawback of this technique is the poor thermal management, as the solar absorber is surrounded by a cold bulk system that dissipates the generated heat (Ghadimi et al., 2011; Ni et al., 2015b).

Interfacial solar desalination is an emerging clean water process that utilizes localized solar energy at the air-water interface to effectively convert sunlight into heat for evaporating water, rather than heating the entire system volume. The system uses a photothermal material, which is mainly responsible for generating localized surface heat. The interfacial heating technique provides a much better evaporation rate compared to bulk and bottom heating because of low thermal loss, effective salt resistance, and enhanced operation stability of the photothermal material (Shi et al., 2020). Given the unique features of interfacial solar desalination, the following section provides a comprehensive overview of this technology.

1.3 Interfacial Solar Desalination

To overcome the drawbacks and obstacles associated with bottom and bulk heating, researchers in the solar desalination field developed an innovative technique called interfacial solar desalination. In interfacial solar desalination, the solar absorber operates at the air-liquid interface, where it captures solar radiation and heats the system's surface, providing high heat localization. At the same time, bulk water moves from the bottom of the solar absorber towards the air phase. Interfacial solar desalination offers various advantages:

- (a) Implementation of a solar absorber with device designing (1D, 2D, and 3D),
- (b) High surface heat localization,
- (c) Prevents heat loss,
- (d) Various kind of substrate utilization,
- (e) Easy to recover the solar absorber,
- (f) High scalability,
- (g) High evaporation rate and efficiency

Owing to these advantages and characteristics, the interfacial solar steam generator has the potential to enhance the adaptation and utilization of solar steam generators in compact, stand-alone, and portable systems.

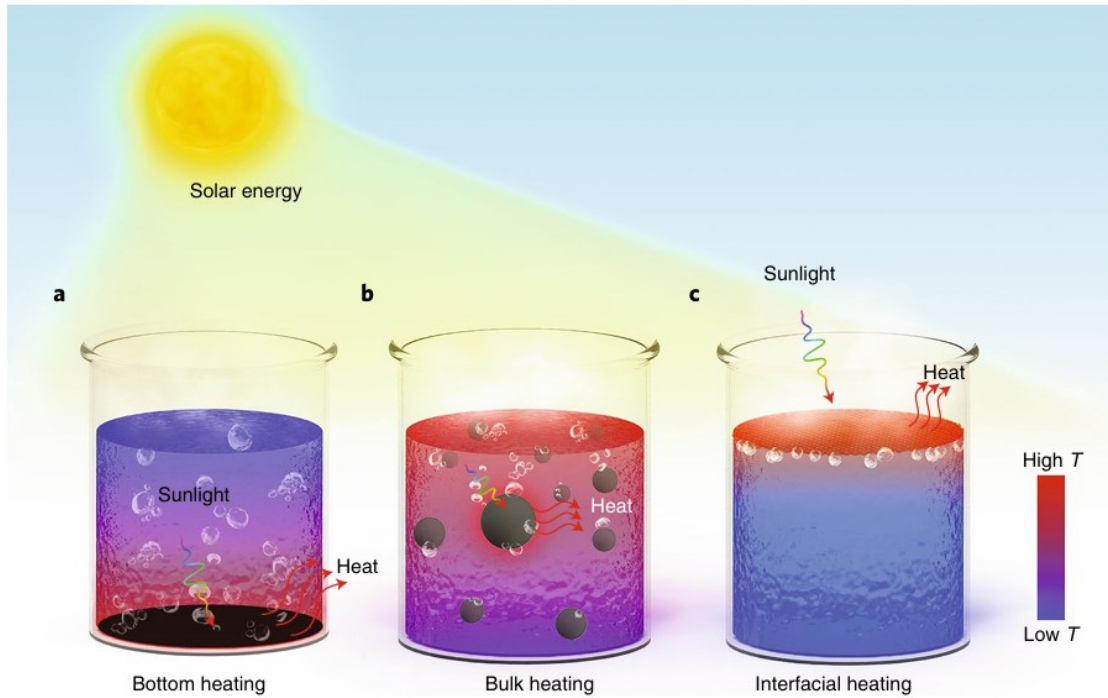


Figure 1.3: Solar-driven evaporation through various forms of solar desalination setup; Copyright Open Access, MDPI (Jia et al., 2024).

1.3.1 Solar to Thermal Conversion Mechanism

Solar desalination uses solar radiation to generate usable heat. This renewable energy-based technology harnesses the sun's radiant energy by capturing it using various types of solar collector assemblies, concentrating materials, and evacuated collectors (Al-Addous et al., 2024). Numerous types of solar absorbers have been developed, and more are on the way with the advancement of materials design and device structures. To achieve high solar-to-thermal conversion, it is crucial to understand the photo-to-heat conversion mechanism of the solar absorber to develop an efficient solar steam generator. Generally, the solar to thermal conversion occurs based on three basic mechanisms (i) local heating relying on surface plasmon resonance, (ii) non-radiative relaxation of photo-excited charge carriers, and (iii) dissipation of energy into lattice vibrations (phonons) that results in heat generation. In most cases, a single solar absorber follows a single conversion mechanism, but more than one phenomenon can coincide in a composite material. The above-mentioned mechanisms will occur due to the interaction between electromagnetic radiation and matter. Figure 1.4 illustrates the different mechanisms of solar-to-heat conversion that depend on the unique characteristics of the solar absorber. The interaction of electromagnetic radiation with plasmonic metallic nanostructures can induce intra-band transitions, exciting electrons to

higher energy levels within the conduction band (Irshad et al., 2021). Near the metal-dielectric interface, the collective electron oscillation can propagate along the interface as a surface propagating plasmon (SPP) or be localized close to the curved surfaces of the metal nanostructures. As a result, the excited surface plasmon acts as a strong damped oscillator that could decay via electron-to-phonon, electron-to-electron, and electron-to-photon transition in the form of thermal energy. Electron-to-electron decay assigns thermal electron energy, which causes the localized metal surface temperature to increase rapidly, as shown in Figure 1.4(a) (Liang et al., 2019). The equilibrium cooling generates towards electron-photon energy conversion due to a change in localized temperature and phonon-to-phonon transformation resulting in heat release to the surrounding medium, Figure 1.4(c) (Irshad et al., 2021; Liang et al., 2019).

In the case of a semiconductor solar absorber, the optical activity presents an apparent dependence on band gap and wavelength. The electron-hole pairs are generated according to the bandgap-like energy by irradiating the semiconductor with solar light. The excited electron reverts to the ground state by releasing energy via radiative relaxation as photons or non-radiative relaxation as phonons, see Figure 1.4(d). The second process entails transferring energy to impurities, defects, or dangling bonds on the material's surface. The energy loss (as phonons) is directed to localized lattice heating, which causes a temperature gradient, depending on the material's optical absorption as well as its bulk and surface recombination characteristics (Y. Zhou et al., 2025). Nanostructures have a wide range of spectral absorption ability to demonstrate photothermal conversion; for example, the work of Zhou et al shows the Au-nanoparticles in an anodized aluminum oxide mask and transformation of transparent anodized aluminum oxide into black material, which shows 99% absorption (400 nm to 10 μ m) (L. Zhou, Tan, Ji, et al., 2016). However, the use of noble metals is not a reliable practice for solar desalination. Xu et al, investigated a cheaper nickel (Ni) nanostructure as the solar absorber that achieved $\approx$ 95% from 200 to 1500 nm wavelength range (R. Xu et al., 2019). Alternatively, the Cu-based semiconductor nano-evaporators are an excellent cost-effective candidate for solar desalination; Hussain et al., reported the CuS functionalized carbon foam, which shows the $\approx$ 95% absorption in UV/Vis-NIR (250 to 2000 nm (Hussain, et al., 2025)

Broadband absorption is a versatile feature of carbon-based materials under solar irradiation due to their natural black color. The majority of carbon-based material skeletons consist of single carbon bonds C-H, C-O, C-C that present a large energy band gap σ - σ^* , and such σ - σ^* transitions are not accessible under solar irradiation. Due to loosely bonded

electrons in pi (π) bonds compared to σ -bonds, the π to the π^* can be simulated with lower energy. As a result, the conjugated π bonds can cause a red shift. As the number of π bonds increases, the energy gap between the lowest unoccupied molecular orbital (LUMO) and the highest-occupied molecular orbital (HOMO) decreases (Y. Zhou et al., 2025). Under the solar irradiation, the electrons are excited from the ground HOMO to the excited LUMO state, and relaxation of the excited electron in the form of electron–phonon coupling converts the light energy into vibrational modes across the atomic lattices that ultimately increase the temperature of the material Figure 1.4(e)(Irshad et al., 2021). Carbon materials, such as graphene-based nanostructures and carbon black nanoparticles, have received significant attention for solar steam generation. Liu et al investigated the role of GO as a solar absorber on a bilayer-wood solar evaporator, which presents a high photothermal conversion efficiency (83%) (K.-K. Liu et al., 2017). Xu et al. have developed a bi-layer solar steam generator in which the polyacrylonitrile (PAN) acts as a hydrophilic water pathway and upper hydrophobic carbon black nanoparticles act as light absorbers (W. Xu et al., 2018) (section 1.3.1) text generated with Copyright 2025, Elsevier, (Shahzadi et al., 2025)).

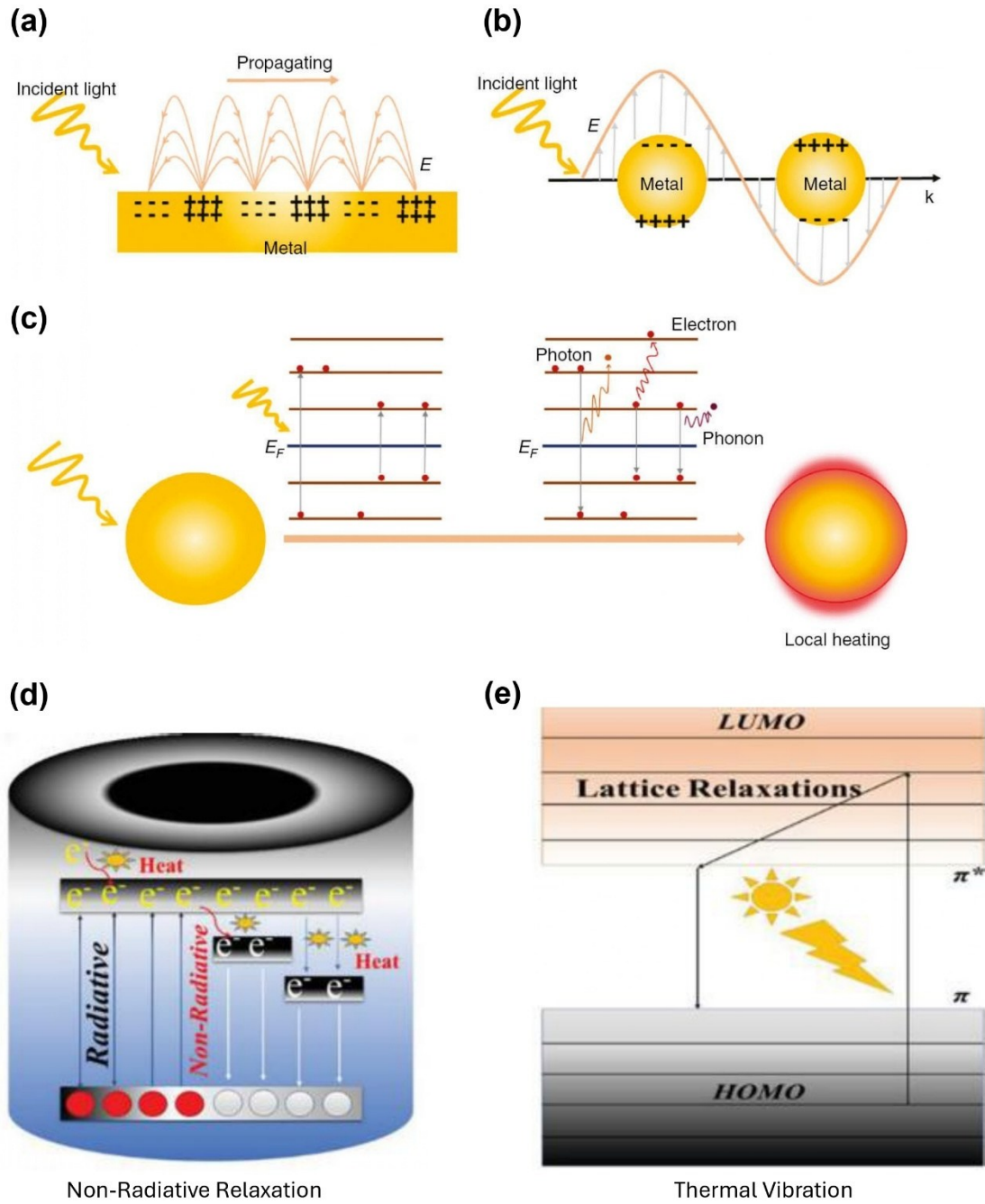


Figure 1.4: Photo to thermal Conversion Mechanism of solar evaporators: (a) Propagating surface plasmon generated (SPP), (b) localized surface plasmon resonance (LSPR), (c) surface plasmon decays, (d) non-radiative relaxation (semiconductors), (e) π - π^* bonds transition from HOMO to LUMO band (carbon materials), Copyright 2025, Elsevier (Shahzadi et al., 2025).

1.4 Experimental Setup and Performance Evaluation of an Interfacial Solar Steam Generator

Evaporation is a natural and well-known phenomenon that can occur at any temperature, but its rate depends strongly on temperature: the higher the surface temperature and the exposed area, the faster the evaporation. Given these well-established considerations, interfacial solar desalination relies heavily on evaporation dynamics. It operates by confining surface heat localization to the material/bulk interface without thermal loss. However, several other factors matter in the performance of solar evaporators. The operational setup of interfacial solar desalination for indoor lab-scale investigation comprises four basic components: Solar simulator (at simulated standardized light of 1 sun (1 kW m^{-2}) with an air mass of 1.5 (AM 1.5G, corresponding to a zenith angle of 48.2°) (Y. Zhang & Tan, 2022), a bulk reservoir (saline water mostly following global standard 3.5% wt.), a precise analytical balance which provides accurate measurements to record changes in mass during experiments, and the solar steam generator (known with several names such as photothermal material, photothermal evaporator, solar steam generator). The general experimental set is illustrated in Figure 1.5(b). In addition, some important considerations must be taken into account to achieve maximum performance.

- Optimum irradiation
- A photomask is advised to align the solar irradiation area with the sample exposure
- A high-precision balance connected with a computer for automatic data recording
- Use of an insulator separating the water reservoir and the surface to avoid heat loss

The performance evaluation of the solar steam generator is crucial for its practical viability; the key parameters in this regard are evaporation rate and evaporation efficiency. Evaporation efficiency is based on the evaporation rate and is widely used to break down the understanding of the evaporation rate. The evaporation rate of a solar desalination device indicates the mass of water evaporated per unit area per unit time under standard solar irradiation. Evaporation rate is typically expressed in $\text{kg m}^{-2} \text{ h}^{-1}$ and could be calculated using the equation given below;

$$\text{Evaporation rate} = \frac{\Delta m}{S \times t} \quad (1)$$

where, Δm is the mass of evaporated water (kg), S is the surface area of the evaporator (m^2), and t is the time of evaporation (h).

Under ideal conditions (100% solar-to-vapor efficiency, constant latent heat of evaporation), the theoretical maximum evaporation rate is $1.47 \text{ kg m}^{-2} \text{ h}^{-1}$ (Taranova et al., 2024).

The evaporation efficiency of a solar evaporator is the fraction of incoming solar power that the system converts into steam. Evaporation efficiency is considered a key metric to assess the performance of solar-driven desalination systems. The evaporation efficiency could be measured with the equation given below;

$$\eta = \frac{\Delta m \cdot h_{lv}}{c_{opt} \cdot q_i} \quad (2)$$

Where, Δm is the mass of evaporated water ($\text{kg/m}^2 \cdot \text{h}$), h_{lv} is the latent heat of vaporization (J/kg), C_{opt} is the optical concentration factor (usually 1 for no concentrators), and q_s is the incident solar flux (W/m^2 , typically 1000 W/m^2 under 1 sun). (Ni et al., 2016) (L. Zhu et al., 2019).

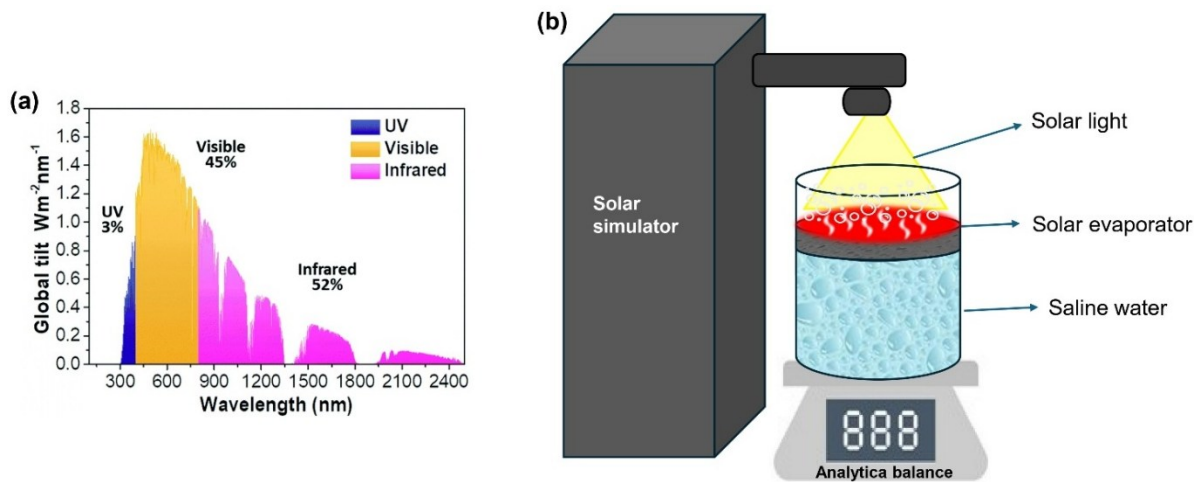


Figure 1.5: (a) Solar spectral irradiance (AM 1.5), Copyright, RSC 2019 (Gao et al., 2019) and (b) a general experimental set-up of interfacial solar desalination.

Interfacial solar desalination operates by using a photothermal material that provides the driving force for a high evaporation rate. But in depth, this technology relies on several factors, as illustrated in Figure 1.6, which shows several factors that can play a significant role in achieving the evaporation rate and evaporation efficiency of solar steam generators;

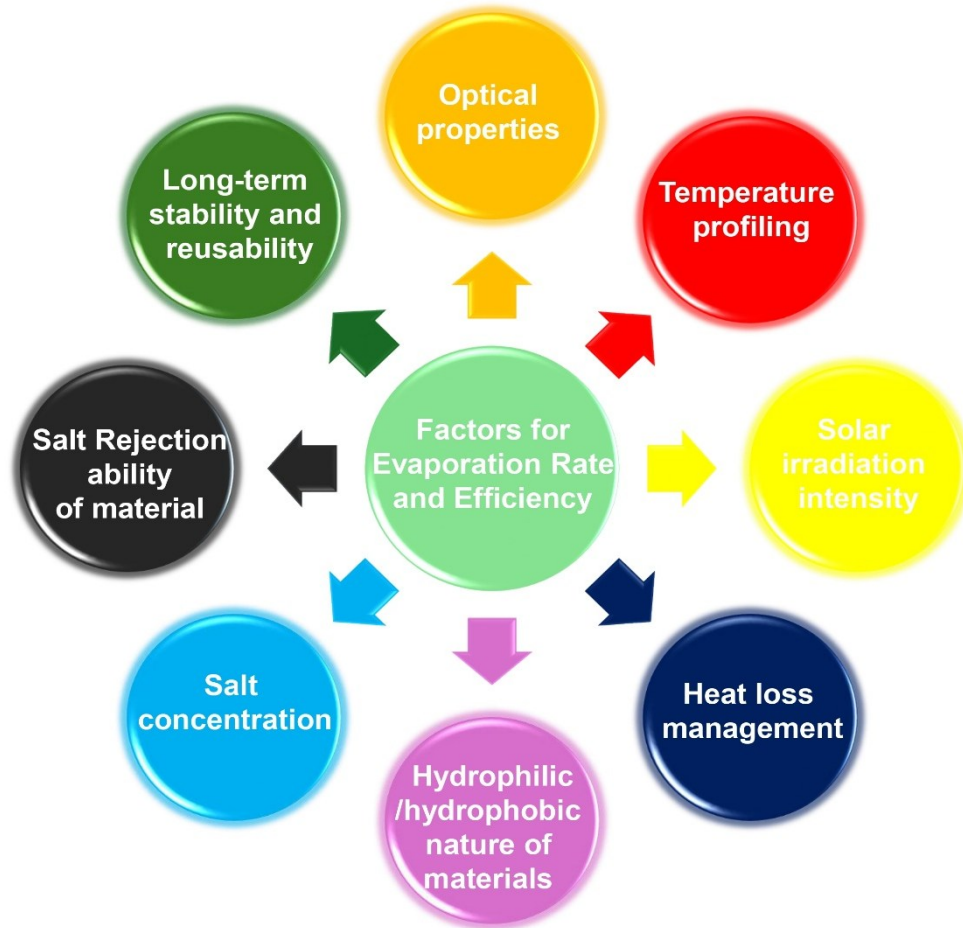


Figure 1.6: Graphical illustration of factors that could affect solar evaporation rate and efficiency of solar steam generator.

1.4.1 Optical Activity

An efficient solar steam generator must possess one of the fundamental characteristics for high performance: high absorption activity across the entire solar spectrum. As discussed earlier, almost 50% of solar energy lies in the near-IR region, and to achieve high thermal output, the photothermal material must absorb as much radiation as possible while maintaining a low thermal emittance (ϵ), which plays a central role in performance. Types of materials that belong to a particular class, such as carbon materials or metallic nanostructures, exhibit broad-spectrum solar absorption and low infrared radiation losses, thus improving energy confinement at the evaporation interface. Figure 1.7(a) shows a typical example

reported by Li et al. where they incorporated carbon nanotubes (CNTs) into diatomite aerogel, which considerably enhanced the optical activity of diatomite from a low base optical absorption (~67%) to over 95%, marking a notable improvement in photothermal capability (J. Li et al., 2022). Kim et al studied the role of nickel (Ni) and gold (Au) as hierarchical nanostructured surfaces on nanowires of an alumina scaffold. As a result, the solar evaporator achieved more than 90% absorption in the 300-2500 nm range, see Figure 1.8(a) (C. Kim et al., 2020).

Liu and his colleagues developed a solar evaporator (Ag/rGO-Alginate hydrogel) by integrating it into polyurethane (PU) foam. The varied concentration of rGO (0.05 to 0.2 wt%) and Ag nanowires pushes the absorption percentage towards > 95% compared to PU (47–58%) in the spectral range 350 to 2000 nm, (Figure 1.10(a) Liu et al., 2020). Incorporating black material into a low-solar-absorptance material can effectively improve the photothermal performance of solar steam generators. The nature-inspired work demonstrated by Ma *et al.*, was based on a highly solar-absorbing material incorporating the rGO into alginate, and further composites were developed with lotus seedpods (H. Ma et al., 2023). The detailed experimental procedure is illustrated in Figure 1.9(a). As a result, the optical activity of the composite was achieved as more than 95% absorption from UV/Vis to Near-IR spectra, Figure 1.9(b). The enhanced activity achieved by utilizing the broad spectral activity of rGo and concave “head” holes on the upper layer of lotus seedpods, which boosts light capture by maximizing absorption of vertical and oblique incidence.

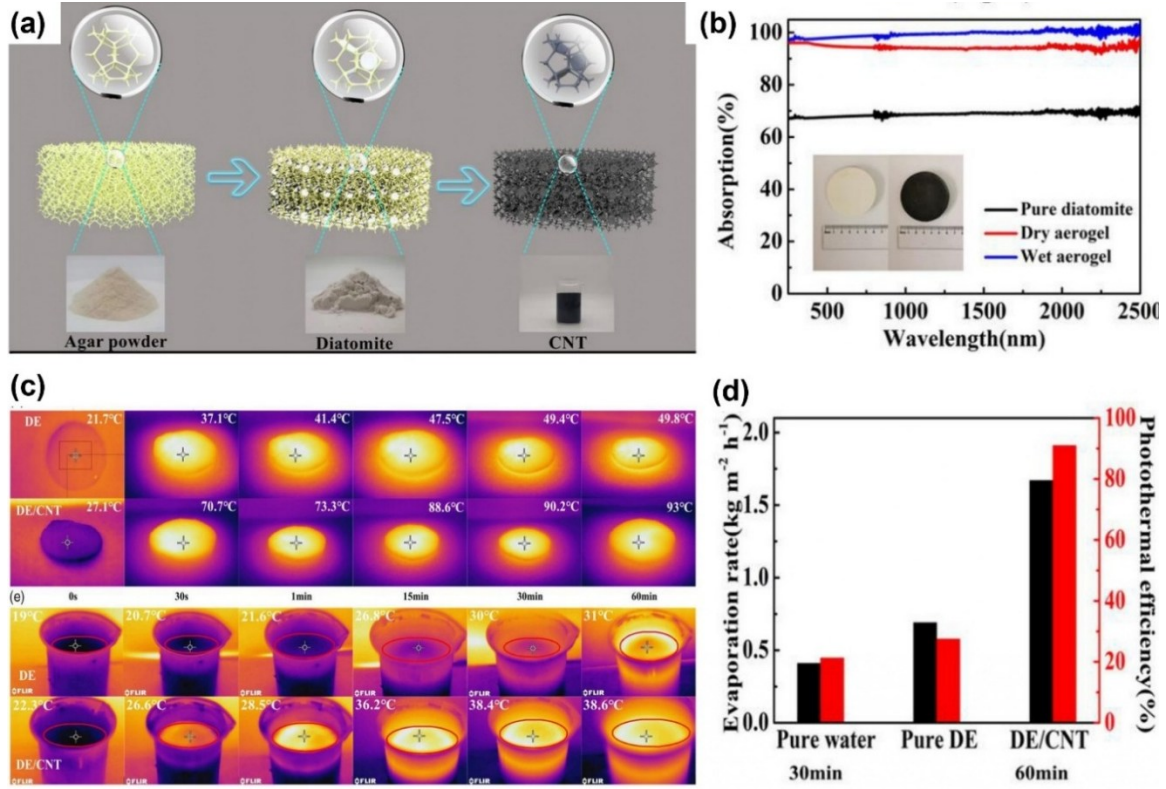


Figure 1.7: Diatomic-CNT-aerogel for solar desalination; (a-b) graphical illustration of aerogel and CNT integration and UV/Vis-NIR spectra, (c) Temperature profiling at dry and wet stage, (d) Evaporation rate and efficiency of material, Copyright 2022, Wiley (J. Li et al., 2022).

1.4.2 Surface Temperature Profiling

Reporting the surface temperature profiling using infrared thermography or sensors further aids in assessing the thermal behavior of the solar steam generator. The evaporation rate in such a solar steam generator depends intensely on how efficiently solar energy is localized at the interface. The uniform, elevated surface temperatures during the solar steam process indicate effective solar energy absorption and thermal conversion. The maximum surface temperature that a material can achieve under photothermal conditions is inherently limited by its intrinsic properties, particularly its thermal conductivity and the onset of photothermal saturation (L. Hou et al., 2025). Sometimes, conductive losses occur due to the presence of a bulk water surface at high surface temperatures, which reduces the net efficiency of the solar evaporator. Similarly, when the surface heat is too low, it ultimately constrains evaporation due to an insufficient vapor pressure difference between the interface and the ambient air (L. Zhou, Tan, Wang, et al., 2016). Furthermore, the nonuniform distribution of heat localization at the interface results in the formation of cold and hot zones that significantly affect solar steam generation by causing heat loss and salt accumulation at the hot side. Rational

optimization includes the design of the device to ensure uniform surface temperature for high instant rates with thermal retaining approaches for continual working, managing temperature profiling, a key design parameter for high-performance solar steam devices for desalination.

Figure 1.7(c) shows that diatomite is a lightweight scaffold with an ordered microporous structure and a high specific surface area, which, when combined with carbon nanotubes, results in the aerogel exhibiting vastly superior broadband solar properties and strong light-harvesting. Under 1 sun illumination, the CNT/diatomite aerogel's surface temperature reached 70.7 °C within 30 seconds, compared to the diatomite aerogel by 33 °C (J. Li et al., 2022). Kim et al. study presents the temperature profiling based on the increase in solar irradiation; the Au and Ni decorated aerogel achieved 80 °C with the increasing effect of solar irradiation (C. Kim et al., 2020) , Figure 1.8(d). Temperature profiling of comparative material study of PU and Ag/rGO-alginate hydrogel with PU is reported in Figure 1.10(c): by incorporating the rGO and silver nanowires, the hydrogel surface temperature reaches 70 °C at the dry state (C. Liu et al., 2020). The localized surface temperature of rGO-alginate combined with lotus seedpods indicates the outperformance of the material. In addition to the material's solar absorption, the design of the material and critical thinking about how to integrate it for device engineering matter a lot. As seen in Figure 1.9(c), the surface temperature of the rGO-alginate combined lotus seedpods is 40.7 °C, compared to 40.0 °C for the rGO-alginate alone during solar steam generation.

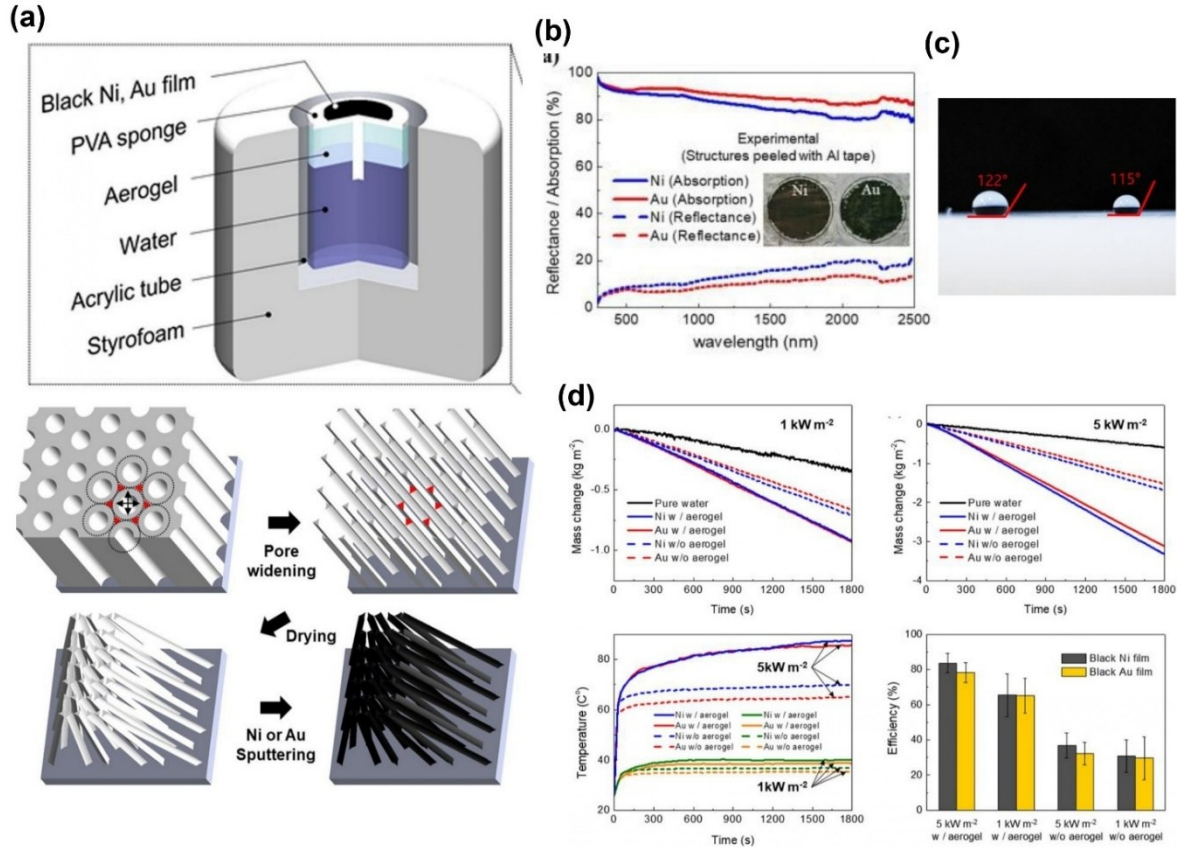


Figure 1.8: (a) Design of solar evaporator of Ni and Au deposited aerogel for solar desalination, (b) optical activity of Ni and Au deposited aerogel, (c) Contact angle measurements of aerogel (d) Temperature profiling and performance of the solar evaporator under different solar irradiation, Copyright 2020, Elsevier, (C. Kim et al., 2020).

1.4.3 Solar Irradiation Intensity

Solar irradiation intensity is one of the most influential factors in the performance of interfacial solar desalination. Variation in solar irradiance directly assesses the photothermal conversion efficiency of the solar evaporator and the rate of vapor generation at the air-water interface. Generally, higher solar irradiance increases the total incident solar energy absorbed by the photothermal layer, leading to greater heat localization at the interface. As a result of this phenomenon, the surface temperature increases, directly accelerating the kinetic activity of water molecules and raising the evaporation rate. Recent studies have demonstrated that increasing solar flux substantially increases evaporation rates in interfacial evaporators, due to enhanced thermal output and reduced bulk heat loss (Ni et al., 2016). However, the performance gain is not always linear with irradiation intensity because of nonlinear thermal losses (F. Zhao et al., 2018).

Figure 1.8(d) illustrates the impact of solar irradiation intensity on the evaporation efficiency of aerogel materials decorated with Au and Ni. The solar steam generator shows evaporation efficiency increased from 25% to more than 80% by varying the solar irradiation from 1 kW/m^2 to 5 kW/m^2 (C. Kim et al., 2020). Apart from the individual characteristics of material and device design, the change in solar irradiation intensity has a direct influence of the evaporation rate during solar steam generation. The increase of solar irradiance intensity from zero to 2 kW/m^2 has a direct relation with the outperformance of rGO-alginate-lotus seedpods solar steam generator (H. Ma et al., 2023). Figure 1.9(d) presents a clear relationship between the change in mass and doubling the solar intensity; the rate of mass change is doubled by doubling the solar flux intensity.

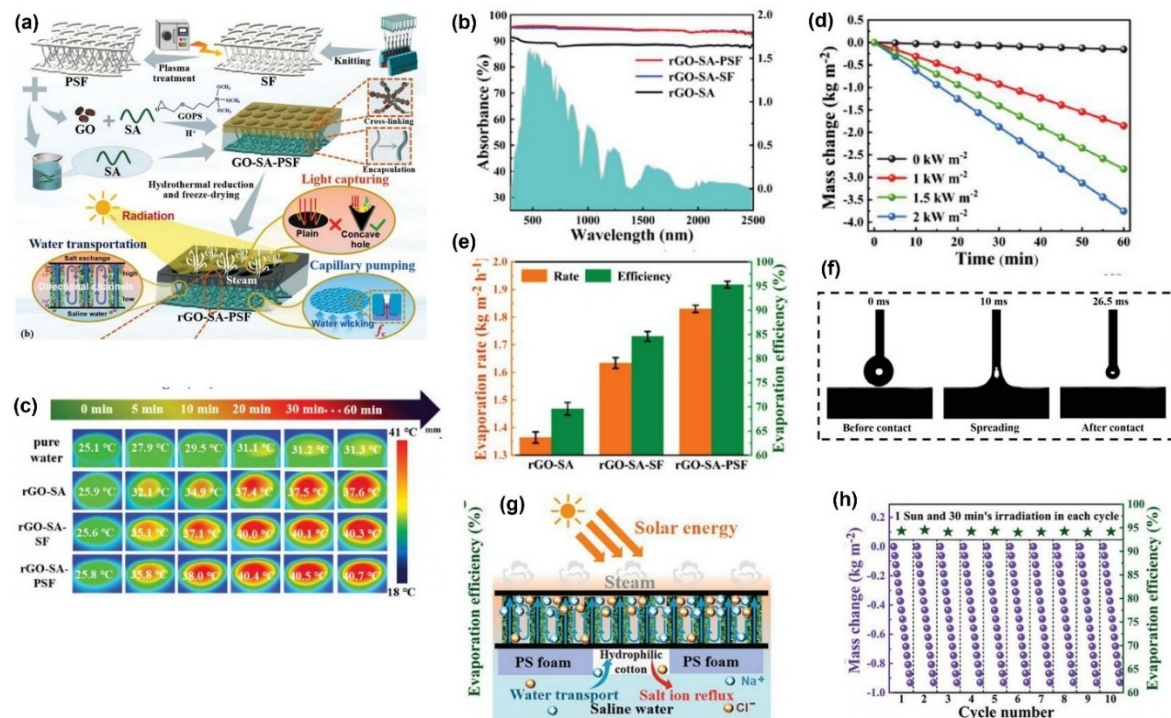


Figure 1.9: (a) Design of solar evaporator rGo-SA-PSF, (b) optical activity, (c) evaporation rate, (d) contact angle measurements of aerogel, (g) thermal heat management strategy, and (f) Stability test of rGO-SA-PSF with cycle number under one sun irradiation, Copyright 2025, Wiley (H. Ma et al., 2023).

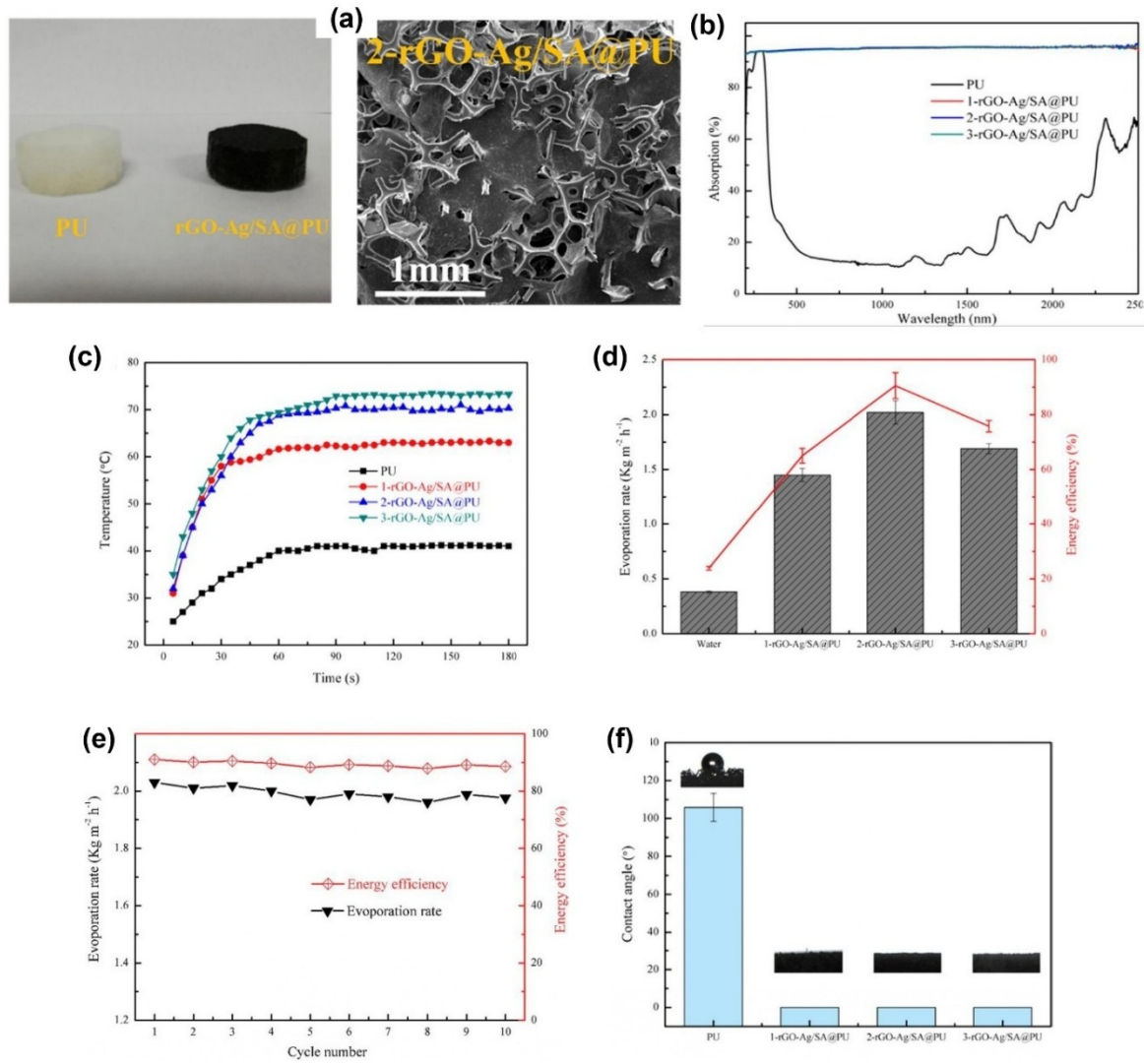


Figure 1.10: (a) Ag/rGo-alginate hydrogel embedded in PU, (b) comparative optical activity of solar steam generator, (c) comparative surface temperature profile, (d) Evaporation rate and efficiency, (e) stability of solar evaporator device, and (f) comparative wettability performance of solar evaporators, Copyright, Elsevier 2025 (C. Liu et al., 2020).

1.4.4 Heat Loss Management

Preventing heat loss from photothermal materials at the interfacial solar desalination interface is a cornerstone for achieving high evaporation rates and efficiency. In interfacial solar desalination, the surface heat localization can be dispersed and lost by conduction to the bulk water, convection to the surrounding air, and radiation to the environment. Utilizing strategies such as thermal localization, structural engineering, and radiative and convective loss suppression could significantly improve the performance of a solar steam generator, see Figure 1.11. Introducing an insulator around the water transport layer could help reduce heat loss (Xiao et al., 2025). The work reported on rGO-alginate combined with lotus seedpods

has been performed by insulating the hydrophilic cotton that acts as water transport channels with polystyrene foam Figure 1.9(g), which effectively acts as a thermal insulator and prevents the heat loss towards the surrounding and bulk water reservoir (H. Ma et al., 2023). Kim et al. applied aerogel as a thermal insulator in a solar steam generator (Au- and Ni-decorated alumina). The aerogel layer prevented heat from conducting downwards into the bulk water and the surroundings, resulting in maximum performance. The configuration of the aerogel used in the solar evaporator is illustrated in Figure 1.8(a). The evaporation rates of the Ni and Au films insulated with aerogels were $6.88 \text{ kg m}^{-2} \text{ h}^{-1}$ and $6.48 \text{ kg m}^{-2} \text{ h}^{-1}$, respectively, which were 4.6 to 4.9 times higher than that of pure water ($1.40 \text{ kg m}^{-2} \text{ h}^{-1}$) (C. Kim et al., 2020).

In addition to material performance, the configuration of the photothermal evaporator as a device design has a greater impact on solar steam generation. Mo *et al.* have designed a molecular organic framework on Cu-mesh as a hierarchical structure and bent it into strips, see Figure 1.12(a). To evaluate the performance, only strips (legs) are dipped into bulk water, and the flat surface area of MHS (MOF-based hierarchical structure) is separated from the bulk water and exposed to solar irradiation. This device configuration reduced heat loss by concentrating the solar heat towards the upper surface of the MHS (Q. Ma et al., 2019). Another study by Wu et al. investigated a similar configuration of a suspended membrane as solar steam generator by immersing the bend-endpoint of the membrane into bulk water. In contrast, a significant portion of the membrane is isolated from bulk water, see Figure 1.12(b). The bulk water moves through the membrane by capillary action, driven by the membrane's high surface area. This configuration not only prevents the heat loss into bulk water but also presents excellent evaporation efficiency (S. L. Wu et al., 2021).

Furthermore, recent advances in interfacial solar desalination have demonstrated that the T-type device configuration outperforms other configurations as a solar steam generator by optimizing heat management and suppressing thermal losses. Huang et al pioneered a 3D T-shaped porous sponge (3DTPS) as an auxiliary shape to conventional 2D photothermal films Figure 1.12(c). This T-shaped geometry enlarged the contact area between heated surfaces and air, supporting additional evaporation beyond the primary interface and achieving an extra evaporation efficiency gain of over 21% by utilizing descending heat transfer for secondary evaporation (Q. Huang et al., 2021). Liu et al. reported a similar investigation on a T-shaped solar steam generator with a surface-carbonized longitudinal wood membrane (C-L-wood) serving as the top for solar-harvested vapor generation and salt collection, and another piece of natural L-wood as the support. The C-L-wood-derived T-

shape solar steam generator presented a high evaporation rate of $2.43 \text{ kg m}^{-2} \text{ h}^{-1}$ under one sun irradiation, which is stable for 7 days of outdoor operation (H. Liu et al., 2021).

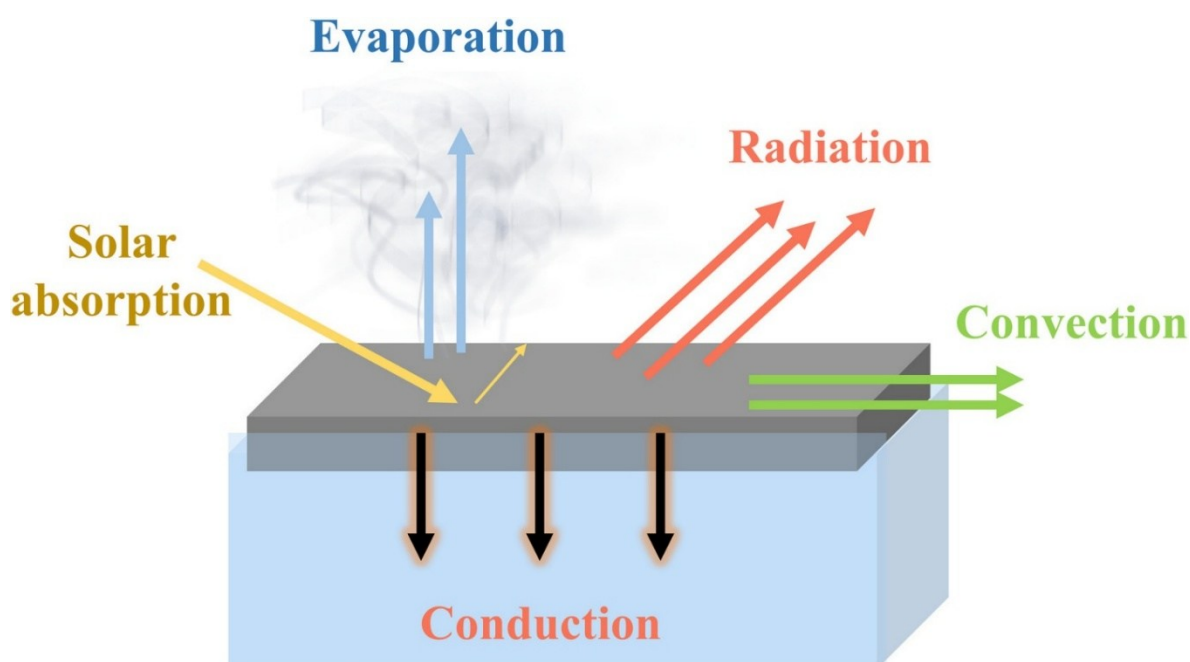


Figure 1.11: Possible pathways for heat loss generated by photothermal material in interfacial solar desalination, Copyright Open Access, Elsevier 2025 (Xiao et al., 2025) .

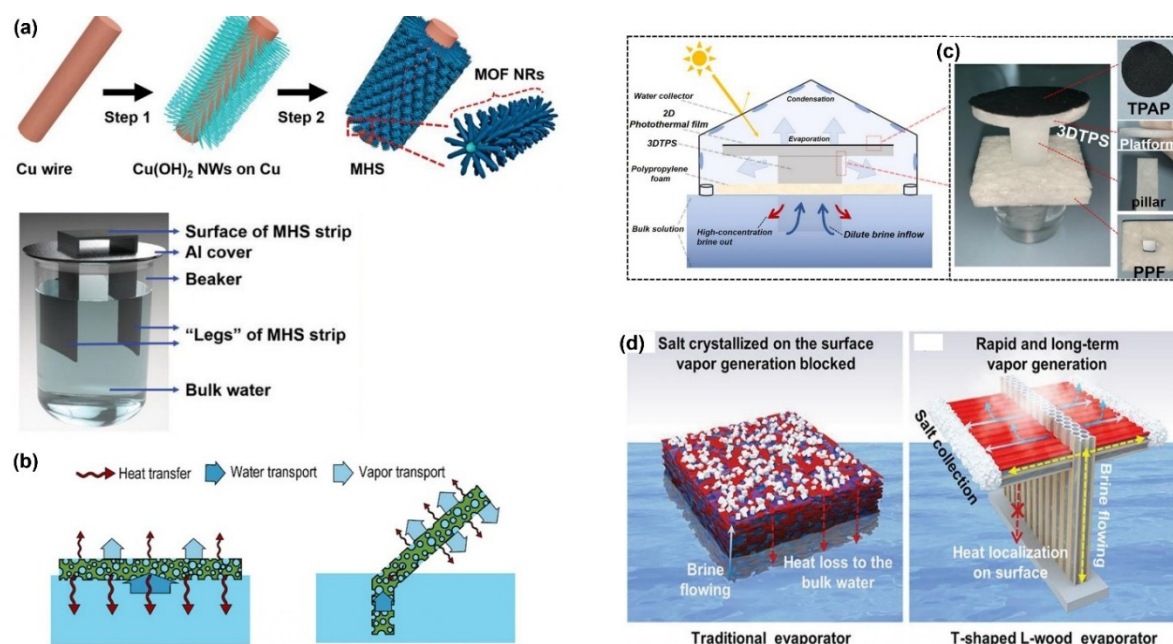


Figure 1.12: Designs of solar evaporators for heat loss management: (a) MOF-Based hierarchical bend strips structure, Copyright, Wiley 2019 (Q. Ma et al., 2019), (b) bend-endpoint design of solar evaporator, Copyright ACS, 2021 (S. L. Wu et al., 2021), (c-d) T-shape architecture of solar evaporators, Copyright Elsevier 2011 and Copyright Wiley 2021 (Q. Huang et al., 2021; H. Liu et al., 2021).

1.4.5 Hydrophilic and Hydrophobic Effects

Hydrophilicity describes the chemical interaction between a material and water, a natural affinity that drives water flow. In the interfacial solar desalination process, the hydrophilicity of the materials plays a crucial role in achieving higher evaporation rates. The hydrophilicity of the solar steam generator enhances capillary-driven water movement to the photothermal surface, ensuring a constant water supply for evaporation. The most common method used to measure hydrophilicity is via contact angle analysis, where angles less than 10° demonstrate the super-hydrophilicity of the material (Y. Hou et al., 2022). Liu et al., 2020 investigated how the hydrophilic behavior of Ag/rGO-alginate improves the evaporation rate and efficiency of PU porous foam. The paper underscores the hydrogel's super-hydrophilicity, improving water uptake and transport, which leads to significant enhancements in the performance of the solar steam generator compared to the base PU material, see Figure 1.10(f) (C. Liu et al., 2020). The rGO-SA-PSF solar steam evaporator shows exceptional hydrophilicity due to the synergistic consequence of plasma treatment of lotus seedpods and sodium alginate (SA) coating, both of which generate abundant polar functional groups and hydrophilic sites on the fabric's surface. As seen in Figure 1.9(f), the contact analysis shows the ultrafast absorption of the water droplet by rGO-SA-PSF. This feature facilitates ultra-fast capillary-driven water transport from the bulk reservoir to the evaporation interface, ensuring a constant supply of fresh water to replace that lost via vaporization. More importantly, the rapid water replenishment actively dissolves any incipient salt crystals, efficiently inhibiting accumulation at the photothermal layer, even under prolonged high-salinity conditions. This enhanced hydrophilicity is thus fundamental for maintaining a constant evaporation efficiency, prolonging operational lifespan, and supporting the system's self-desalination capability during cyclic use.

1.4.6 Salt concentration of the bulk and the rejection ability of evaporators

The bulk reservoir's salt concentration significantly influences the evaporation performance of the solar steam generator. Complex salinity can be central to fast salt crystallization on the evaporation surface, a process known as 'salt passivation'. This process can obstruct light absorption, disrupt water transport, and reduce evaporation efficiency over time. Understanding and managing salt passivation is crucial in maintaining high evaporation rates and efficiency in solar desalination systems (Xu et al., 2019). Designing a material that provides an excellent evaporation rate and efficiency under harsh high-salt conditions is crucial to achieving high output. Ma et al have developed a material that offers robust

performance. This development, as seen in Figure 1.9 (e), holds promise for practical applications, as it demonstrates outstanding salt resistance (no salt accumulation throughout nonstop evaporation for 10 h in 10% brine). (H. Ma et al., 2023). As a result, outstanding salt resistance (no salt accumulation throughout nonstop evaporation for 10 h in 10% brine) Figure 1.9(e).

In addition to material characteristics, the device configuration provides deeper insight into the conceptual understanding of the practical implementation of the solar steam generator with salt-rejection capability. Figure 1.12(d) illustrates the concept of C-L wood-derived photothermal material T-shape device engineering, which achieves an excellent evaporation rate by concentrating the salt at the edge of the solar evaporator and the main surface, thereby boosting the evaporation rate for high vapor flux (H. Liu et al., 2021). Anisotropic transport ensures that salts drift toward the edges rather than precipitating on the main evaporation surface. This directional transport of salt is a key strategy in preventing salt accumulation, a common issue in solar desalination systems. As a result, long-term outdoor tests (7 days) under one sun illumination showed steady evaporation ($2.43 \text{ kg m}^{-2} \text{ h}^{-1}$) with no performance degradation due to salt accumulation.

1.4.7 Stability and durability of solar steam generators

Finally, prolonged stability and reusability are vital for the scaling up of solar steam generators towards real-world applications. The durability of photothermal coatings, resistance to biofouling, and sustained performance over multiple cycles must be rigorously evaluated. Kim et al. investigated the durability of the material over four months by nine cycles (8 times in the first month, and once after 3 months), and the results show that there is no effect on solar evaporation efficiency of prolonged use of an Au and Ni decorated alumina device with aerogel insulation (C. Kim et al., 2020). The durability of the optimized Ag/2-rGO-alginate integrated PU solar evaporator was investigated through a repetitive solar-steam experiment under one-sun irradiation. Figure 1.10(e) reports the stability of material with a ten-cycle number that presents an excellent stable evaporation rate of $1.96 - 2.03 \text{ kg m}^{-2} \text{ h}^{-1}$ (C. Liu et al., 2020). The work reported by Ma et al presents the excellent durability of rGO and alginate combined with lotus seedpods. The solar steam device achieves around 95% evaporation efficiency even after 10 repeated cycles, as shown in Figure 1.9(h). The performance credit goes to the robust mechanical structure, thanks to the aerogel-encapsulated spacer fabric which supports stable evaporation, and durability through repeated

cycles and saline mitigation further inhibits channel clogging and surface degradation (H. Ma et al., 2023).

1.5 Solar Absorber for Solar Desalination

Solar energy is a vast source of renewable energy that can be converted into heat via photon excitation in numerous materials, including plasmonic metals, semiconductors, organic molecules, carbon-based materials, and their composite materials (see Figure 1.13). Gaining the benefits of these materials and adding innovation to develop new materials could offer a promising pathway to next-generation solar steam generators. An ideal solar steam generator should feature key attributes such as broad solar absorption, minimal reflection and transmission losses, efficient thermal management, and high photon-to-heat conversion efficiency. The resulting thermal energy is crucial for maximizing solar utilization, enabling high overall efficiency and elevated evaporation rates.(Shahzadi et al., 2025). The following sub-sections focus on the different classes of solar absorbers and their merits in enhancing light-to-heat conversion, optimizing thermal utilization, and ultimately improving the overall performance of solar steam generation systems.

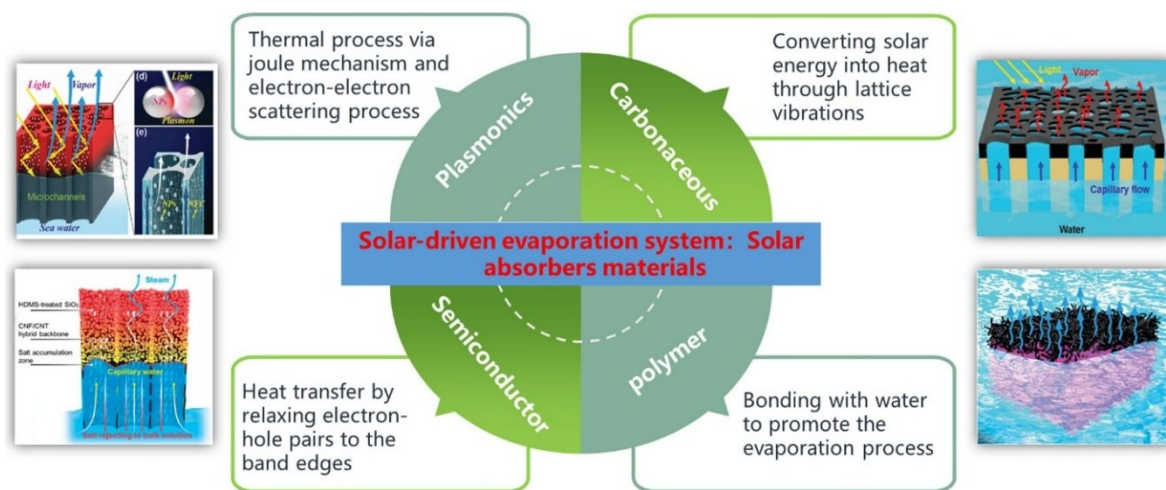


Figure 1.13: Different types of solar absorption materials used in a solar-driven evaporation system, Copyright 2020, Elsevier, (Shi et al., 2020).

1.5.1 Metallic nano evaporators

Metallic nano-evaporators are among the most attractive materials for solar steam generators due to their unique optical properties, which provide excellent photothermal performance. The interaction of metallic nano-evaporators with specific wavelengths of solar radiation results in highly energetic surface plasmons, which promote photochemical charge transfer

processes at the nanoparticle surface. Furthermore, the variable local surface plasmon resonance (LSPR) of metal nanoparticles enables accurate manipulation of their optical properties and exhibits excellent stability and reusability. Preventing chemical degradation and photo-corrosion ensures the reliability and durability of metallic nanomaterials as solar evaporators. The metal nanostructures of gold (Au), palladium (Pd), and silver (Ag) are versatile photothermal materials due to their high absorption activity from UV/Vis to the near-IR region . These materials for photothermal applications are considered excellent, but they have some limitations, such as low abundance and high cost (Opoku et al., 2025). For solar steam generators, the plasmon material is most likely integrated with other base materials such as aerogel, hydrogel, GO, and cotton filter. A detailed comparison of plasmon-based materials with respect to evaporation rate and efficiency is illustrated in Table 1.2.

Table 1.2: Plasmon-based solar steam generators for desalination.

Solar Evaporators	Conversion Efficiency (%)	Evaporation rate (kg m⁻² h⁻¹)	Sun Intensity	References
CuS/BC gel membrane	98.5	1.79	1	(D. Zhang et al., 2020)
CuS/BC foam	83.5	1.44	1	(D. Zhang et al., 2021)
Cu _x S/Cu foam	94.5	1.96	1	(W. Huang et al., 2020)
CuS/agarose aerogel on cotton pad	94.9	1.63	1	(Le et al., 2019)
CuS/Sn ₂ S ₃ /MCE membrane	82.93	1.42	1	(Ibrahim et al., 2021)
CuS/semipermeable collodion membrane	68.6	1.09	1	(Tao et al., 2018)
Au/CuS gyroid-structured materials/airlaid paper	88.8	1.54	1	(Sun et al., 2020)
rGO/CuS/melamine sponge	95.60	2.09	1	(Xue et al., 2022)
Ag/rGO/wood	75.75	3.71	1	(Ebrahimi et al., 2022)(Ebrahimi et al., 2022)
Core-shell structured Ag/PDA/wooden flower	97.0	2.08	1	(H. Li et al., 2017)(H. Li et al., 2017)
Ag/ppy/cellulose fibers	92.6	1.55	1	(Xu et al., 2020)(Xu et al., 2020)
Ag QDs/rGO/filter paper	94.0	2.11	1	(Gong et al., 2021)(Gong et al., 2021)
Ni ₁ Co ₃ /PDA/SA/sponge	109	2.42	1	(Shao et al., 2020)(Shao et al., 2020)
Fe/Ni/rGO/wood	90.23	1.43	1	(Mehrkhah et al., 2021)(Mehrkhah et al., 2021)

1.5.2 Semiconductors

Semiconductor-based materials are excellent candidates for photothermal applications due to their broad spectral response, low cost, and ease of functionalization. The interaction of light with semiconductor matter can excite electrons by overcoming the bandgap threshold, leading to the generation of electron-hole pairs. Semiconductor photo-materials feature adjustable band gaps, stability, environmental friendliness, and suitability for operation under a mild reaction environment. Semiconductor materials excite electrons through interaction with light, a non-radiative process. As a result, during non-radiative deexcitation (when photo-excited electrons and holes move to lower-energy states), phonons are generated, which lead to localized surface heating and maintain the surface temperature according to the material's unique characteristics, such as optical influence and bulk/surface recombination. These features make semiconductor material an excellent potential photothermal material for solar steam generation (Opoku et al., 2025). In the field of solar steam generators, the literature showed that the most reported materials were based on Cu, Mo, TiO, Ni, Bi, and Ag integrated with PVDF (poly(vinylidene fluoride) and PTFE (polytetrafluoroethylene) membranes, polymer-based hydrogels, metallic foam, GO, and wood structures. The detailed performance comparison of semiconductor-based evaporators, including evaporation rates and efficiencies, is shown in Table 1.3.

Table 1.3: Semiconductor-based solar steam generators for desalination.

Solar Evaporators	Conversion Efficiency (%)	Evaporation rate (kg m ⁻² h ⁻¹)	Sun Intensity	References
MoS ₂ /PU sponge	86.2	1.204	1	(Q. Wang et al., 2020)
MoS ₂ /poly(ether sulfone) membrane	83.8 ± 0.8	1.68 ± 0.08	1	(L. Zhang et al., 2020)
PEGylated MoS ₂ /cotton cloth	80.1	1.3	1	(Z. Guo et al., 2018)
Ti ₃ C ₂ /MoS ₂ /filter membrane	87.2	1.36	1	(R. Xu et al., 2021)
1D TiO ₂ /2D MoS ₂ core-shell/Ti mesh	72.2	1.42	1	(Yuan et al., 2021)
MoS ₂ /C/PU sponge	88	1.95	1	(W. Li et al., 2018)
Fe-Mo ₂ S ₃ /SA/starch hydrogel	91.4	2.36	1	(Z. Guo et al., 2020)
Ni ₃ S ₂ /Ni foam	87.2	1.29	1	(Jiang et al., 2020)
NiS ₂ -x/agar Janus hydrogel	97	1.45	1	(Y. Zhang et al., 2022)
TiO ₂ /CuO/Cu foam	86.6	1.28	1	(Tian et al., 2022)
TiO ₂ /TiN/carbonized wood	94.01	1.5252	1	(P. Ren et al., 2020)
TiO ₂ nanorods/carbon foam	67.1	2.23	1	(S. Kim et al., 2021)
Carbon (from fruits)/TiO ₂ /Ti foam	51.79	0.83	1	(Q. Wang et al., 2019)
Ti ³⁺ /TiO ₂ /cellulose membrane	77.1	1.20	1	(Ying et al., 2020)
Tree-like CuO/Cu mesh	84.4	1.42	1	(Y. Xu, Ma, et al., 2019)
CuO/CN/fiber membrane	72	1.14	1	(Zuo et al., 2021)
CuO/PDA/PB on Cu foam	87.10	1.39	1	(R. Zhu et al., 2021)

Cu ₃ BiS ₃ /MXenes/PVDF membrane	91.9	1.32	1	(Z. Wang et al., 2021)
BiVO ₄ /rGO hydrogel	87	1.6	1	(Noureen et al., 2021)
Ag ₃ PO ₄ /rGO/textile	86.8	1.31	1	(Noureen et al., 2020)
rGO/g-C ₃ N ₄ /wood	92.64	1.31	1	(Karimi-Nazarabad et al., 2021)

1.5.3 Carbon-based Materials

Carbon materials, whether used alone or primarily as coupled materials, are superior photothermal materials due to their characteristics and versatility. Carbon materials are classified into numerous categories with unique characteristics, such as graphene oxide (thermal conductivity, expansive surface area, flexible electronic structure, precise management of light absorption and heat emission), carbon nanotubes (mechanical strength, thermal durability, electrical conductivity, efficient light absorption), biochar (low cost, absorption activity, porous structure), and carbon foam (low cost, lightweight, high optical activity, durability) (Opoku et al., 2025). Carbon-based solar steam generators have potential for desalination due to their three-in-one characteristics: solar absorption across almost the full solar spectrum, light-to-heat conversion with minimal heat loss, and management of water/salt at the evaporation-localized surface interface, which keeps running rather than choking. Moreover, carbon chemistry is easy to tweak: O₂/N₂ functional groups and slight oxidation architecture open hydrophilic pathways for fast wicking. At the same time, hierarchical pores (micro for capillary rise, meso/macro for flow and vapor escape) reduced transport resistance along with a salt-dissolution path. They can easily suppress the crystallization at the hot interface. The work reported by Jin et al demonstrated the incorporation of CNTs and rGO into a cellulose matrix, which provides a remarkable photothermal evaporation rate of 1.85 kg m⁻² h⁻¹ with a conversion efficiency of 90.2% (Jin et al., 2022). The carbon-based materials comparison based on evaporation rate and conversion efficiency is illustrated in Table 1.4.

Table 1.4: Carbon and hydrogel-based solar steam generators for desalination.

Solar Evaporators	Conversion Efficiency (%)	Evaporation rate ($\text{kg m}^{-2} \text{h}^{-1}$)	Sun Intensity	References
Laser-induced graphene (LIG)/wood	110	1.60	1	(L. Huang et al., 2020)
Gtube/PTFE membrane	90	1.44	1	(Yin et al., 2021)
Graphene/Ni foam	91.4	1.4	1	(H. Ren et al., 2017)
Graphene film	90	1.37	1	(G. Li et al., 2018)
3D graphene/wood	91.8	1.64	1	(K. Kim et al., 2018)
Graphene/PVA/polyurethane sponge with pyramid-like structure	85.27	1.306	1	(Q. Yang et al., 2019)
Graphene/PVA hydrogel	92	1.77	1	(Lei et al., 2021)
N-doped graphene aerogel	86.2	1.41	1	(Deng et al., 2020)
Vertically vessel-like GO membrane	86.5	1.62	1	(P. Zhang et al., 2017)
GO/silica aerogel/PAM-PVA hydrogel		Around 2.6 (2 sun)	1	(L. Zhao et al., 2019)
3D-printed GO-based evaporator inspired by vascular stomata-like structure	94.5	1.4	1	(Z. Wang et al., 2020)
Janus rGO/GO/PVA hydrogel	99.98	3.24	1	(Y. Chen et al., 2022)
rGO/PVA hydrogel	95	2.5	1	(X. Zhou et al., 2018)
rGO/nanofibrous hydrogel	95.4	1.85	1	(Zang et al., 2021)
COF/rGO-rGO hydrogel	92	3.69	1	(C. Li et al., 2022)
rGO/cotton fabric/PAN foam		1.47	1	(Q. Zhang et al., 2019)
rGO/PS foam	83	1.31	1	(Shi et al., 2017)
Bridge-like rGO/melamine foam	92.9	1.476	1	(Meng et al., 2020)
rGO/MWCNT/PVDF membrane	80.4	1.22	1	(Y. Wang et

				al., 2018)
rGO/CNC/melamine foam	97.5	1.66	1	(H. Li et al., 2021)
rGO/chitosan/blank hollow spacer fabric	86	1.4352	1	(F. Wang et al., 2019)
3D rGO/geopolymer	104.6	2.39	1	(Deng et al., 2022)
Jellyfish-inspired MWCNTs–COOH/cotton fabric	86.01	1.18	1	(Qi et al., 2020)
CNT/silica substrate	82	1.32	1	(Y. Wang et al., 2016)
CNT film (edge)/CNT–PVA foam (center)		3.5–4.2	1	(Cao et al., 2021)
CNT/PAM hydrogel	97	4.3	1	(X. Zhang et al., 2020)
CNT/hydroxyapatite (HAP) aerogel	89.4	1.34	1	(Qin et al., 2019)
Amino-CNT/DAC membrane	90.86	1.58	1	(R. Zhu et al., 2022)
CNT/PVA/sodium lignosulfonate (SLS) hydrogel	80.4	2.09	1	(Hao et al., 2022)
CNT/covalent triazine framework (CTF) PVDF membrane	93.2	1.59	1	(L. Guo et al., 2020)
CNT/PVDF/filter paper/PU foam with paper belt	88.1	1.36	1	(C.-L. Guo et al., 2019)
CNT/PVDF–HFP/freeze-dried radish	≈121.6	2.35	1	(Lv et al., 2021)

1.5.4 Hydrogel materials

Hydrogel-based photothermal materials have demonstrated remarkable potential for solar-driven desalination owing to their integrated threefold functionality. Firstly, they facilitate efficient water transport, thereby accelerating evaporation. Secondly, they exhibit strong solar light absorption, significantly improving the photothermal conversion efficiency. (Anjali et al., 2019). Lastly, the polymer matrix exhibits excellent heat-retention properties, which is a significant challenge in solar-driven interfacial desalination (Opoku et al., 2025). Recent advancements in solar-driven evaporators include dual-functional materials that enhance performance as composite materials. To this end, composite hydrogels combine multiple photothermal agents and additional materials, enabling twofold functionality for both photothermal water evaporation and electricity generation. A hydrogel-based solar steam

generator can be synthesized by simple, cost-effective, biodegradable raw materials using simple synthesis procedures. For example, the solar evaporator designed by Li et al from polyelectrolyte hydrogel-functionalized photothermal sponge provides excellent evaporation efficiency (98.6%) and evaporation rate of $3.53 \text{ kg m}^{-2} \text{ h}^{-1}$ under 1-sun radiation intensity (L. Li et al., 2024). Hydrogels are a highly active material due to their outperforming evaporation rate. However, the hydrogel-based evaporators are formulated with other high-solar-absorber materials, such as semiconductors, plasmons, and carbon structures. The hydrogel-based materials are presented in Table 1.3, along with their evaporation rates and efficiencies under 1-sun irradiance.

1.6 Strategies to design efficient solar absorbers: Key points to consider

Apart from the configuration, device design, and the application of solar steam generators to investigate performance, the rational design of photothermal materials from a synthesis perspective is a crucial factor. Based on the literature review, frequently used nano-evaporators, such as metal nanoparticles, semiconductors, and carbon-based materials, are favored for their unique characteristics, including elevated surface area, tunable pore structures, and exclusive optical properties. Upcycling of waste through carbonization and graphitization, doping with heteroatoms like S and N₂ provides excellent viability in terms of cost and economy. Surface functionalization and integration/combination of one or more materials is an excellent approach to achieve a high-performance multifunctional solar steam generator (Opoku et al., 2025). Material development, considering environmental profile, material issues, and economic factors for the performance of the solar evaporator, is crucial.

The humidity and wind speed: are the significant factors that directly affect the solar steam generation. High humidity has a greater impact on the performance of solar evaporators because it reduces the evaporation rate by reducing the pressure gradient. To reduce the humidity factor on evaporation, the material exhibits a high hydrophilicity and should have an increased surface area, which could provide continuous water transport to maintain the steady evaporation. High wind speed not only reduces localized surface heat but also challenges the scalability of solar evaporators; the moderate wind speed helps to achieve an enhanced evaporation rate (Ristanto Wirangga et al., 2023).

Material factors: The Stability and durability of material, as solar steam generators, are one of the most important factors for the scalability of solar desalination on a commercial level. Solar evaporators based on plasmonic nanoparticles or hydrogels may degrade over prolonged use in harsh environmental conditions, such as saltwater and high temperatures,

because, for high system efficiency, it is crucial to maintain material stability. These factors can be minimized by using corrosion-resistant materials or protective coatings.

Economic affordability: Cost utilization is a significant consideration for any system processing. For the commercial adoption of solar steam generators for desalination, economic feasibility is a very important consideration. Photothermal material based on noble metals (Au, Ag, Pd etc), along with an expensive synthesis process, should be avoided to comply with the goals of sustainability. On the other hand, the use of low-cost materials, such as waste-derived materials, could be a practical approach to achieving an efficient desalination process.

For commercial-scale upgrading of this technology, a balance among connection costs, key properties, and synthesis issues is essential to pursue. Emphasizing the material, environmental, and economic factors of the solar-derived desalination process will boost innovation and adaptability.

1.7 Circular Economy: A Way Forward Towards Sustainable Materials

(Berg et al., 2018) A circular economy is an approach that ensures materials remain in use and natural systems are restored. Instead of becoming waste, products and materials are continuously cycled through maintenance, reuse, refurbishment, remanufacturing, recycling, and composting. By separating economic growth from reliance on finite resources, the circular economy addresses climate change, biodiversity loss, waste, and pollution.

The circular economy has been designed to support the Sustainable Development Goals (SDGs) and align precisely with responsible consumption and production (SDG 12), climate action (SDG 13), and clean energy (SDG 7). By utilizing waste as a resource, the circular economy supports reduced environmental pollution and promotes economic resilience through material cycles. Solar desalination uses renewable solar energy to produce fresh water from seawater, an area where the circular economy holds immense transformative potential. Enabling the circular economy in solar desalination is a way to advance this technology by replacing conventional materials with sustainable, recyclable, upcycled, or bio-derived alternatives. In this field, recent advances have been reported by upcycling biowaste and polymer into advanced photothermal material for solar desalination (Ogunmakinde et al., 2022; Rahimi-Ahar et al., 2025).

The annual plastic production volume exceeded 400 million metric tons (Mt) with a projected value of \$593 billion in 2021, and it is expected to grow by 3.7% over the coming

decade. (Plastic market size worldwide 2030, n.d.) .Plastic production is an essential part of advancement, but the end-of-life management of plastic is highly complex.

Figure 1.14(a) illustrates the global plastic production (413.8 Mt in 2023) analysis: China leads with one-third (33.3%), followed by North America (19.7%) and EU27⁺³ (17.1%). Together, these three regions make up about 70% of global plastics output. China is the largest overall producer of plastics, but Europe stands out in recycling and bio-based plastics, showing a stronger tilt toward sustainability. Global Recycled plastics production (36.5 Mt in 2023) and stand with EU27⁺³ (27.2%) compared to China (25.8%), with North America close behind (19.8%) (Plastics – thefast Facts 2024, n.d.). Incinerating and landfilling plastic waste not only harms the environment but also represent the loss of a valuable resource and an essential circular feedstock needed to transform the plastics system. The report highlights a concerning trend: the amount of post-consumer plastic waste being incinerated has risen by more than 15% since 2018. Conversely, the amount of post-consumer plastic waste sent to landfill has continued to decline, dropping by 6% since 2018. While this decrease is a positive development, landfill still accounted for nearly 25% of plastics waste treatment in 2022. Moreover, despite the Landfill Directive’s goal to ban the landfilling of separately collected waste by 2030, 11% of such waste was still landfilled in 2022, see Figure 1.14(b). (The Circular Economy for Plastics – A European Analysis 2024). Polyethylene terephthalate (PET) is one of the most common plastic along with polypropylene (PP), polyethylene (PE), polyurethanes (PU), and polystyrenes (PS), with global production volumes of 166, 68, 33, 27, and 25 Mt. The PET, PP and PE is most recycled plastic with occupancy of 95.2% Figure 1.15 (Zheng et al., 2023).

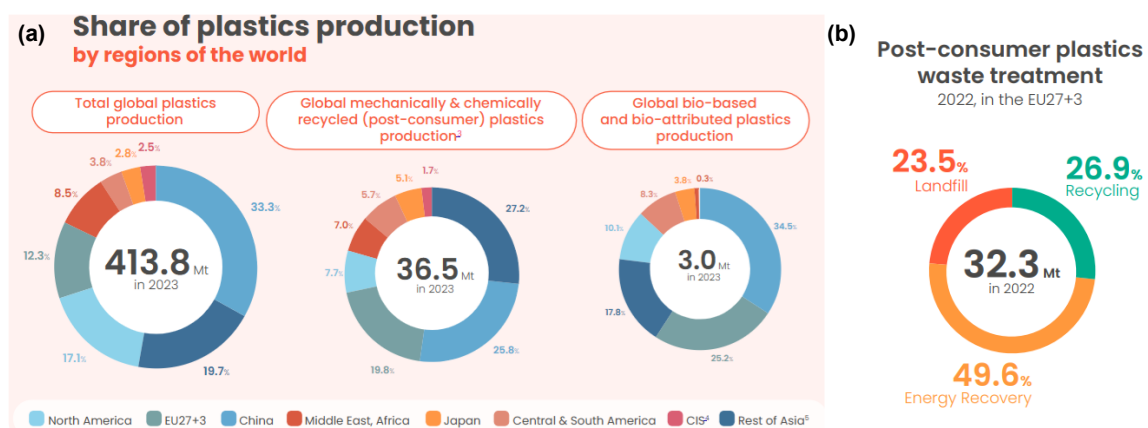


Figure 1.14: (a) Share of plastics production in 2023 by regions of the world, and (b) Post-consumer plastics waste treatment 2022, in the EU27⁺³ (Plastics – thefast Facts 2024; The Circular Economy for Plastics – A European Analysis 2024).

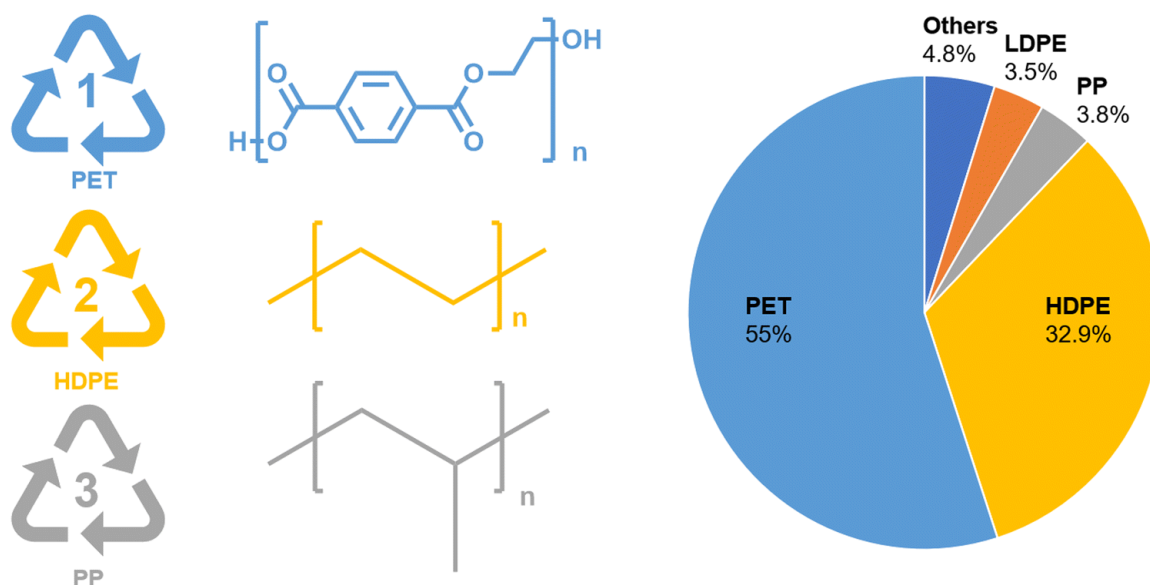


Figure 1.15: Types of most commonly used synthetic polymers making up the majority of the plastic recycling market, Copyright RSC, 2023 (Zheng et al., 2023).

Plastics can be recycled through various methods; the most common are mechanical and chemical recycling. Mechanical recycling is considered one of the most win-win solutions for plastic reuse, but at a certain point it hits the recycling wall. During mechanical recycling, plastic, such as PET, is shredded, melted, and reshaped. As a result, its long polymer chains start to fray (due to heat, moisture, and oxygen exposure). During this process, it drops its molecular weight, loses clarity, and tensile strength, and elongation at break consistently fall with each cycle (Umdagas et al., 2025). The circular economy is a promising solution to push the linear economy toward circularity, and upcycling waste plastic into advanced materials for environmental and energy applications is an emerging strategy to give waste plastic a new life. Catalytic upgrade of waste PET into carbons, foams, and aerogels with tailored porosity and light absorption to derive materials functional in processes such as water purification, energy storage, and solar-driven desalination, means that the embedded carbon is not rapidly lost to another short-life packaging cycle but instead locked into functional products with long service lives (Lin et al., 2025; Song et al., 2022).

Based on the above-discussed literature review, the present thesis aims to investigate the following aspects of the research work:

- Conduct bibliometric analysis to understand the progress and global trend in the field of nano evaporators for solar desalination.

- Synthesize highly hydrophilic carbon foam (CF) by catalytic upcycling of waste plastic PET at low carbonization temperature.
- Functionalize the synthesized CF with sulfide nanostructures to achieve maximum photothermal conversion due to superior optical activity in the UV/Vis-NIR region.
- Perform detailed characterization of the synthesized nanostructures through a multi-technique approach based on X-ray diffraction (XRD), Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDS), High-Resolution Transmission Electron Microscopy (HRTEM), X-ray Photoelectron Spectroscopy (XPS), and Ultraviolet-Visible-Near Infrared spectroscopy (UV/Vis-NIR) analysis.
- Conduct interfacial solar desalination experiments to analyze the potential of these nano evaporators for solar steam generation; perform contact analysis to investigate wettability
- By tackling both plastic pollution and water scarcity, the reported results directly support the United Nations Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). In this way, the research integrates waste valorization with clean-energy-driven desalination, offering a pathway in which environmental remediation and resource recovery converge within a circular-economy framework.

2 Experimental Details

2.1 Bibliometric analysis

The bibliometric analysis was conducted on the period of 2017 to 2024 using the WoS (Web of Science) database. The search type was "advanced search" with the following logic operation: TS = (("nano*") AND ("solar evaporator" OR "photothermal material" OR "solar steam generator") AND ("solar desalination" OR "solar water evaporation" OR "solar thermal conversion" OR "solar-driven evaporation" OR "solar steam generation" OR "photo-vapor conversion")). Document types are sorted to include "Article" and "Review article". The data was collected from 2017 to 2024 without a year filter. Furthermore, the language of choice was English. On Web of Science, 270 papers were collected (Research articles: 265 and Review articles: 5). Afterwards, the R Bibliometric library and the biblioshiny software were operated to determine the top authors' productivity, and the dataset was examined using the VOS viewer software, which resulted in author keyword clusters and networks of authors, sources, and countries.

2.2 Chemicals used in Experiment

All the listed chemicals and reagents that are used in this study for experimental purposes were purchased from Sigma Aldrich: Sodium Chloride (NaCl), Zinc Chloride (ZnCl_2), Copper Nitrate Trihydrate ($\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$), Cobalt Nitrate Hexahydrate $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, Copper Chloride Dihydrate $\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$, Antimony (III) Chloride Pentahydrate ($\text{SbCl}_3 \cdot 5\text{H}_2\text{O}$), Ammonium Hydroxide (NH_4OH), Hydrochloric acid (HCl), Thiourea ($\text{CH}_4\text{N}_2\text{S}$) and Melamine ($\text{C}_3\text{H}_6\text{N}_6$).

2.3 Synthesis of Carbon Foam

Carbon foam was synthesized from the upcycling of waste PET bottles via a low-thermal catalytic process, using an established method (Bai et al., 2022a). For the synthesis of carbon foam, the waste PET (Polyethylene Terephthalate ($\text{C}_{10}\text{H}_8\text{O}_4$)_n) bottle was used as a raw material for carbon foam synthesis, and the waste PET was cut into small sheets and placed (1.5 g) in a ceramic dish. Afterwards, the 3 g $\text{ZnCl}_2/\text{NaCl}$ (58/42 wt%) and 0.75 g of melamine were mixed with the PET sheets and placed in the muffle furnace. For thermal treatment, the reaction was performed under an air environment at 340 °C for 30 minutes with a 10 °C/min rate. After the reaction was completed, the muffle environment was allowed to cool to room temperature, and the ceramic dish was removed. The obtained black material was immersed in 0.5 M HCl overnight to remove impurities and unreacted material. Lately, the material was washed repeatedly with deionized water until the pH of the solution became

neutral. Finally, the washed black material was dried in a drying oven at 60 °C and packed in a polyethylene zip bag. The sample was labeled as CF and placed in a desiccator.

2.4 Decoration of CuS on CF (Chapter 1)

The hydrothermal method was adopted to synthesize covellite CuS on CF. In detail, 0.2 mmol of $\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$ was dissolved in a beaker containing 80 mL of deionized water, followed by the addition of 2 mmol of thiourea. In the next step, 0.15 g of CF powder was added to the precursor solution and stirred for 20 minutes. The precursor mixture was transferred to a Teflon-lined stainless autoclave and placed in a pre-heated oven for 12 hours at 120 °C. After the reaction is complete, let it cool to room temperature. The obtained black powder was collected and washed with deionized water three times and ethanol once. At last, after drying at 60 °C the powder was packed in plastic vials and placed in a desiccator for further characterization and analysis. Similar steps were used to synthesize covellite CuS without the addition of CF.

2.5 Synthesis of CuCo_2S_4 /CF (Chapter 3)

The carrolite (CuCo_2S_4) nanobeads were functionalized on the CF substrate using a solvothermal approach. Initially, 1.5 mmol of $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ were added in 10 mL of distilled water, followed by the addition of 0.75 mmol of $\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$ and 0.15 g of CF. Then, the solution precursor was sonicated for 20 minutes after the addition of 25 mL of ethanol. After sonication, the precursor mixture pH was adjusted to 9 with ammonium hydroxide. In the next step the 0.228 g of thiourea was added, and the precursor mixture was stirred at 80 °C for 12 hours. Finally, the precursor was heated in an oven for 6 hours at 180 °C to facilitate further reaction. Lastly, the black powder was obtained after cooling the autoclave to room temperature and several washes of distilled water and ethanol, and drying at 60 °C. The obtained powder was packed in a plastic vial and placed in a desiccator for further examination later on. The same method was applied to obtain the carrollite phase without the addition of CF.

2.6 Hydrothermal Synthesis of $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3$ /CF (Chapter 4)

In this study, the hydrothermal synthesis of $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3$ /CF comprises two different compounds, Sb_2S_3 and $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3$ on CF. Starting with the synthesis of Sb_2S_3 on CF, 1.5 mM of $\text{SbCl}_3 \cdot 5\text{H}_2\text{O}$ was dissolved in 100 mL of distilled water and sonicated for 20 min until a clear, milky solution formed. The beaker containing the precursor mixture was placed on a magnetic stirrer (500 rpm), and 0.2 mM thiourea was added, followed by the addition of

0.15 g CF with continuous stirring for 30 minutes. The precursor mixture was transferred to a Teflon-lined autoclave and heated at 180 °C for 24 hours. For the synthesis of $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3$ heterostructure on CF all steps and reaction conditions were utilized similarly, to optimize the Cu and Sb concentration, the following ratio of mM was adopted (1:1, 1.5:1, 0.5:1, 1:1.5 and 1:0.5), and samples were labeled as $\text{Cu}_1\text{Sb}_1\text{S/CF}$, $\text{Cu}_{1.5}\text{Sb}_1\text{S/CF}$, $\text{Cu}_{0.5}\text{Sb}_1\text{S/CF}$, $\text{Cu}_1\text{Sb}_{1.5}\text{S/CF}$, and $\text{Cu}_1\text{Sb}_{0.5}\text{S/CF}$. For these sample preparations, the copper concentration was induced at the very initial step during the sonication. Finally, after completion of the hydrothermal treatment, the collected powder was washed with deionized water and ethanol, dried at 60 °C in a drying oven, and then packed in plastic vials. The vials were placed in a desiccator. For comparison purposes in further investigation, the $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3$ was similarly synthesized without CF.

2.7 Microwave synthesis of $\text{Co-Bi}_2\text{S}_3\text{/CF}$ (Chapter 5)

In this project, the microwave synthesis approach was applied to synthesize Bi_2S_3 on a CF substrate. Initially, 1.2 g of $\text{Bi}(\text{NO}_3)_3 \cdot 5\text{H}_2\text{O}$ was dissolved in 50 mL of deionized water and sonicated for 20 minutes, then the milky white precursor was placed on a magnetic stirrer for 30 minutes, followed by the addition of 0.2mM thiourea and 0.15g of CF. The pH of the solution was set to pH-12 and transferred to a poly(tetrafluoroethylene) (PTFE)-lined pressure-resistant microwave vessel and fixed in a microwave reactor. The reaction was operated for a total of 20 minutes at 170 °C (T_1 as 7 minutes to reach the set temperature and another 7 minutes as T_2 for heat treatment) at 400 W microwave irradiation. For the preparation of $\text{Co}_x\text{Bi}_2\text{S}_3\text{/CF}$, a series of reactions was performed by adding $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ (0.012mM, 0.025, 0.05mM, and 0.1mM) at the initial step, along with the addition of $\text{Bi}(\text{NO}_3)_3 \cdot 5\text{H}_2\text{O}$, before sonication of the precursor mixture. After the reaction was complete, the reactor was cooled to room temperature, and the black powder was collected by centrifugation, followed by several washes with deionized water and a final wash with ethanol. Finally, the black powder was dried at room temperature at 60 °C, and the sample was kept in a desiccator by inserting the powder in plastic vials.

2.8 Material Characterization

The crystal structure of the synthesized samples was investigated using a Philips PW1050/37 diffractometer for X-ray diffraction (XRD) analysis. For the phase identification/match, the JADE-6 was used to match the crystal structure of the synthesized samples with the standard JCPDF data. The UV/Vis absorption spectroscopy analysis (UV/Vis-NIR) was performed using an ultraviolet-visible spectrophotometer LAMBDA 1050⁺, Perkin Elmer, with an

integrating sphere; the data were recorded in reflectance units and later converted into absorption percentage. To investigate the chemical composition and oxidation state of metal in nanostructure the surface analysis of samples was performed using X-ray photoelectron spectroscopy (XPS) an ESCALAB 250 (Thermo Fisher Scientific USA) spectrometer with an x-ray source monochromated Al K α 150W and energy pass 200 eV for the survey and 30 eV for high-resolution scans. The surface morphology and elemental mapping (SEM-EDS) analysis were carried out using an FEI Magellan 400 FEG-SEM with EDS detector, X-Max 80 mm² SDD (Oxford Instrument). The HR-TEM (High-resolution Transmission Electron Microscopy) micrographs were obtained via the JEOL ARM 200F microscope with 2 CS correctors of CC3M competence center of Institut Jean Lamour. The microscope was equipped with an MSC794 camera, Gatan One View, JEOL HAADF detector, and a double-tilt sample holder. The wettability analysis of was performed using the FTA 1000 Analyzer System for the contact angle measurements. Differential Scanning Calorimetry (DSC) analysis was carried out using a 1020 Series DSC 7 thermal analysis system, with the following temperature range 20 °C to 150 °C at 5 °C/min. The Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) was performed with a Perkin Elmer Optima 5300SV spectrometer.

2.9 Interfacial Solar Desalination Test

For the interfacial solar desalination test, 0.1g of the synthesized nanomaterial was added to 20 mL of distilled water and sonicated for five minutes. After sonication, the material was deposited on a glass microfiber filter (Whatman GF/F, CAT No. 1825-047) using a vacuum filtration assembly. After deposition of the material, the membrane was dried at 60 °C, and then cut into several 1×1 cm² pieces for further investigation. A piece of membrane was taken and placed on a vertical cotton sponge that serves as a saline-water transport medium towards the membrane. The cotton sponge was passed through a thermal insulator, typically polyethylene foam, also used to cover the beaker. In a separate 50 mL beaker, 40 mL of deionized water was taken, and a saline solution was prepared by the addition of 0.6 mol/L NaCl solution in the deionized water, that are 3.5% (mass fraction) average global seawater salinity. The cotton sponge holding the photothermal layer was placed on the surface of the water at the top edge of the beaker, and the surrounding area of the beaker was covered with parafilm to prevent extra evaporation. Finally, the interfacial photothermal desalination was conducted under one sun radiation (air mass 1.5 global, AM1.5G, 1000W/cm²), and the surface temperature was recorded using a thermal camera (FLIR C3-X) during the

desalination process. For the dry stage, surface temperature profiling was recorded with the same device design but without the addition of saline water. For the performance evaluation of the material, the change in mass was recorded using an analytical balance. The equation given below was used to calculate the evaporation rate.

$$\text{Evaporation rate} = \frac{\Delta m}{S \times t} \quad (3)$$

Where, Δm is the mass of evaporated water (kg)

S is the surface area of the evaporator (m^2)

Moreover, t is the time of evaporation (h).

Evaporation efficiency of a solar evaporator refers to how efficiently the system transforms incoming solar power into steam. Evaporation efficiency is considered a key metric to assess the performance of solar-driven desalination systems. The evaporation efficiency could be measured with equation given below;

$$\eta = \frac{\Delta m \cdot h_{lv}}{C_{opt} \cdot q_i} \quad (4)$$

Where,

Δm is the mass of evaporated water ($\text{kg}/\text{m}^2 \cdot \text{h}$)

h_{lv} is the latent heat of vaporization (J/kg)

C_{opt} is the optical concentration factor (usually 1 for no concentrators)

and q_s is the incident solar flux (W/m^2 , typically $1000 \text{ W}/\text{m}^2$ under 1 sun)

3 Results and Discussion

3.1 Chapter 1: Bibliometric Analysis of Photothermal Nano-evaporators

Bibliometric analysis is a quantitative method used to investigate scientific literature and uncover patterns, trends, and impact within a research field. It covers several aspects such as publication counts, citation frequencies, keywords, and authorship to reveal how knowledge evolves, which authors or institutions lead the trend, and how themes emerge and interact. The methodology involves selecting and extracting data from sources such as Scopus, primarily Web of Science, or Google Scholar, cleaning the data, and then applying analytical methods using software tools like VOSviewer, CiteSpace, or Bibliometrix. Bibliometric analysis results are a macro-level approach and are excellent for mapping a field's intellectual structure; they complement rather than replace traditional literature reviews. Bibliometric analysis has become a newfound drift in academic research in recent years (Öztürk et al., 2024; Passas, 2024).

Solar desalination has introduced recent advances in fresh water production to address water scarcity. Based on this ongoing trend, a large number of papers have been published in recent years. From this end, to estimate the ongoing trend in this research area, there was no such bibliometric analysis on nano-evaporators as solar steam generators. To examine the trends mentioned above, the bibliometric analysis was performed on the period of 2017 to 2024 collecting data from Web of Science.

The key results of the bibliometric analysis are presented here in a summary, with details appended as Paper-1. From 2017 to 2024, the consistent growth in published papers (with an annual publication rate increasing by 14.63%) on nano-evaporators resulted in the highest numbers in 2022 (73 papers) and 2023 (70 papers), as shown in Figure 3.1(a). The investigation reveals that the authors keywords “desalination”, “photothermal conversion”, “solar desalination”, “water purification”, and “seawater desalination” with “solar steam generation” were found to be most frequently used (Figure 3.1(b)), and Individually clustered in the visual picture replicates the total link strength of individual keywords through circle size scale indicators. The bibliometric analysis assessed 638 keywords; the 20 best encountered with keywords across the field are ranked in Table 3, Appended Paper-1. The top three frequently operated keywords in the research area are “solar steam generation” (79 occurrences), “desalination” (37 occurrences), and “photothermal conversion” (33 occurrences). The results also reveal that 1315 writers are contained in relevant publications. All papers contain co-authorship, and the mean total of co-authors per document is

approximately 6.86, which also reflects the 16.67% as a high percentage of international cooperation.

The bibliometric results emphasize the international trend (the most important countries, institutions, and journals) as an important part of the research field. The results showed that China is the top producer of documents, based on the corresponding authors (SCP (Single Country Publication) and MCP (Multi Country Publication)) for nano-enhanced solar evaporators. Figure 3.1(c) presents the top countries by the number of documents produced. In institutional rankings, the Chinese Academy of Sciences leads in document production, followed by Donghua University and Huazhong University of Science and Technology. The most important part of academia is the ranking of journals based on the number of papers they publish. The results show that Desalination published approximately 22 articles, Journal of Materials Chemistry A published 18, ACS Applied Materials & Interfaces published 16, and Nano Energy published 10 (see Figure 3.1(d)). The bibliometric analysis examined global interest in the growth of nano-evaporators for photothermal desalination and provided a deep understanding of the current state of research worldwide. The outcomes pool knowledge and drive the field forward, which could be a feasible solution for addressing global water scarcity and achieving sustainability goals, with a particular focus on SDG-6, SDG-7, and SDG-13.

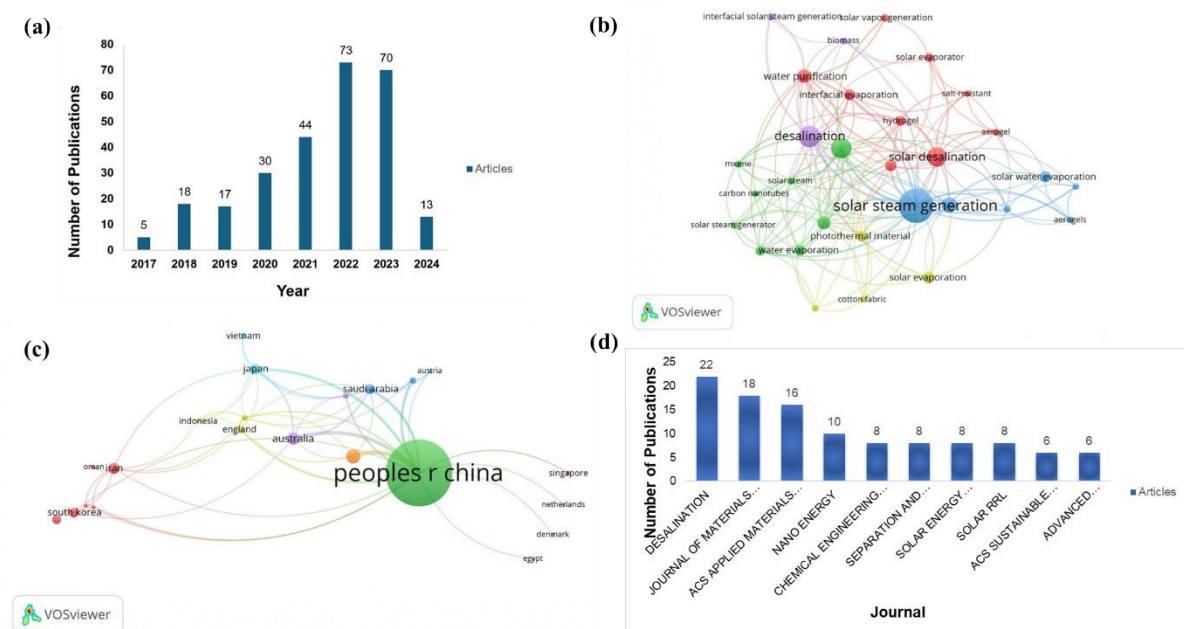


Figure 3.1: (a) Number of publications annually, (b) keywords in the field of nano-enhanced solar evaporator network visualization map, (c) The most representative countries in the field of nano-evaporators, and (d) Journals source in terms of publication, Copyright 2025, Elsevier (Shahzadi et al., 2025).

Appended Paper-1

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Review

Nano-enhanced solar evaporators for desalination: A comprehensive bibliometric review

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ABSTRACT

Nanostructures gained popularity in recent years because they exhibit preferable thermo-physical and optical properties for solar desalination applications. Solar steam generation presents an effective solution to worldwide water scarcity issues through its solar-powered desalination process which uses solar energy. To obtain high evaporation rates, the development of cost-effective and highly efficient photothermal evaporators is still challenging. The objective of this bibliometric review is to analyze the keywords, authors, countries, and key sources in the field of nano-enhanced solar evaporators for desalination. The WoS (Web of Science) database was used to collect the documents, and bibliometric analysis was carried out through VOS viewer and Bibliometrix software. The results showed that 270 papers (Research articles: 265 and Review articles: 5) studied nano-enhanced solar evaporators for desalination from 2017 to 2024. Over the prior five years, the number of publications has increased significantly, which shows the imperative for advanced nanostructured photothermal absorbers for solar desalination applications. Commercialization requires improved absorber stability, salt blocking, scalability, low toxicity, and affordability.

3.2 Chapter 2: Turning Trash into Treasure: Waste PET Upcycled Carbon Foam Decorated with CuS Nanocrystal for Interfacial Solar Desalination, enabling Circular Economy

Interfacial solar desalination is an emerging technology for producing fresh water that utilizes renewable solar energy. To achieve the maximum output, the design of material for solar evaporators requires achieving some merits such as high hydrophilicity and efficient photo-to-thermal conversion (Z. Chen et al., 2022). Circular economy plays a crucial role in the development of materials for the energy and environment sector. Considering the waste source for material development could be an excellent approach to target sustainable material development. Due to the high consumption of plastic in daily life, the end-of-life management of plastic products poses a considerable challenge to waste management. In recent years, the upcycling of waste plastic into carbon material has been exploited for energy and environmental applications (Hansen et al., 2022; Q. Hou et al., 2021). In literature, numerous studies have been reported on the use of carbon-based materials for the solar desalination process, but these materials fail to meet the ideal characteristics, such as high hydrophilicity, high evaporation rate and efficiency, low thermal conductivity, and high absorption in the UV/Vis to NIR region of a solar evaporator (Bai et al., 2022; Taranova et al., 2023)

Recently, a new approach has been adopted to upcycle the waste PET into carbon material, such as carbon foam. The carbon foam got much attention as a solar evaporator due to the following characteristics: meso/microporous channels, maximum light absorption from UV/Vis-NIR region, highly reduced heat loss, lightweight, and porosity. The carbon foam is considered as a suitable substrate for decoration with metallic nanostructures in 3D pores with high chemical and thermal stability, resulting in an excellent composite system for energy applications. Some literature presents the use of plasmonic metals, such as gold, silver, and platinum nanoparticles, for solar desalination to harness solar energy and convert it into heat (Bai et al., 2022). Nevertheless, their high cost and low abundance have limited the scope of solar evaporation. In the present research work, the waste PET is initially upcycled into carbon foam via a low-thermal catalytic approach using the eutectic salt NaCl/Zn₂Cl. In the second step, covellite CuS nanocrystals were supported on a CF substrate via a hydrothermal route to achieve high photo-to-thermal conversion due to the plasmonic properties of CuS. The synthesized nano-evaporator is expected to achieve a higher evaporation rate for interfacial solar desalination than bare CF. The results of this study are

summarized below, and important results are illustrated in Figure 3.2(a); A detailed investigation is included as Appended Paper 2.

The synthesized (CF, CuS, and CuS-CF) material was characterized in the angular range of 20°-80° for XRD analyses to investigate its phase and crystal structure. The obtained results show the broad Bragg peak at $2\theta = 18^\circ$ -32°, attributed to the graphitic (002) plane (JCPDS no. 41-1487), which is in good agreement with the literature reported (Bai et al., 2022). Moreover, the CuS grown on CF presents diffraction peaks at 2θ values of 27.1°, 31.7°, and 47.7° corresponding to the three crystal planes (100), (103), and (107) of Covellite CuS (JCPDS no. 06-0464), see Figure 3.2(b). The surface morphology of CF shows an open-cell structure with pores; the flat sheets also reflect the presence of multilayer graphitic sheets, consistent with the recently reported morphology of CF. SEM images reveal that the covellite phase of CuS exhibits a nanocrystal shape decorated on the surface of CF. The EDS presents the uniform distribution of elements on the substrate surface, and HR-TEM magnification has confirmed the polycrystalline Covellite phase of CuS. The obtained d-spacing values of 0.33, 0.19, and 0.28 nm successfully matched the corresponding XRD patterns with the crystal planes (100), (103), and (107) for the Covellite phase of CuS, see Figure 3.2(c).

To investigate the surface composition, the XPS (X-ray photoelectron spectroscopy) analysis was performed; detailed analysis description and spectra are presented in Appended Paper 2 (Supporting Information Figure 3 and Figure 4). The XPS analysis confirms the graphitic nature of the synthesized CF, as indicated by its corresponding binding energies of the high-resolution core-level peaks of C1s, N1s, and O1s. The CuS/CF XPS analysis presents the doublet $2p_{3/2}$, $2p_{1/2}$ at 932.6 eV and 952 eV, and the S $2p$ core level spectrum, which exhibits two doublets with the $2p_{3/2}$ at 162.3 eV and 164.2 eV, assigned to sulfide of Covellite CuS nanocrystals and S(0), respectively. In the case of CuS/CF, the high-resolution C 1s, O 1s, and N 1s spectra exhibit a similar pattern to those obtained from CF; these results indicate that the hydrothermal decoration of CF with CuS nanocrystals does not alter the graphitic character of CF.

In principle, a photothermal evaporator must exhibit high absorption activity across the UV/Vis to NIR region to achieve high photo-to-thermal conversion. The UV/Vis-NIR analysis was conducted to investigate the absorption activity of CF and to examine the role of CuS. Figure 3.2(d) shows that the CuS/CF exhibits more than 95% absorption activity throughout the UV/Vis to NIR region, compared to bare CF, with a decrease from 95% to 72% in the UV/Vis to NIR range. The enhanced optical absorption activity is achieved due to

LSPRs (local surface plasmonic resonance) of the p-type semiconductor covellite CuS (Tao et al., 2018).

For the performance evaluation of nano-evaporators, an interfacial solar desalination experiment was performed under simulated solar light (AM 1.5G, one-sun irradiation) using 3.5% saline water. The evaporation rate of solar evaporators (CF, CuS, and CuS/CF) and glass microfiber under one sun irradiation and in the dark is presented in Figure 3.2(e). The CuS/CF nanocomposite achieved an enhanced evaporation rate of $1.92 \text{ kg m}^{-2} \text{ h}^{-1}$ compared to bare CF $1.58 \text{ kg m}^{-2} \text{ h}^{-1}$. The photothermal conversion of the material before and during solar desalination was recorded using a photothermal camera, and in the case of CuS/CF the maximum temperature at the dry state is achieved as 75.1°C compared to CF 68°C . The surface temperature during solar desalination was extensively higher for CuS/CF 41.4°C compared to the CF as 37.1°C Figure 3.2(f), and literature reported for CuS membranes of 35.2°C under one sun radiation (Tao et al., 2018). The evaporation rate of CuS ($1.41 \text{ kg m}^{-2} \text{ h}^{-1}$) without CF clearly demonstrates the role of CF in achieving a high evaporation rate; CF helps to move water vapors faster, thereby facilitating evaporation. Moreover, the wettability of CuS/CF was investigated using contact angle analysis (Figure 3.2(g)), which demonstrates the material's high hydrophilicity. The decoration of CF with CuS nanocrystals does not affect the hydrophilicity of the CF substrate. Furthermore, the evaporation efficiency (η) of CuS/CF was investigated based on DSC (Differential Scanning Calorimetry), which presents the 91% compared to the literature-reported value CF/PVDF 53% and CuS/SCM 68.6% (Hu et al., 2017; Song et al., 2021). The obtained results indicate a promising approach for the sustainable development of new solar evaporators from waste plastic, combined with functionalization with low-cost plasmonic metals for freshwater production via interfacial solar desalination. The approach met the goals of mitigating the water and plastic crises by upcycling plastic waste through circular-economy practices.

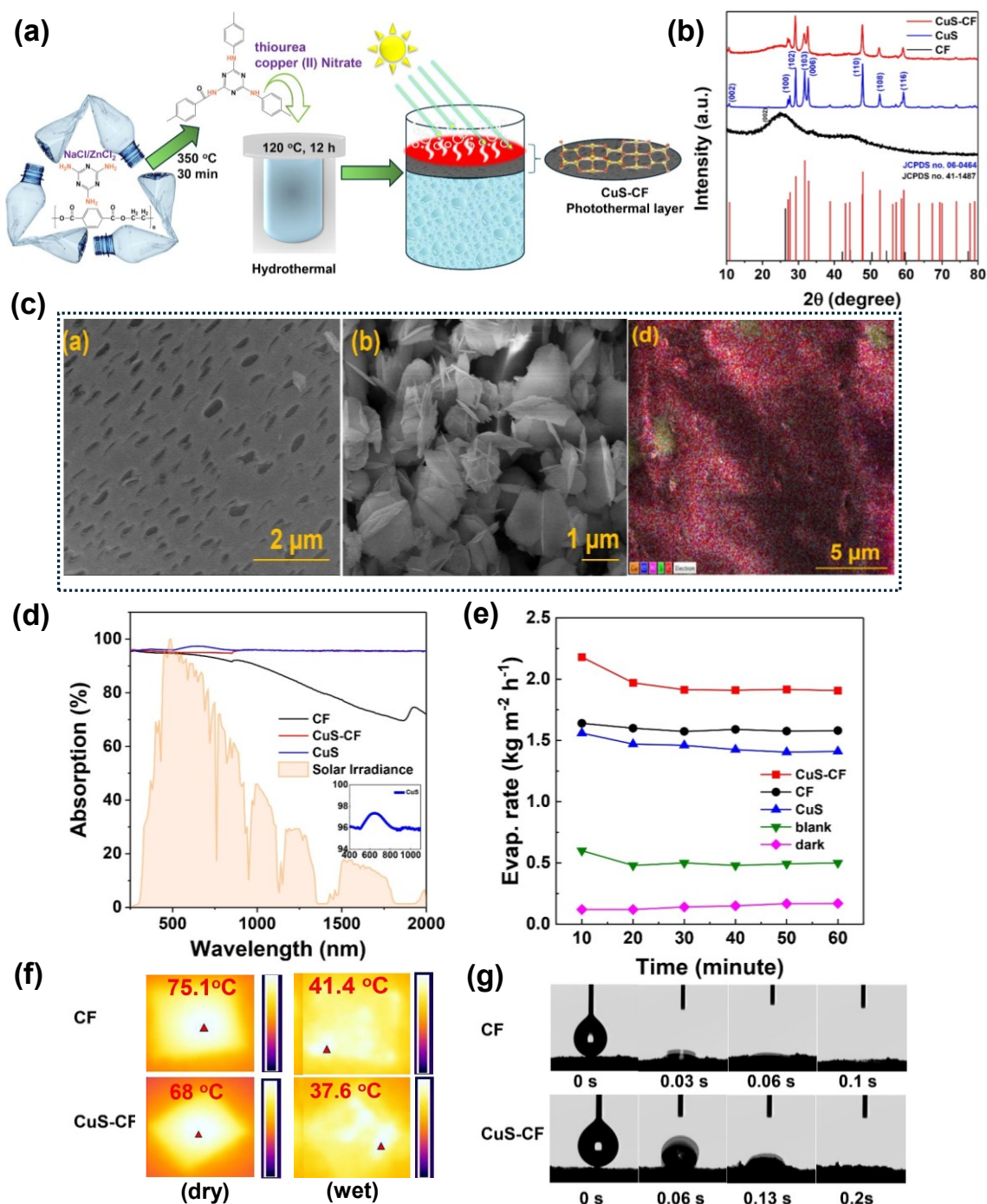


Figure 3.2: (a) Graphical illustration of the work on CuS/CF, (b) XRD pattern, (c) SEM-EDS images, (d) UV/Vis-NIR spectra, (e) Evaporation rate, and (f-g) Photothermal surface images and contact angle analysis of CF and CuS/CF, Copyright 2025, Wiley (Hussain, Taranova, et al., 2025).

Appended Paper-2

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RESEARCH ARTICLE OPEN ACCESS

Decoration of Two-Dimensional CuS Nanoflakes on Graphitic Carbon Foam Derived from Waste Plastic for Interfacial Solar Desalination

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Keywords: 2D materials | circular economy | covellite CuS | photothermal desalination

3.3 Chapter 3: CuCo₂S₄ Nanobeads Functionalized Carbon Foam Derived from Waste PET for Interfacial Solar Desalination

For efficient interfacial solar desalination, the engineering of solar evaporators is crucial. Ideally, photothermal evaporators consist of a solar absorber and a substrate material. The combination of these two components should play an equal role in performance output. The solar absorber should provide high absorption activity along with maximum thermal energy production, and should not affect the hydrophilicity of the substrate material to achieve a smooth evaporation rate (Karami et al., 2021). The combination of carbon material with semiconductors has been reported recently for various environmental and energy applications such as photocatalytic, photovoltage, and synergetic functions of photothermal application (J. Zhu et al., 2024). In such a combined nanocomposite, the nanostructures primarily harvest solar radiation and convert it into heat. At the same time, the carbon material, serving as a substrate, primarily acts as a hydrophilic water-transport channel and plays a significant role in preventing heat loss from the photothermal absorber.

Cobalt-based nano-evaporators display robust photothermal performance due to their broadband solar absorption, efficient nonradiative relaxation, and favorable structural properties. Due to their low band gap, cobalt nanostructures and composites possess narrow band gaps (1–2 eV), enabling them to capture a vast portion of the solar spectrum from the UV/Vis to the near-IR region, which is vital for efficient solar-to-thermal conversion. In nanostructured or carbon-composite forms, metallic cobalt can also exhibit plasmon-like resonances that enhance local electromagnetic fields and thereby further increase light-harvesting efficiency. In addition, their comparatively low thermal conductivity and porous architectures confine heat at the air-water interface. Importantly, cobalt-based nanostructured and composite materials exhibit high corrosion resistance in a saline environment, making them stable candidates for continued desalination processes. These combined optical, electronic, and structural features position cobalt-based materials as promising photothermal agents for solar-driven desalination (Dhandapani et al., 2025; Y. Zhao et al., 2022). The ternary cobalt and copper sulfide (Co₂CuS₄) thiospinel nanostructure has recently attracted attention for its outstanding performance in supercapacitors, solar cells, and lithium-ion batteries. The remarkable thermal stability and tunable morphology also make CuCo₂S₄ a strong runner for photocatalytic applications, including dye degradation and hydrogen evolution (M. Guo et al., 2016; Konwar et al., 2022; Vadivel et al., 2018).

Based on the literature survey, the carrollite Co₂CuS₄ nanostructure has never been reported for solar desalination. Considering the excellent optical activity of carrollite

Co₂CuS₄ sulfide nanostructures, it could be a great idea to develop nano-evaporators by combining this material with C-based material. The rationale behind focusing on carrollite is due to its excellent track record in various applications, where it exhibited remarkable optical and electrical responses. In this research work, we have synthesized the nanobeads of carrollite Co₂CuS₄ by adopting the solvothermal method with carbon foam CF, which is upcycled from the waste PET bottles. The work is described as graphical in figure 3.3(a), the key results of the study are elaborated here, and detailed investigations with complete comparison are attached as Appended Paper 3.

Starting with the characterization of the material, the crystal structure of Co₂CuS₄/CF was confirmed with XRD (X-ray diffraction) analysis. Figure 3.3(b) presents the XRD pattern of Co₂CuS₄ and Co₂CuS₄/CF, which perfectly matches the standard peaks of the carrollite phase. The Bragg peaks at $2\theta = 16.1, 26.5, 31.27, 37.96, 46.99,$ and 49.96° correspond to crystal planes (111), (022), (113), (004), (224), and (115) of carrollite (JCPDS no. 42 1450). The surface morphology of the Co₂CuS₄ on CF was studied using SEM-EDS. Figure 3.3(c) shows the uniform generation of Co₂CuS₄ nanobeads on the graphitic sheet of CF, which presents the open cell structure on the surface. The elemental mapping image of Co₂CuS₄/CF recorded with EDS clearly indicates the uniform distribution of all the elements present on the surface. The detailed morphological investigation of CF, Co₂CuS₄, and Co₂CuS₄/CF with comparison is illustrated in Appended Paper 3 in Fig.3, Fig.4, and Fig. S.1 of Supporting information. The results obtained with XRD analysis and SEM images indicated that synthesizing the Co₂CuS₄ with CF does affect the crystal structure and morphology of Co₂CuS₄ nanobeads.

Figure 3.3(d) shows the comparative absorption percentage result of UV/Vis-NIR for sample CF, Co₂CuS₄, and Co₂CuS₄/CF. The obtained results show a significant reduction in CF absorption activity when moving from UV/Vis (90%) to NIR (67%). On the other hand, the CF functionalized with nanobeads of Co₂CuS₄ presents more than 96% throughout the spectrum range from UV/Vis to the NIR region. Based on the solid arguments of enhanced optical activity, the material was tested for interfacial solar desalination. The interfacial solar desalination experiment was performed by depositing the sample material onto a glass microfiber membrane using vacuum filtration. After drying, a piece of the membrane was used for the interfacial solar desalination experiment, which was carried out under one-sun solar irradiation. Figure 3.3(e) presents the comparative results of CF, Co₂CuS₄ and Co₂CuS₄/CF for the evaporation rate based on the change in mass during the desalination process. The sample CF functionalized with Co₂CuS₄ presented an outperforming evaporation

rate ($2.40 \text{ kg m}^{-2} \text{ h}^{-1}$) compared to CF $1.6 \text{ kg m}^{-2} \text{ h}^{-1}$ and $1.62 \text{ kg m}^{-2} \text{ h}^{-1}$ for Co_2CuS_4 . These results clearly indicate the outperformance of the nanocomposite material and the role of CF, which helps transfer water vapor for escape through the micropores observed on the surface of CF in SEM images. For photothermal conversion, the surface temperature of the material was recorded before solar desalination (dry state) and during desalination (wet state). Figure 3.3(f) presents the surface temperature profile of all the samples at the dry and wet stages, which indicates the enhanced surface temperature of $\text{Co}_2\text{CuS}_4/\text{CF}$ at the dry and wet state compared to bare CF and pristine Co_2CuS_4 . Furthermore, the material hydrophobicity was investigated with contact angle analysis, and the obtained results show that the highly rapid absorption of a water drop by $\text{Co}_2\text{CuS}_4/\text{CF}$, the similar wettability of CF and $\text{Co}_2\text{CuS}_4/\text{CF}$ nanocomposite clearly illustrate that there is no effect on the hydrophilicity of graphitic CF, see Figure 3.3(g). In conclusion, the results demonstrate the progressive improvement in the performance of nanocomposites due to the hydrophilic CF and the excellent photothermal performance of carrollite Co_2CuS_4 nanobeads; furthermore, the outcomes open a new approach for Co_2CuS_4 as an excellent candidate for photothermal evaporators.

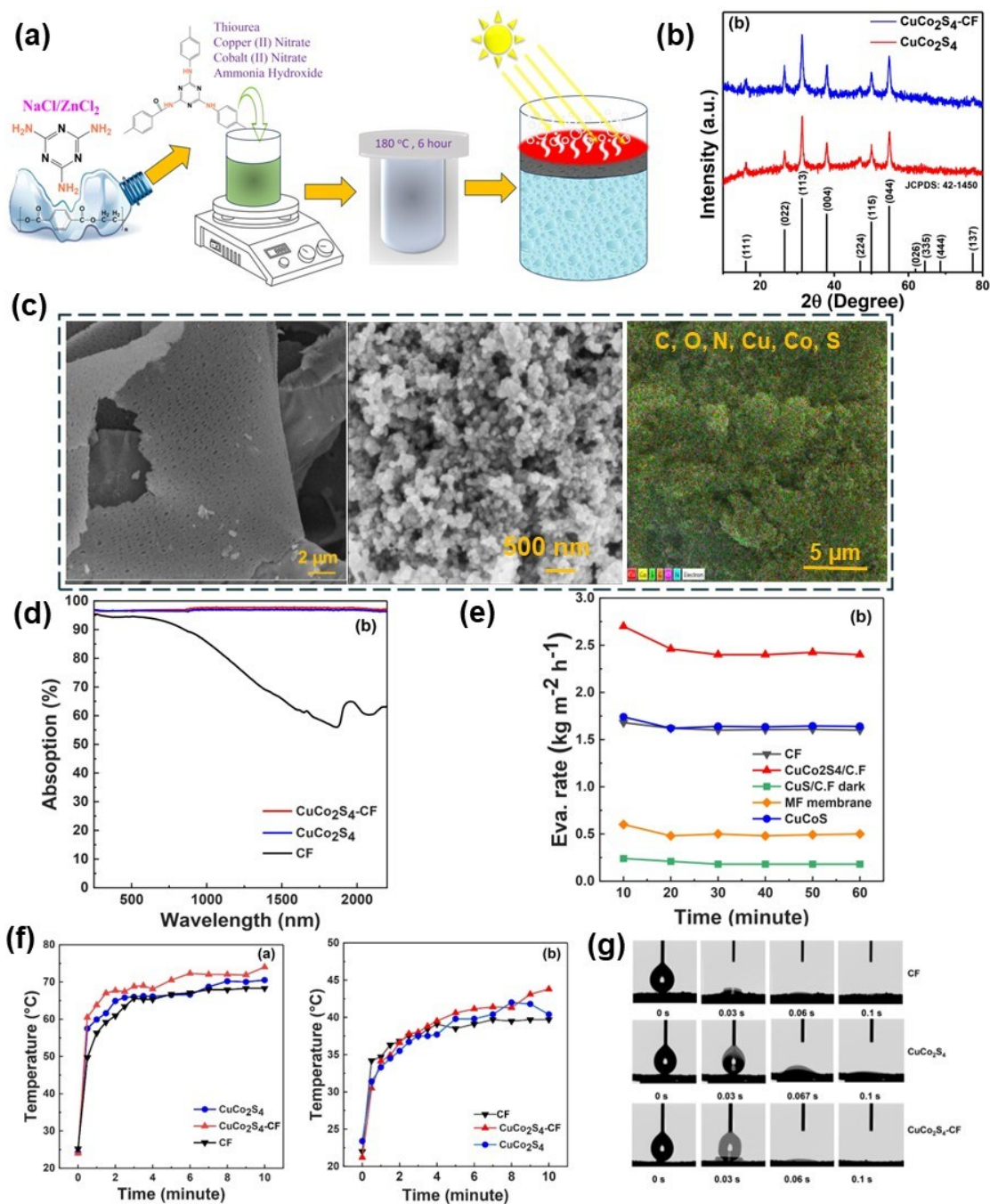


Figure 3.3: (a) Graphical illustration of the experimental work, (b) XRD pattern, (c) SEM-EDS images, (d) UV/Vis-NIR spectra, (e) evaporation rate, and (f-g) surface Temperature profile and contact angle analysis of CF and $\text{Co}_2\text{CuS}_4/\text{CF}$, Copyright 2024, Springer (Hussain et al., 2024) .

Appended Paper-3

<https://doi.org/10.1007/s40242-024-4091-8>



Article

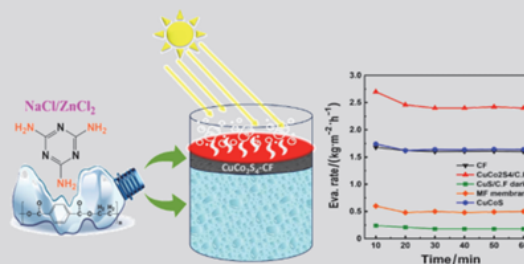
Enhanced Solar Water Desalination by CuCo_2S_4 -decorated Carbon Foam Derived from Waste Plastics

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Interfacial solar desalination is an emerging technology for freshwater production, but the finding of novel solar evaporators is still challenging. In the present research, graphitic carbon foam (CF) was synthesized from the upcycling of waste plastic polyethylene terephthalate (PET) waste bottles functionalized with carrollite CuCo_2S_4 as a photothermal layer. Analytical characterization [X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), and scanning electron microscopy-energy dispersive spectroscopy (SEM-EDS)] confirms the functionalization of carrollite CuCo_2S_4 on graphitic carbon foam. The UV-Vis spectroscopy analysis showed an enhanced optical absorption in the UV-Vis-near IR region (>96%) for functionalized CuCo_2S_4 -CF foam compared to carbon foam (67%). The interfacial solar desalination experiment presented a significantly enhanced evaporation rate of $2.4 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ for CuCo_2S_4 -CF compared to that of CF ($1.60 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) and that of CuCo_2S_4 ($1.60 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$).

The obtained results proved that the newly synthesized CuCo_2S_4 -CF from the upcycled plastic into new material for the photothermal desalination process can enhance the practice of a circular economy to produce fresh water.



Keywords Photothermal desalination; Cobalt; Copper; Chalcogenide; Waste upcycling; Circular economy

3.4 Chapter 4: Sb₂S₃ Nanocrystal to Cu₃SbS₄-Sb₂S₃ Nanochannels Functionalized Carbon Foam: A Morphology-dependent Enhanced Photothermal Interfacial Solar Desalination

Apart from the substrate, the engineering of the solar absorber is a tricky process that plays a crucial role in the outperformance of photothermal evaporators (Karami et al., 2021). In interfacial solar desalination, morphology is not just a detail, but it is the pedal that sets the whole system's heat-mass balance. Engineering of the solar absorber assembled with hierarchical porosity and micro and nanochannels wicks bulk water films to the localized hot surface (X. Wu et al., 2024; Z. Yu et al., 2023). The creation of nanochannels in photothermal material enables vigorous capillary pumping, which feeds the photothermal layer without flooding, thereby maintaining a thin liquid film where localized heat converts water to vapor most efficiently (Min et al., 2021).

Semiconductor, plasmonic, and hydrated transition metal chalcogenide-based nano-evaporators play a crucial role in solar steam generation. Bibliometric analysis indicates that in recent years, these nano-evaporators have drawn significant attention from the research community, reflected in a sharp rise in related publications (Shahzadi et al., 2025). A highly efficient photo-to-thermal conversion requires a solar steam generator that provides high solar absorption across the UV/Vis to near-IR region. In this context, sulfide-based chalcogenide nanostructures feature narrow band gaps, enabling them to absorb a broad spectrum of solar radiation and underscoring their potential to advance efficient and sustainable solar desalination processes. Recently, Cu-based sulfide nanostructures have demonstrated their excellent capability as solar steam generators (W. Huang et al., 2020; N. Li et al., 2019). In addition, copper–antimony–sulfide ternary chalcogenides have drawn intense interest for solar cells due to their high optical activity and tunable morphologies, with promising performances in areas such as dye degradation and CO₂ reduction (Li et al., 2024; Ramasamy et al., 2014; Tablero, 2014; L. Yu et al., 2013). Although they exhibit interesting optical and thermal properties, their potential as photothermal materials for interfacial solar desalination remains largely unexplored. In this research project, we upcycled waste PET to CF, studied the proposed mechanism for CF formation, and then functionalized it with Sb₂S₃. To develop an efficient solar-harvesting photothermal evaporator, we rationally designed a heterostructure of Cu₃SbS₄-Sb₂S₃/CF by incorporating Cu at different molar ratios. The experimental process for synthesizing this material is illustrated graphically in Figure 3.4(a). The detailed comparative investigation of this work is included as Appended Paper 4, and important results highlights are discussed below.

The upcycling of Waste PET bottles into CF includes a thermal catalytic process; for this reason, eutectic salt of NaCl and ZnCl₂ was used along with melamine and processed at 350 °C for 30 minutes under air environment in a furnace. The mechanism of CF formation involves several steps, as illustrated in Figure 3.4(b). Initially, the PET chain degrades by the random break of the ester bond (beta-hydrogen transfer), which yields two chain fragments (1-carboxyl-terminated chain and 2-vinyl-terminated chain). The vinyl-terminated fragment (2) decomposes into a carboxyl-terminated fragment (1) by eliminating acetylene. During the first crosslinking, the amide reaction between the carboxyl group of the carboxyl-terminated chain and the amino group of melamine forms a carboxyl-terminated PET degradation intermediate (5). The crosslinking of melamine with a carboxylic group suppresses the formation of aromatic ring-terminated fragments (4) from the carboxyl-terminated chain (2) and (3), and during the carbonization process, the decarboxylation and dehydration result in the formation of a stable framework due to the catalytic action of molten salt, owing to the Lewis acidity of ZnCl₂. The compound (3) from vinyl-terminated chain fragments undergoes intermolecular condensation to ease the self-crosslinking structure (6). A similar mechanism has been proposed in a recently reported study for upcycling of PET into carbon foam (Song et al., 2022). ZnCl₂ breaks the weak bonds of the crosslinked structure, while also promoting decarboxylation, which yields a more stable crosslinking structure (7). Foaming effect during degradation and crosslinking process occurs due to the physical template effect of salt used, and the formation of small molecules, such as CO₂ and H₂O.

The crystal structure of the synthesized CF, Sb₂S₃, and Cu₃SbS₄-Sb₂S₃/CF was investigated with XRD analysis. Figure 3.4(c) shows the typical graphitic Bragg peak for CF (JCPDS no. 41-1487), confirming the formation of the stibnite phase on the CF substrate. All the peaks are well-matched with the standard peaks of Sb₂S₃ (JCPDS no. 42-1393). The heterostructure Cu₃SbS₄-Sb₂S₃ presents two-phase formation stibnite (Sb₂S₃) and famatinite (Cu₃SbS₄) with the addition of Cu as 1mM with Sb 1.5 mM. The XRD pattern of compounds with varied concentrations of Cu and Sb is presented in Appended Paper 4, Figure S1(a). Furthermore, the XRD of heterostructure Cu₃SbS₄-Sb₂S₃ without CF presents a similar XRD pattern which indicates that the CF substrate does not affect the phase formation of Cu₃SbS₄-Sb₂S₃. Figure 3.4(d) presents the morphology transformation of elongated nanoribbons of Sb₂S₃ to the formation of nanochannels in Cu₃SbS₄-Sb₂S₃ with the addition of Cu into Sb₂S₃ on the CF substrate. The elemental mapping images reveal a uniform distribution of all elements present in Cu₃SbS₄-Sb₂S₃. The obtained d-spacing (SAED) values of 0.48, 0.32, and 0.16 nm were successfully matched to the corresponding XRD crystal planes of Cu₃SbS₄

(101), (112), and (312); and the d-spacing of 0.503 nm corresponds to Sb_2S_3 crystal planes (020), (120). These observations confirmed the successful synthesis of the heterostructure, retaining its crystallinity.

To understand the material's absorption activity, UV/Vis-NIR analysis was performed, as shown in Figure 3.5(a). The UV/Vis-NIR region analysis presents a similar trend as seen in earlier investigations on CF, with a trend of significant reduction in absorption of material while moving from UV/Vis to NIR region. On the other hand, Sb_2S_3 shows even lower absorption activity as it moves from the UV/Vis to NIR region, and these outcomes were the opposite of what was expected to improve the material's absorption efficiency for photothermal behavior. However, the absorption activity of the heterostructure $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3\text{/CF}$ achieved an outperformance (>95%) in UV/Vis-NIR compared to bare CF and $\text{Sb}_2\text{S}_3\text{/CF}$, as shown in Figure 3.5(a).

Interfacial photothermal desalination testing was performed by depositing the sample material onto a glass microfiber membrane (Whatman GF/E, CAT No. 1825-047) via vacuum filtration. After drying, a piece of the membrane was used for the interfacial solar desalination experiment, which was carried out under one-sun solar irradiation. Figure 3.5(b) presents the comparative results of CF, $\text{Sb}_2\text{S}_3\text{/CF}$, and $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3\text{/CF}$ for the evaporation rate based on the change in mass during the desalination process. The sample CF functionalized with nanochannels of $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3\text{/CF}$ presented an outperforming evaporation rate ($2.82 \text{ kg m}^{-2} \text{ h}^{-1}$) compared to CF ($1.58 \text{ kg m}^{-2} \text{ h}^{-1}$) and $\text{Sb}_2\text{S}_3\text{/CF}$ ($1.4 \text{ kg m}^{-2} \text{ h}^{-1}$). The complementary absorption of $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3\text{/CF}$, jointly with the incorporation of Cu_3SbS_4 , extends the spectral response beyond that of Sb_2S_3 -functionalized CF. Working together, these components foster interfacial charge separation under solar irradiation, forming a heterostructure that enhances non-radiative energy dissipation as heat. Figure 3.5(c) shows the surface temperature profile of the investigated samples captured at the dry state (before desalination), and wet surface temperature (during desalination). At the dry state, the heterostructure $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3\text{/CF}$ achieved the highest surface temperature of 76.4°C , substantially surpassing that of bare CF (68.3°C) and $\text{Sb}_2\text{S}_3\text{/CF}$ (52.4°C). A similar trend has been noted in wet surface temperature as 41.4°C for nanochannels of $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3\text{/CF}$, followed by CF (37.6°C) and $\text{Sb}_2\text{S}_3\text{/CF}$ (31.1°C).

The contact angle analysis indicates high wettability of all investigated samples for interfacial solar desalination. The CF graphitic substrate exhibited high hydrophilicity and rapid water absorption, as shown in Figure 3.5(d). The contact angle images of the heterostructure $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3\text{/CF}$ demonstrated a similar wettability, which reflects that the

functionalization of CF with heterostructure $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3/\text{CF}$ does not alter the wettability performance. Figure 3.5(e) presents the result graph of the stability test that was performed under one sun irradiation using a glass microfiber filter. The graph shows the minor decline in evaporation from $2.86 \text{ kg m}^{-2} \text{ h}^{-1}$ to $2.51 \text{ kg m}^{-2} \text{ h}^{-1}$ over a period of five hours. The minor decline over the test interval signifies good operational stability of the photothermal system. Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES) was performed to analyze the concentration of sodium ions in a sample of saline water before desalination and in condensed evaporated water vapors. The results present the 99% removal of sodium ions after solar desalination. Present outcomes of the study confirm the critical role of morphology engineering of solar absorber, the enhanced performance of absorption activity and evaporation rate achieved due to the combined photothermal effect of Cu_3SbS_4 and Sb_2S_3 in enhancing both photothermal conversion and water evaporation performance applications.

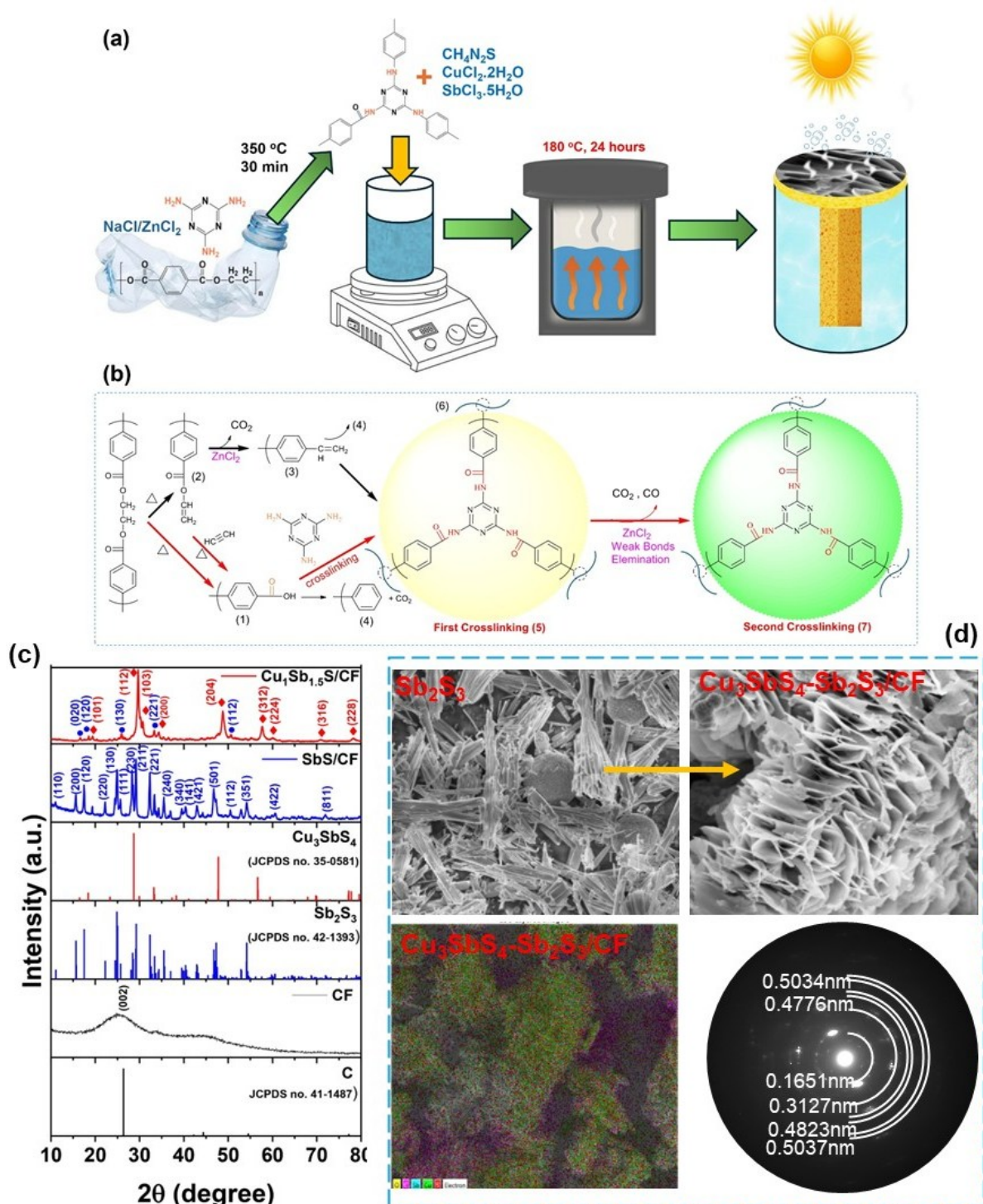


Figure 3.4: Graphical illustration of experimental work, mechanism description of the upcycling of PET to CF, XRD pattern and morphology of the synthesized solar evaporator, Copyright 2025, Wiley (Hussain et al., 2025).

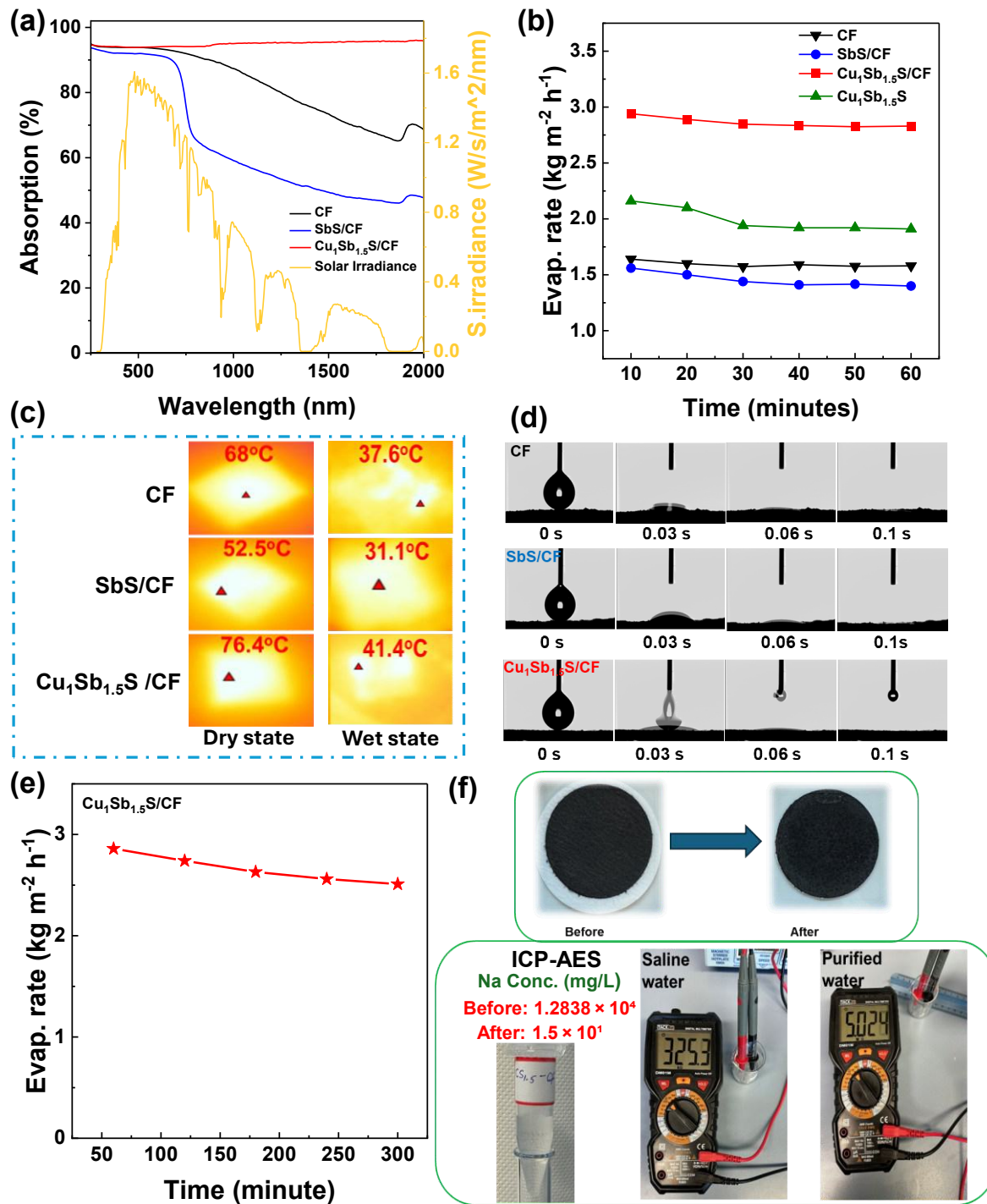


Figure 3.5: Results illustration of CF, Sb₂S₃/CF, and Cu₃SbS₄-Sb₂S₃/CF: (a) absorption spectra (UV/Vis-NIR), (b) Evaporation rate, (c) surface temperature profile, (d) contact angle analysis, (e-f) stability test of solar evaporators and quantitative analysis of condensed vaporized water Copyright 2025, Wiley (Hussain et al., 2025).

Appended Paper-4

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RESEARCH ARTICLE

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Upcycled PET-Derived Carbon Foam Functionalized with $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3$ Heterostructures for Efficient Interfacial Solar Desalination

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Solar desalination is an emerging technique to produce fresh water utilizing renewable solar energy. However, the engineering of efficient photothermal material is a significant obstacle. In the present study, a carbon foam is synthesized from the upcycling of waste PET and hydrothermally functionalized with a heterostructure composed of Cu_3SbS_4 and Sb_2S_3 . Material characterizations demonstrated the successful decoration of nanochannels on graphitic carbon foam (CF). The analysis of the optical properties in the UV/Vis-NIR spectral range demonstrated excellent absorption properties of 96% for $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3/\text{CF}$ compared to $\text{Sb}_2\text{S}_3/\text{CF}$ (48%) and CF (68%) in near-IR. Photothermal desalination results reveal the evaporation rate of $2.82 \text{ kg m}^{-2} \text{ h}^{-1}$ for $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3/\text{CF}$ compared to $1.4 \text{ kg m}^{-2} \text{ h}^{-1}$ for $\text{Sb}_2\text{S}_3/\text{CF}$ and $1.58 \text{ kg m}^{-2} \text{ h}^{-1}$ for CF, with 99% salt removal in condensed water. The formation of the composite leads to a high surface temperature and enhanced evaporation rate. The contact angle analysis confirmed the hydrophilic nature of the material that plays a crucial role in the solar desalination process. These findings elucidate the effective photothermal performance achieved through chalcogenide heterostructure engineering supported on upcycled carbon foam derived from waste PET, demonstrating a practical application aligned with circular economy principles in solar desalination.

1. Introduction

Fresh and clean water is a basic need of humans and is highly associated with human survival. However, due to the blooming in industrialization and urban development, the water resources are highly affected.^[1-3] The utilization of seawater for drinking and energy production has consistently raised concerns, prompting the development of various strategies for desalinating seawater. A series of energy-intensive methods with complex technologies are used for water desalination, including electrodialysis (ED), forward osmosis (FO), multiple-effect distillation, reverse osmosis (RO), thermal desalination, solar desalination, and multi-stage flash distillation.^[4] Among them, solar desalination is one of the emerging methods to treat seawater using renewable solar energy. Interfacial solar steam generation using solar energy is not only a cost-effective and straightforward technology, but it also

3.5 Chapter 5: Microwave Synthesis Approach for Bi₂S₃ Nanocrystals to Co_xBi₂S₃ Hexagonal Nano-disc: An Efficient Photothermal Interfacial Desalination Material

Advancements in technology have spurred the development of novel materials across academic research institutes and the industrial sector. Fostering this aim of novelty in the field of material science requires a new synthesis direction and optimization of the existing synthesis route. Developing new materials requires numerous experimental trials to determine the optimal product. Time is a vital parameter, and it is necessary to meet the time-effective synthesis goals. Advanced science and technology have persuaded the research community to adopt environmentally friendly synthesis routes for cost and time efficiency. In green synthesis, microwave (MW) chemistry offers a promising approach to control matter at the nanoscale and to rapidly produce materials with tailored properties (Nageswara Rao & Satyanarayana, 2021). The development of inorganic nanostructures for environmental and energy applications is a significant and multifaceted field in materials chemistry, encompassing the synthesis of metal nanoparticles, metal oxides, metal sulfides, and metal tellurides (Becerra-Paniagua et al., 2022). For this purpose, the most common method adopted is the hydrothermal process, but considering the goals of low cost and reduced time consumption, it suffers from some disadvantages. One of the main drawbacks is the extensively longer reaction time in the hydrothermal process. Advancements in technology have spurred the development of novel materials across academic research institutes and the industrial sector. Fostering this goal of novelty in material science requires a new synthesis approach and optimization of existing methods. Developing new materials involves many experimental trials to identify the best product options. Time is a crucial factor, and achieving efficient synthesis processes is essential. Advanced science and technology have encouraged the research community to select environmentally friendly synthesis routes that are also cost-effective and time-efficient. In green synthesis, microwave (MW) chemistry provides a promising way to control matter at the nanoscale and rapidly produce materials with tailored properties (Nageswara Rao & Satyanarayana, 2021).

The development of inorganic nanostructures for environmental and energy applications is a significant and broad area in material chemistry, including the synthesis of metal nanoparticles, metal oxides, metal sulfides, and metal tellurides. While the hydrothermal process is common, it has drawbacks, such as long reaction times that can last up to 24 hours or more, depending on the product. In contrast, microwave-assisted synthesis can reduce this time to minutes without sacrificing material quality. Traditional methods also require more

energy and are less sustainable, making them costly for large-scale or industrial use. Conversely, microwave synthesis offers advantages like shorter reaction times, lower energy consumption, and better control over crystal size and morphology, leading to finer, more uniform nanoparticles crucial for catalysis and electronics (Luo et al., 2024; Strachowski et al., 2021). Microwaves, part of the electromagnetic spectrum, range from approximately 0.3 to 300 GHz and correspond to wavelengths between 1 meter and 1 millimeter, primarily used in telecommunications and radar. In chemistry, the standard frequency used is 2.45 GHz, with a wavelength of 12.25 cm. Microwave synthesis uses dielectric heating, in which the solvent absorbs microwave energy and converts it into heat. Because a single microwave photon carries very little energy (about 1×10^{-5} eV at 2.45 GHz), microwave chemistry primarily heats materials efficiently through electromagnetic radiation rather than driving reactions by breaking bonds (Nageswara Rao & Satyanarayana, 2021).

Metal sulfides (e.g., CuS, MoS₂, Cu₇S₄) are promising materials for photothermal desalination due to their narrow band gaps and plasmonic properties, which enable strong absorption across a broad spectrum, including visible and near-infrared light, allowing them to convert solar energy into heat at or near the water-air interface and thus increase evaporation rates (Cui et al., 2024; X. Li et al., 2019). Bismuth sulfide (Bi₂S₃), a p-type semiconductor with a low direct band gap (E_g of 1.3 eV) and high absorption coefficient (104-105 cm⁻¹), has potential applications in thermoelectric, electronic, and optoelectronic devices, as well as electrochemical hydrogen storage and photocatalysis (Becerra-Paniagua et al., 2022). On the other hand, the potential of bismuth sulfide for interfacial solar desalination is not well understood. In this research, we employed microwave synthesis to decorate bismuth sulphide (Bi₂S₃) on carbon foam derived from waste PET. Then we incorporated a range of cobalt concentrations to further enhance the nanocomposite's absorption activity, and to understand the changes in morphology and photothermal performance for interfacial solar desalination. The detailed experimental procedure is explained previously in the experimental section. Detailed characterization and performance output for solar desalination are given below.

X-ray Diffraction (XRD) analysis was performed in the range of $2\theta = 10$ to 80° to evaluate the phase formation of the synthesized material. CF shows the graphitic characteristics peak at $2\theta = 18^\circ$ - 32° (JCPDS no. 41-1487), see Figure 3.6 (b). Figure 3.6 show illustrates the ample Bi₂S₃ functionalized CF sample (Bi₂S₃/CF) confirms the bismuthinite phase formation with its unique characteristics peaks at 15.8° , 17.5° , 22.3° ,

23.7°, 24.9°, 27.3°, 28.6°, 31.7°, 32.9°, 33.9°, 35.5°, 39.0°, 39.8°, 42.6°, 43.5°, 45.5°, 46.4°, 47.3°, 49.0°, 52.6°, 59.0°, 62.5°, 65.7°, 72.0° corresponding to the crystal planes (020), (120), (220), (101), (130), (021), (211), (221), (301), (311), (240), (041), (141), (421), (520), (002), (431), (530), (160), (351), (241), (171), (721), and (741) (JACPDs no. 42-1393). The XRD pattern of $\text{Co}_x\text{-Bi}_2\text{S}_3/\text{CF}$ confirms peak match with the bismuthinite (Bi_2S_3) phase. As seen in Figure 3.6 (a) the varied concentration of Co (0.012mM, 0.024mM, 0.05mM and 0.1 mM) presents no additional peak of the bismuthinite Bi_2S_3 , and the reason to this effect is that cobalt is present in an amorphous form in the nanocomposite, which is confirmed from the XRD pattern of CoS/CFP in Figure 3.6 (b).

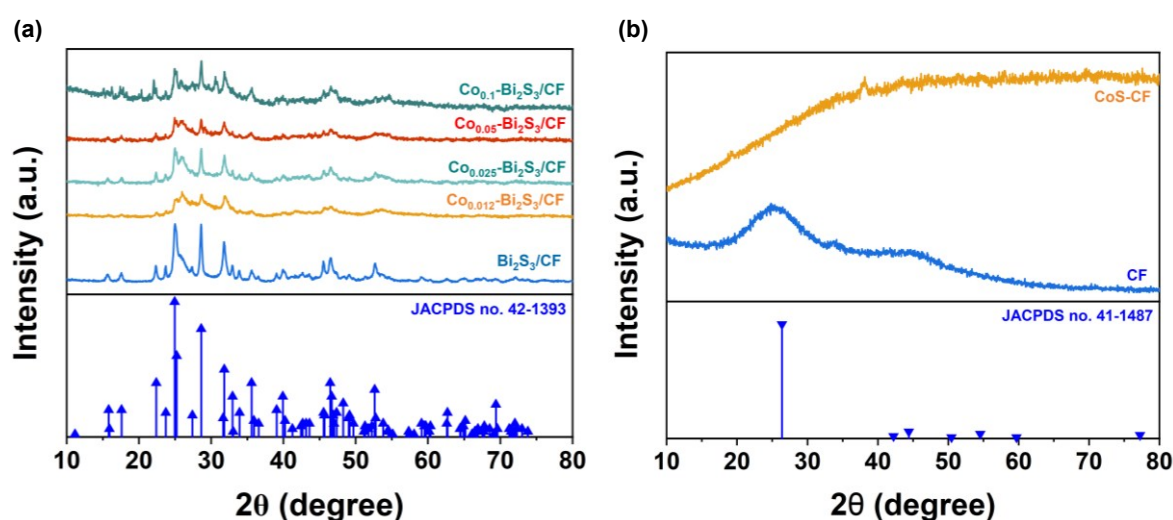


Figure 3.6: XRD Pattern of (a) $\text{Bi}_2\text{S}_3/\text{CF}$ and $\text{Co}_x\text{-Bi}_2\text{S}_3/\text{CF}$, and (b) CF and CoS/CF .

The surface composition and chemical state of the constituent elements of the synthesized samples were determined by X-Ray Photoelectron Spectroscopy (XPS). Figure 3.7(a) presents the survey spectrum of CF , which shows that the sample consists of C, N, and O with atomic percentages of 74.39, 14.00, and 10.70%, respectively. Figure 3.7 (b-c) presents the high-resolution core-level spectra of the synthesized CF , illustrating the four contributions for C 1s at 284.7 eV ($-\text{C}-\text{C}-$, $-\text{C}=\text{C}-$) and 286. eV ($\text{C}-\text{O}$), 287.2 eV ($-\text{C}=\text{N}$), and 288.5 eV ($-\text{COOH}$); and three contributions for O 1s at 530.8, 532.0, and 533.4 eV that are assigned to $-\text{COOH}$, $-\text{C}-\text{O}-\text{C}$, $-\text{C}-\text{OH}$, and H_2O , respectively. The two contributions for the N 1s core level spectrum at 398.5 and 400.2 eV, are assigned to pyridinic N and graphitic N which confirms the graphitic structure of the synthesized CF , see Figure 3.7(d).

Figure 3.7(a) presents the survey spectrum of $\text{Co-Bi}_2\text{S}_3/\text{CF}$, with the following chemical composition: C, 16.71%; N, 2.30%; O, 41.53%; Co, 6.26%; Bi, 12.10%; and S,

20.39%. Figure 3.7(b-c) shows the four contributions for the high-resolution C 1s spectrum at 284.5 eV (-C-C-, -C=C-), 285.5 eV (C-O), 286.7 eV (-C=N), and 288.6 eV (-COOH). The high resolution of the O 1s core level spectrum shows three contributions at 529.9 eV (-COOH and lattice oxygen), 531.7 eV (-C-O-C and C-OH), and 533.1 eV (H₂O). The high-resolution N 1s core level exhibits a contribution at 399.9 eV for graphitic N, as shown in Figure 3.7(d). The functionalized nanostructure Co-Bi₂S₃ presents the two doublets for Bi 4f and S 2p. The high-resolution Bi 4f spectrum presents a characteristic doublet at 159.07 eV for Bi 4f_{7/2} and 164.3 eV for Bi 4f_{5/2} (Figure 3.7(f)) assigned to Bi³⁺ in Bi₂S₃. The observed binding energy values and the energy separation between these components (~5.3 eV) are consistent with reported values for Bi₂S₃ (Navale et al., 2025). The S 2p core level spectrum presents the doublet S 2p_{3/2} and S 2p_{1/2} at 161.3 eV and 162.5 eV, respectively, corresponding to S²⁻ anions (Navale et al., 2025). Simultaneously, the Bi4f and S2p profiles confirm the stoichiometry and phase purity of Bi₂S₃. The high-resolution Co 2p spectrum shows a 2p_{3/2} main peak at 778.4 eV and its doublet Co 2p_{1/2} at 794.0 eV, with a spin-orbit splitting of 15.6 eV, which indicates the presence of Co as Co²⁺ (Lázaro-Martínez et al., 2016). These observation confirms that the peak positions with their binding energy for Bi₂S₃ are consistent with literature-reported studies as well (Navale et al., 2025; D. Yang et al., 2021), which clearly indicate that the incorporation of Co and CF does not affect the chemical state of Bi₂S₃.

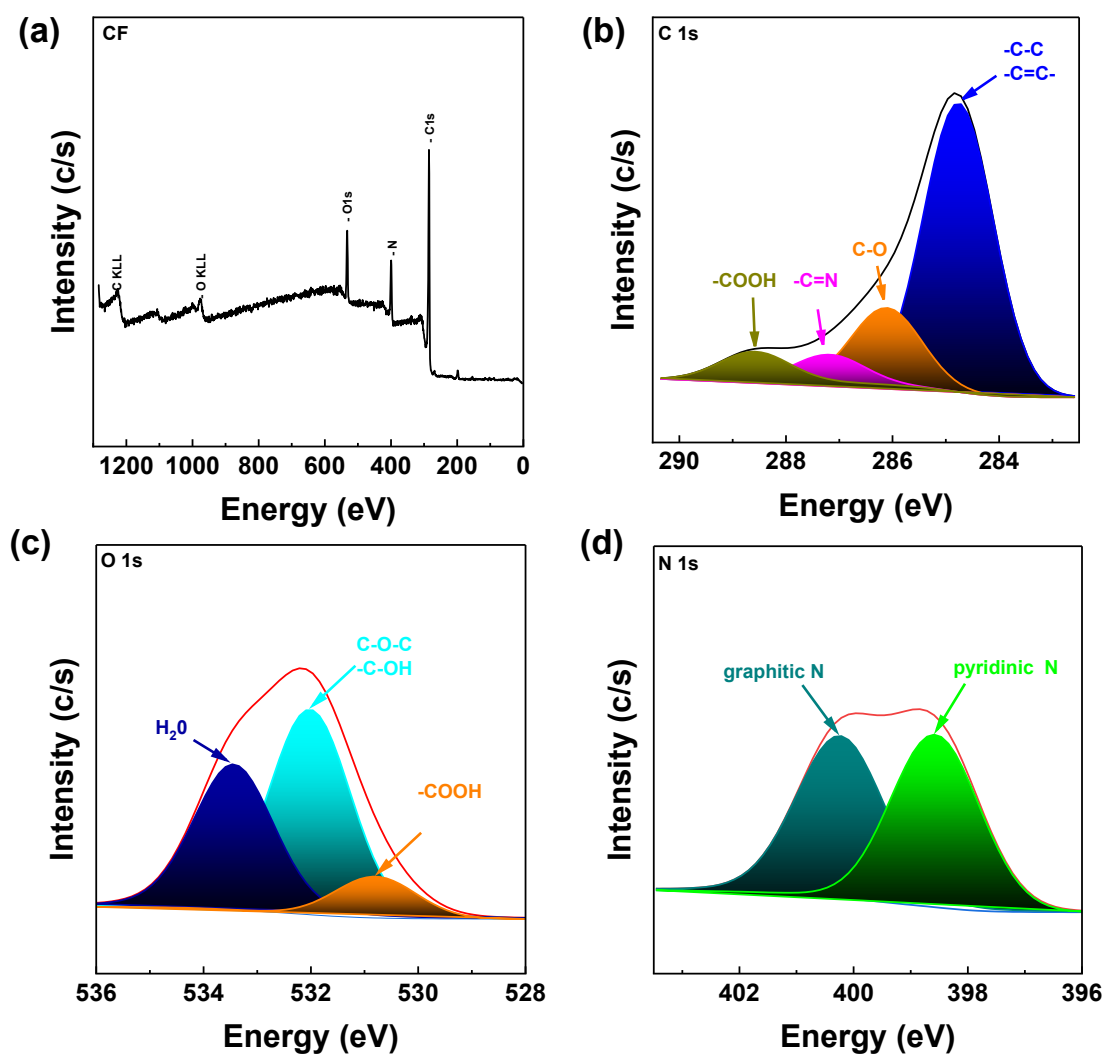


Figure 3.7: (a) XPS survey spectrum of CF, high-resolution C 1s (b), O 1s (c), N 1s.

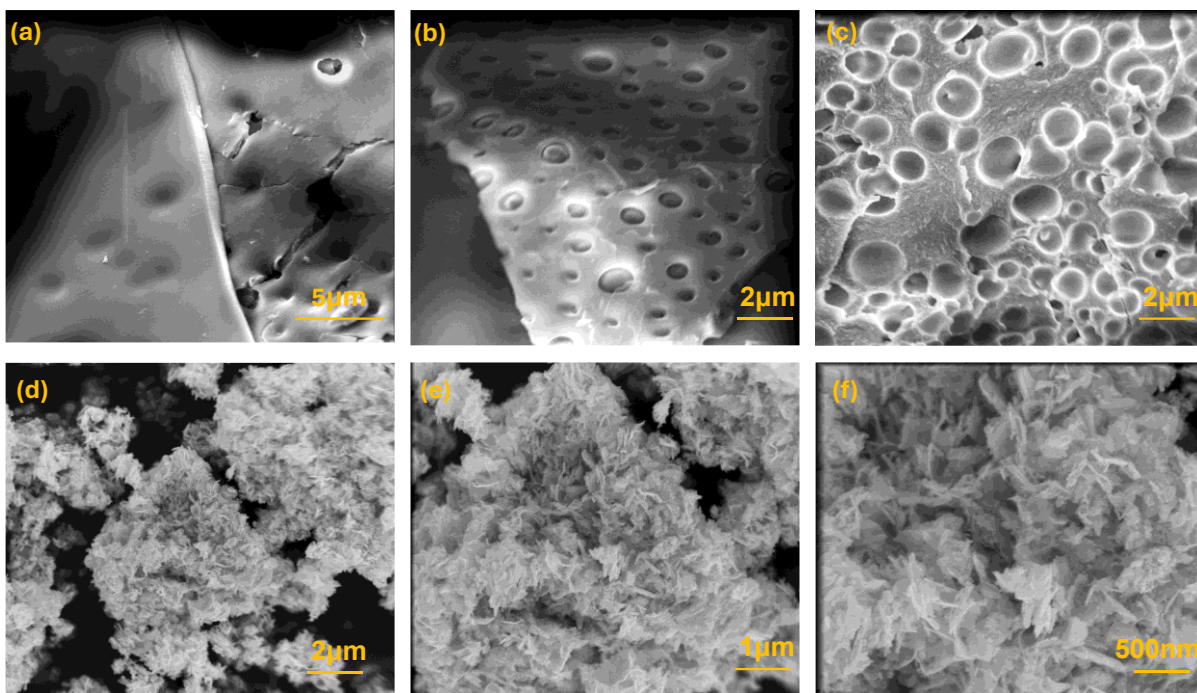


Figure 3.8: Surface morphology images: (a-c) CF, and (d-f) Bi₂S₃/CF.

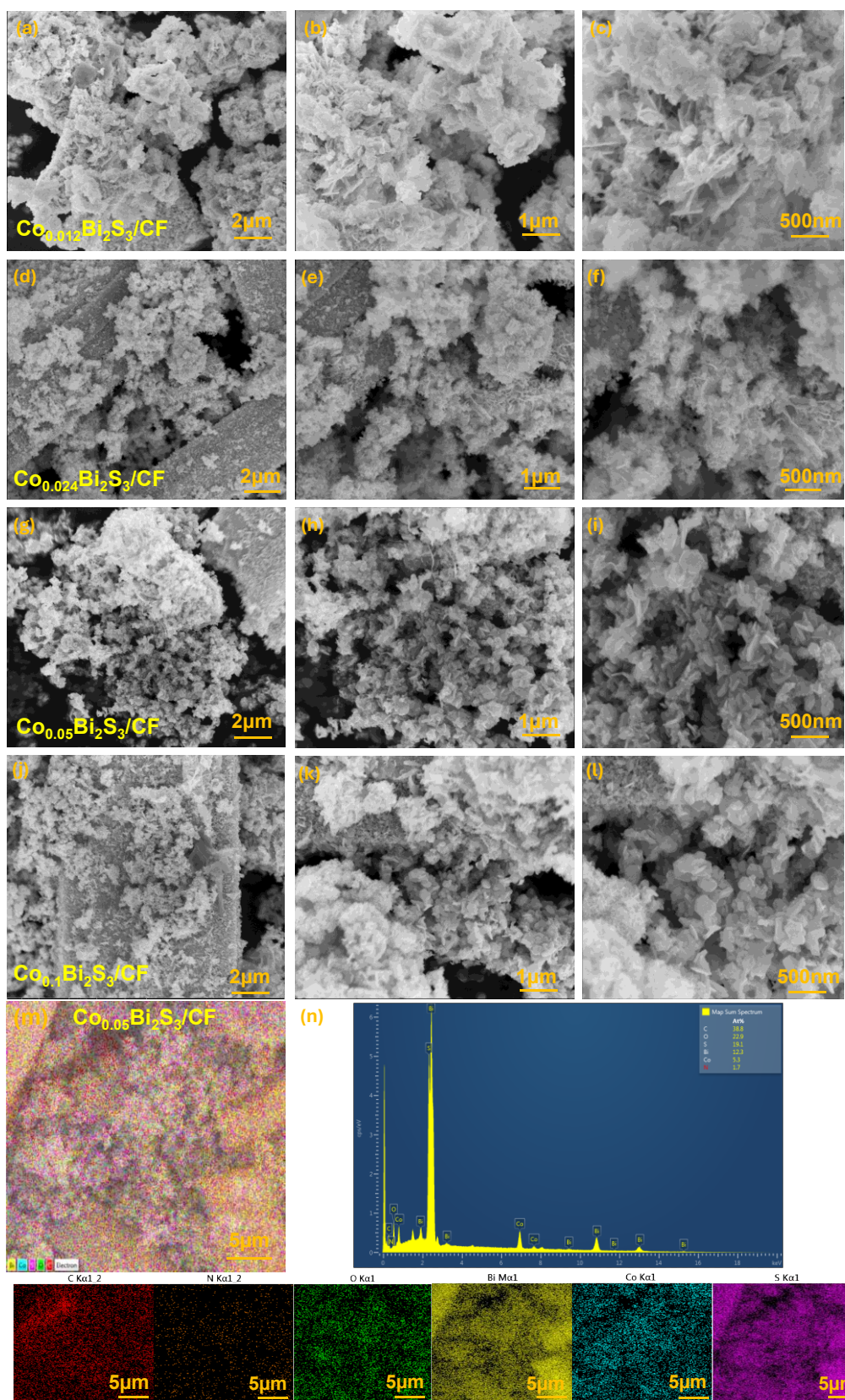


Figure 3.9: SEM images $\text{Co}_{(x=0.012-0.1)}\text{-Bi}_2\text{S}_3/\text{CF}$ (a-l), EDS spectra and elemental mapping of $\text{Co}_{0.05}\text{-Bi}_2\text{S}_3/\text{CF}$ (m-n).

For outperformance of photo to thermal conversion, the material should provide high optical absorption activity throughout the region (UV/Vis-NIR). Before the solar desalination experiment, the absorption activity of the synthesized samples was evaluated using UV/Vis-NIR spectroscopy (Figure 3.10(a)). The obtained results show that the waste PET-derived CF exhibited >90% absorption in the UV/Vis region, but upon entry into the IR region, a continuous decrease in absorption was observed, reaching 67%. Sample Bi₂S₃/CF and Bi₂S₃ demonstrated a better absorption activity at the start of the NIR region compared to CF, and a sudden, dramatic decline in absorption activity was noticed above 1200nm. The nanocomposite of Bi₂S₃/CF presented even less absorption activity above 1500nm compared to bare CF. The decrease in absorption activity could be due to the growth of Bi₂S₃ nanocrystals on CF, which mask its surface and cause increased reflectance, thereby interfering with optical activity. For comparison, the Bi₂S₃ absorption spectrum presented a similar effect, see Figure 3.10(a). Figure (a) illustrates the excellent enhanced activity with the incorporation of Co concentration, which ultimately reached above 91% absorption percentage throughout the UV/Vis to NIR region. After successfully characterizing the synthesized pristine and modified nanocomposites, specifically their morphological transformation and enhanced optical activity, this indicates that the modified nanocomposite can work excellently for photothermal desalination. An interfacial solar desalination experiment was performed under one-sun irradiance, and a detailed experimental setup is described in the experiment section. Figure 3.10(b) presents the change in mass during the photothermal evaporation, which provides a linear decrease in bulk mass. Figure 3.10(c) presents the evaporation rate calculated from mass change; it demonstrates an outperformance of 2.35 kg m⁻² h⁻¹ for Co_(0.05)-Bi₂S₃/CF compared to the remaining samples. To understand the photothermal behavior of the material, thermal images were recorded before desalination at the dry state and during interfacial solar desalination at the wet state, see Figure 3.10(d). Thermal images present the maximum surface temperature at the dry state 76.6 °C for Co_{0.05}-Bi₂S₃/CF. During the interfacial solar desalination process, the sample Co_{0.05}-Bi₂S₃/CF presents an enhanced surface temperature of 44.4 °C compared to bare CF, 41.9 °C. To further strengthen the enhanced evaporation rate, contact angle analysis was performed to investigate the samples' wettability. Figure 3.10(d) presents the excellent hydrophilicity of CF, Bi₂S₃/CF, and the outperformed sample Co_{0.05}-Bi₂S₃/CF. The excellent hydrophilicity of CF belongs to the presence of O₂ and N₂ groups in CF architecture. Bai et al. reported a similar observation for the upcycling of plastic waste into carbon foam, achieving high hydrophilicity due to oxygen- and nitrogen-containing functional groups (Bai

et al., 2022a). Furthermore, the functionalization of CF with nanostructures has not compromised the material's hydrophilicity. The excellent evaporation is a result of the combined driving effect of the hydrophilic characteristics of CF and enhanced photothermal behavior of $\text{Co}_{0.05}\text{-Bi}_2\text{S}_3/\text{CF}$. In this project, our findings clearly demonstrated the engineering of a photothermal absorber, especially the transformation of nanocrystal morphology to hexagonal nanodisks, which significantly improved the evaporation rate and provided outstanding photothermal behavior.

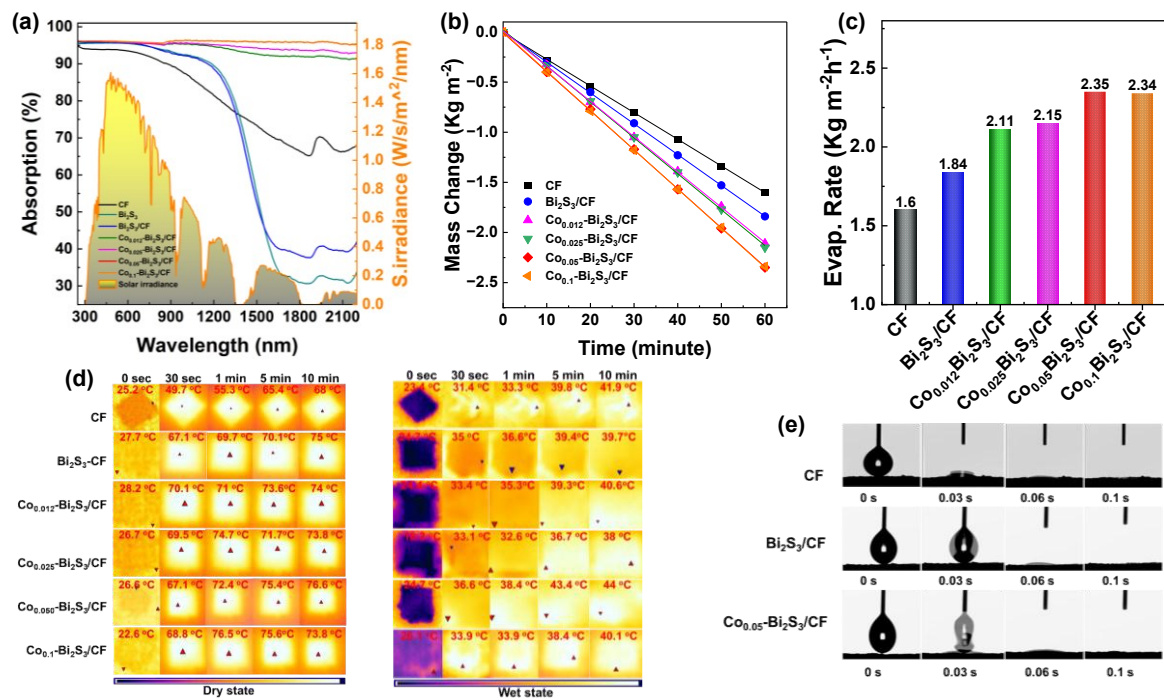


Figure 3.10: (a) UV/Vis-NIR absorption activity, (b-c) change in mass and evaporation rate (d) photothermal images of surface temperature at dry and wet state (e) contact angle analysis.

4 Conclusion and Future Prospects

Clean water is one of the vital necessities that makes a unique contribution to sustaining life on earth. Advancements in technology have introduced numerous benefits to human life, but at the same time, they have raised highly concerning issues, including water scarcity. To meet clean water demand, numerous methods have been developed in recent years, and desalination is among the most important and widely used methods for producing water from readily available sources such as seawater. Desalination is an efficient method that produces large quantities of water compared to other water treatment processes; however, in the modern era, it contributes to energy crises due to high energy consumption. To overcome this problem, in recent years, researchers have introduced an interfacial photothermal desalination process, which can be easily operated on a never-ending renewable energy source called solar energy. Interfacial solar desalination operates at the water-air interface, and developing materials for this technology is a challenging task due to the need to consider various factors. An efficient solar steam generator should possess several fundamental characteristics, including broad spectral absorption, high solar-to-thermal energy conversion efficiency, high wettability, low thermal conductivity, and an engineered morphology, which collectively facilitate solar steam generation. To maintain sustainability protocols, the material innovation should consider environmental and economic impacts.

In this study, we have focused on the concept of the circular economy to develop sustainable materials from raw materials to advanced photothermal material to achieve the following goals;

- Waste PET was upcycled into CF using low-temperature catalytic carbonization, and the reaction mechanism of catalytic degradation of PET into CF during carbonization was studied.
- To enhance the absorption activity to gain an outperforming photo-to-thermal conversion, metal sulfide nanostructures CuS, CuCo₂S₄, and Cu₃SbS₄-Sb₂S₃ via conventional hydrothermal, and Co_xBi₂S₃ via microwave synthesis process were grown.
- The detailed analytical material characterization was performed to elucidate the structural and functional properties of bare CF and CuCo₂S₄, Cu₃SbS₄-Sb₂S₃, and Co_xBi₂S₃ functionalized carbon foam. The UV/Vis-NIR results confirm the success of the objective, demonstrating >95% absorption in the near IR for metal sulfide-decorated CF nano-evaporators compared to bare CF. XRD confirms the expected

phase formation, and XPS provides deeper insight into the chemical state of the metal elements. The SEM images reflect the successful engineering of solar absorber morphology, which plays a crucial role in achieving an enhanced evaporation rate in the case of $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3/\text{CF}$ and $\text{Co}_x\text{Bi}_2\text{S}_3/\text{CF}$.

- The engineering of these solar steam generators demonstrated excellent photo-to-thermal performance. As a result, the metal sulfide-functionalized CF exhibited an excellent evaporation rate. Furthermore, the material's high wettability highlights its critical role in performance during interfacial solar desalination.

This work demonstrates that metal sulfides prepared via small-scale hydrothermal and microwave methods exhibit strong solar-driven desalination performance. Scaling these materials for practical viability beyond the laboratory is more complex than simply increasing the batch size for the hydrothermal and microwave synthesis processes. As the reaction volume increases, hydrothermal and microwave syntheses can suffer from uneven heating, poor mixing, and inconsistent nucleation. These challenges often manifest as batch-to-batch variability and increased energy consumption. Safety is another concern, as pressurized vessels do not scale seamlessly, which restricts the scalability of batch methods. To address these limitations, the research community has been investigating continuous-flow synthesis as a practical solution for moving from laboratory-scale to industrial-scale material production. This approach provides more precise control over temperature gradients, allows for shorter, adjustable residence times, and offers a safer method for managing pressure. In larger reactor systems, these advantages help maintain uniform reaction conditions. Moreover, flow-based microwave or hydrothermal reactors enable continuous operation rather than discrete batches, reducing variability and potentially lowering production costs. As a natural extension of this study, for material synthesis, future work could focus on mapping our optimized synthesis conditions using a continuous-flow reactor. This would help bridge the gap between the high performance observed at lab scale and the performance required for real-world interfacial solar desalination systems at larger scales.

Material Science covers a wide range of possible innovations for environmental and energy applications. The development of sustainable materials is an attractive means of achieving high solar energy harvesting. In this scenario, the circular economy plays a dominant role in advancing photothermal technologies by giving new life to waste products, surpassing the linear economy towards zero-waste discharge for a sustainable, eco-friendly process. Innovative carbon material, such as hydrophilic carbon foam derived from ever-increasing waste plastic, and further functionalization with nanostructures of low-cost metals such as

Cu, Co, Sb, and Bi can act as an excellent photothermal steam generator. The outcomes of the present study directly contribute to the Sustainable Development Goals, more precisely SDG-6, SDG-7, SDG-12, and SDG-13.

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List of Publications

- 1 **Muzammil Hussain**, Kassa Belay Ibrahim, Enrique Rodríguez-Castellón, Silvia Gross, Pawan Kumar, Stéphanie Bruyère, David Horwat, Elisa Moretti, Alberto Vomiero, Tofik Ahmed Shifa (2025). Upcycled PET-Derived Carbon Foam Functionalized with $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3$ Heterostructures for Efficient Interfacial Solar Desalination. *Small*. e06862. <https://doi.org/10.1002/sml.202506862>
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- 3 **Muzammil Hussain**, Tofik Ahmed Shifa, Pratik V Shinde, Pankaj Kumar, Stefano Centenaro, Silvia Gross, Elisa Moretti, Alberto Vomiero (2024). Enhanced Solar Water Desalination by CuCo_2S_4 -decorated Carbon Foam Derived from Waste Plastics. *Chemical Research in Chinese Universities*. 40. 548–555. <https://doi.org/10.1007/s40242-024-4091-8>
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Appended Papers



Review

Nano-enhanced solar evaporators for desalination: A comprehensive bibliometric review

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ABSTRACT

Nanostructures gained popularity in recent years because they exhibit preferable thermo-physical and optical properties for solar desalination applications. Solar steam generation presents an effective solution to worldwide water scarcity issues through its solar-powered desalination process which uses solar energy. To obtain high evaporation rates, the development of cost-effective and highly efficient photothermal evaporators is still challenging. The objective of this bibliometric review is to analyze the keywords, authors, countries, and key sources in the field of nano-enhanced solar evaporators for desalination. The WoS (Web of Science) database was used to collect the documents, and bibliometric analysis was carried out through VOS viewer and Bibliometrix software. The results showed that 270 papers (Research articles: 265 and Review articles: 5) studied nano-enhanced solar evaporators for desalination from 2017 to 2024. Over the prior five years, the number of publications has increased significantly, which shows the imperative for advanced nanostructured photothermal absorbers for solar desalination applications. Commercialization requires improved absorber stability, salt blocking, scalability, low toxicity, and affordability.

1. Introduction

Freshwater shortage is a significant worldwide problem and is increasing gradually due to factors like population expansion, urbanization, and climate change [1]. As a result, to overcome this issue the 6th Sustainable Development Goal (SDG), which focuses on access to clean water and sanitation, is extremely important [2]. This prompted research into alternative sustainable methods, such as desalination for freshwater production. Since seawater makes up 97 % of the world's water resources, efforts are being made to desalinate seawater to alleviate the freshwater shortage [3]. Various desalination technologies, such as forward osmosis (FO), membrane distillation (MD), reverse osmosis (RO), electrodialysis distillation (ED), solar still (SS), humidification-dehumidification desalination (HDH), etc., and other approaches, have been employed [4]. Of these, recently the concept of the direct solar steam generation (DSSG) method has gained significant

interest for its unique benefits, including sustainability, cost-effectiveness, safety, and eco-friendliness [5].

Solar energy is an abundant, inexpensive, renewable, and ecologically clean energy source, which gives it significant advantages over conventional energy sources like coal and oil. The solar desalination enables freshwater production from various sources of impractical water including seawater along with river/lake water and contaminated water resources [6]. The solar spectrum shows a distinct distribution of energy where UV light makes up ~ 7 % while vis light accounts for ~ 43 % and near-infrared light comprises ~ 50 % of the total [6]. To achieve the best photothermal effects in desalination processes, the optimal materials need to capture all solar wavelengths (UV–Vis–NIR) with low reflection and transmittance properties while converting incident light energy into heat efficiently [7]. A photothermal material requires four essential features that combine high and broad-spectrum light absorption with super-hydrophilic properties and low thermal conductivity along with

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open pathways for water transport [8–10]. Scientists have studied four fundamental groups of photothermal materials for optimizing solar evaporation efficiency: these include polymeric materials, inorganic semiconductors, metallic nanostructures and carbon-based light-absorbing materials. Nano-enhanced solar evaporators use solar energy to boost the process's evaporation rate or evaporation efficiency. The key concept of using nanostructures in solar-powered evaporators is to improve light absorption, surface area, and overall performance [11]. The engineering of nanostructures increases the surface roughness and effective surface area, facilitating faster evaporation by increasing water contact that accelerates the evaporation of water [12]. No previous bibliometric analysis exists to elaborate on the importance of nanostructured solar evaporators for solar desalination applications. Compared to recent reviews on various materials toward solar desalination [13,14], this review analyzes the keywords, authors, countries, and key sources in the field of nano-enhanced solar evaporator for desalination.

“Bibliometric analysis” uses statistical approaches that provides detailed insights into citation trends across large publication datasets [15]. The tool of bibliometric analysis helps researchers identify data sources, locate previous studies, along with validating their statements

and finding unexplored research areas. The software tools VOS viewer, Cite Space, and Bibliometrix enable researchers to transform bibliographic data into visualization outputs such as graphs, charts, and indicators[16]. This review aims to thoroughly investigate recent advancements in nano-enhanced solar evaporators for desalination, while examining the contributions from major sources and authors of research. The analysis studies research output trends across time and investigates the relationship between freshwater scarcity and the role of nano-enhanced solar evaporators during the investigation period (2017 to 2024).

1.1. Methodology of bibliometric analysis

The bibliometric analysis was conducted using the WoS (Web of Science) core collection database. This database is regarded as the most effective source for generating citation data for scientific study. The search type was “advanced search” with the following logic operation: TS = ((“nano*”) AND (“solar evaporator” OR “photothermal material” OR “solar steam generator”) AND (“solar desalination” OR “solar water evaporation” OR “solar thermal conversion” OR “solar-driven evaporation” OR “photo-vapor conversion” OR “solar steam generation” OR “solar steam generation” OR “photo-vapor conversion”)).

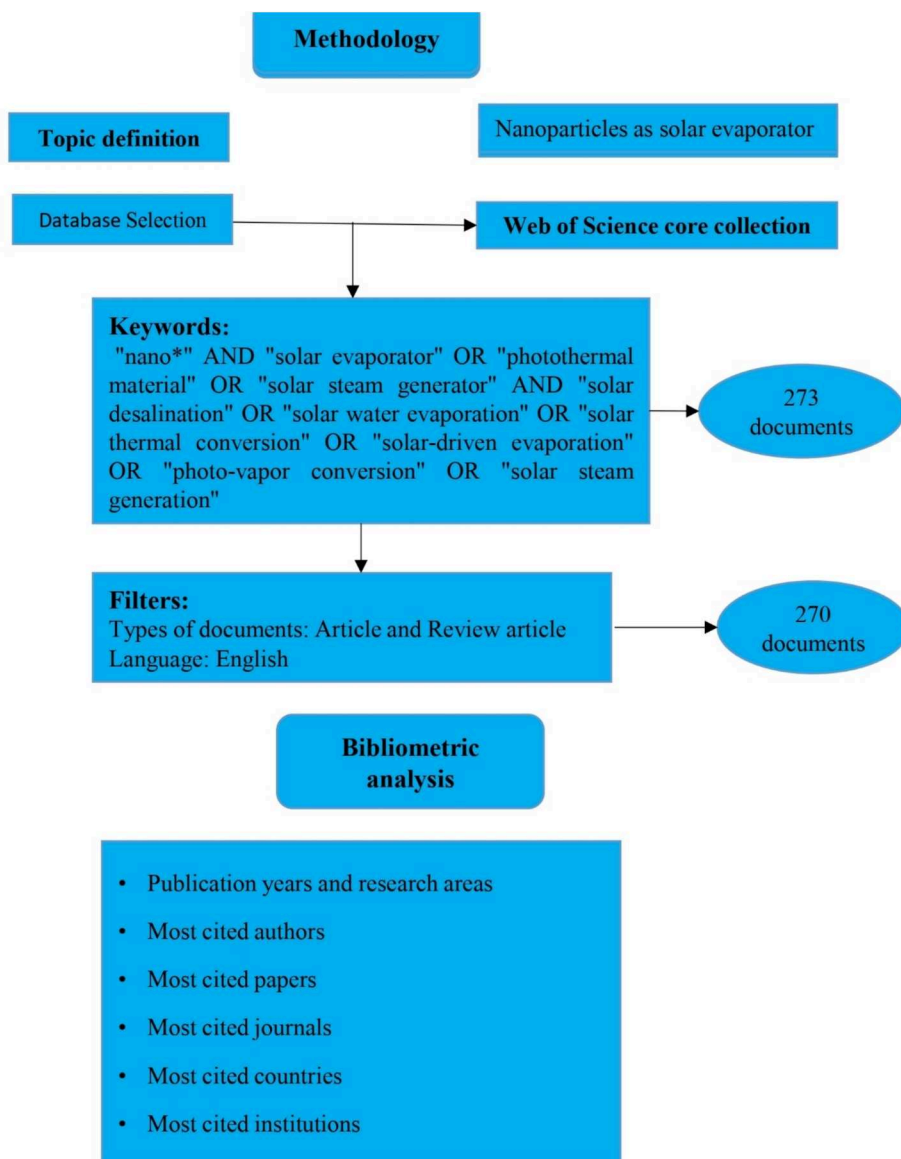


Fig. 1. Flow sheet diagram illustrating Literature Search and Bibliometric Analysis.

Document types are sorted to include “Article” and “Review article”. The data was collected from 2017 to 2024 without a year filter. Furthermore, the language of choice was English. On Web of Science, 270 papers collected (Research articles: 265 and Review articles: 5).

Using a timing diagram and a three-field plot, the R Bibliometrix library, and the biblioshiny application were utilized to determine the top authors’ productivity. After that, the dataset was examined using the VOS viewer software, which resulted in author keyword clusters and networks of authors, sources, and countries Fig. 1.

2. Results and discussions

2.1. General document data

Between 2017 and 2024, 270 papers regarding nanostructures as solar evaporators were published in 95 different sources covering books and academic journals. Each paper on average receives 40.57 citations, while the publication rate continues to grow by 14.63 % annually. The research period shown in Fig. 2(a) depicts the number of articles. It shows a consistent growth in the number of published articles in the prior five years due to an increase in interest for advanced nanostructured-based photothermal evaporators for solar desalination applications.

Fig. 3(b) shows the growth trend of average total citations received by documents published within this studied field. The statistical evaluation depends on the number of available citation years for each article published yearly since the greater the available years, the higher the citation likelihood. The average number of total citations per document in 2018 was approximately 22.83, which is much higher than in other years. Only 18 documents were published in 2018, and all of them were research articles. The number of citations has remained lower in the recent few years than it was in previous periods. The elevated publication numbers coupled with short citable periods, explain why citation statistics have remained low. The indicator shows strong projections to significantly increase its value from 2024 to 2026.

2.2. Most frequently used keywords in research field

Bibliometric studies need thorough analysis of the most frequently used keywords as their main research component. Keyword co-occurrence analysis discovers main research areas and new research directions that need exploration [17]. This field uses the author keywords displayed in Fig. 3 representing the thirty most frequent terminology. Each cluster in this network map contains unique keywords shown by various colors, while the clusters emerged through keyword (co-occurrence) relationships across multiple documents to show related

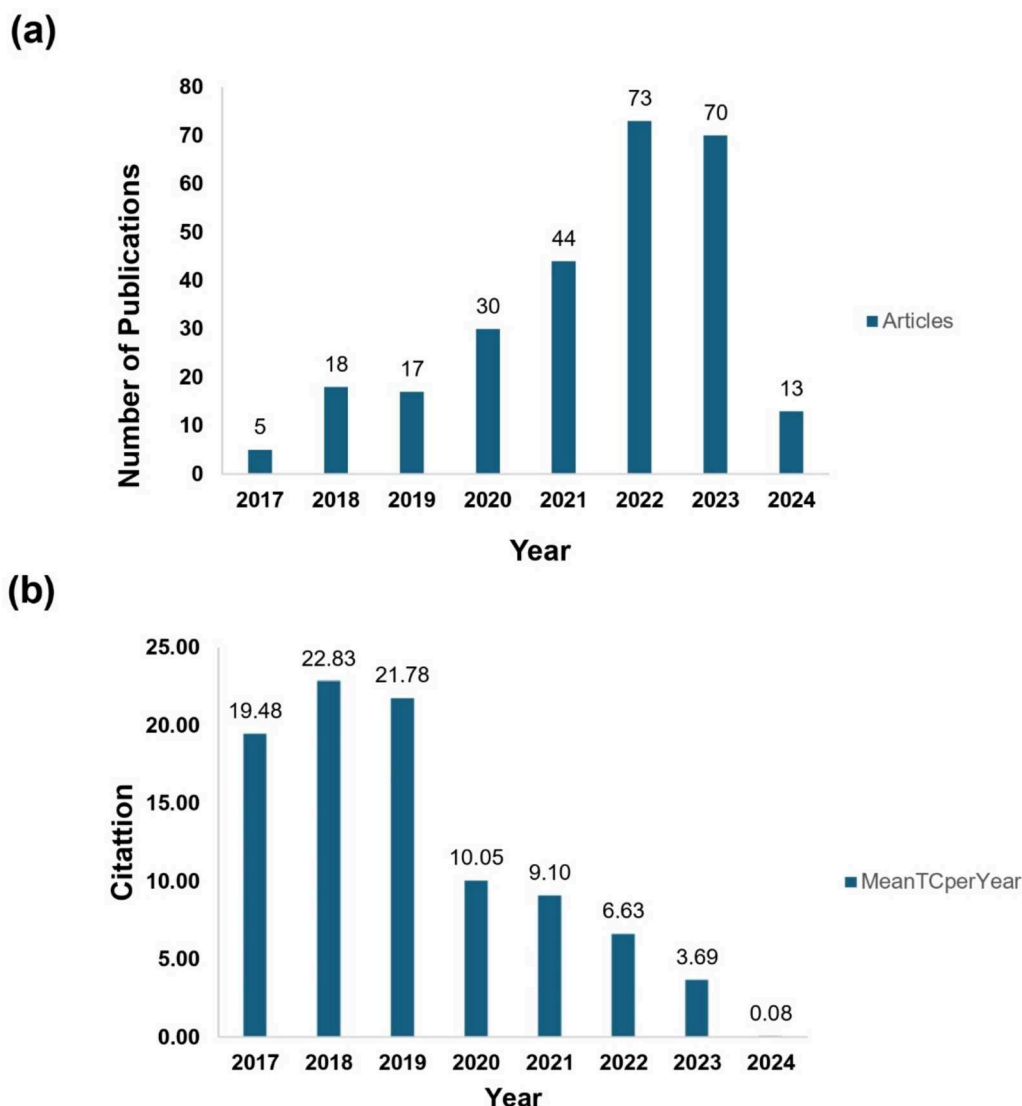


Fig. 2. (a) Number of publications during the investigation period, (b) Average total citation per document over the year.

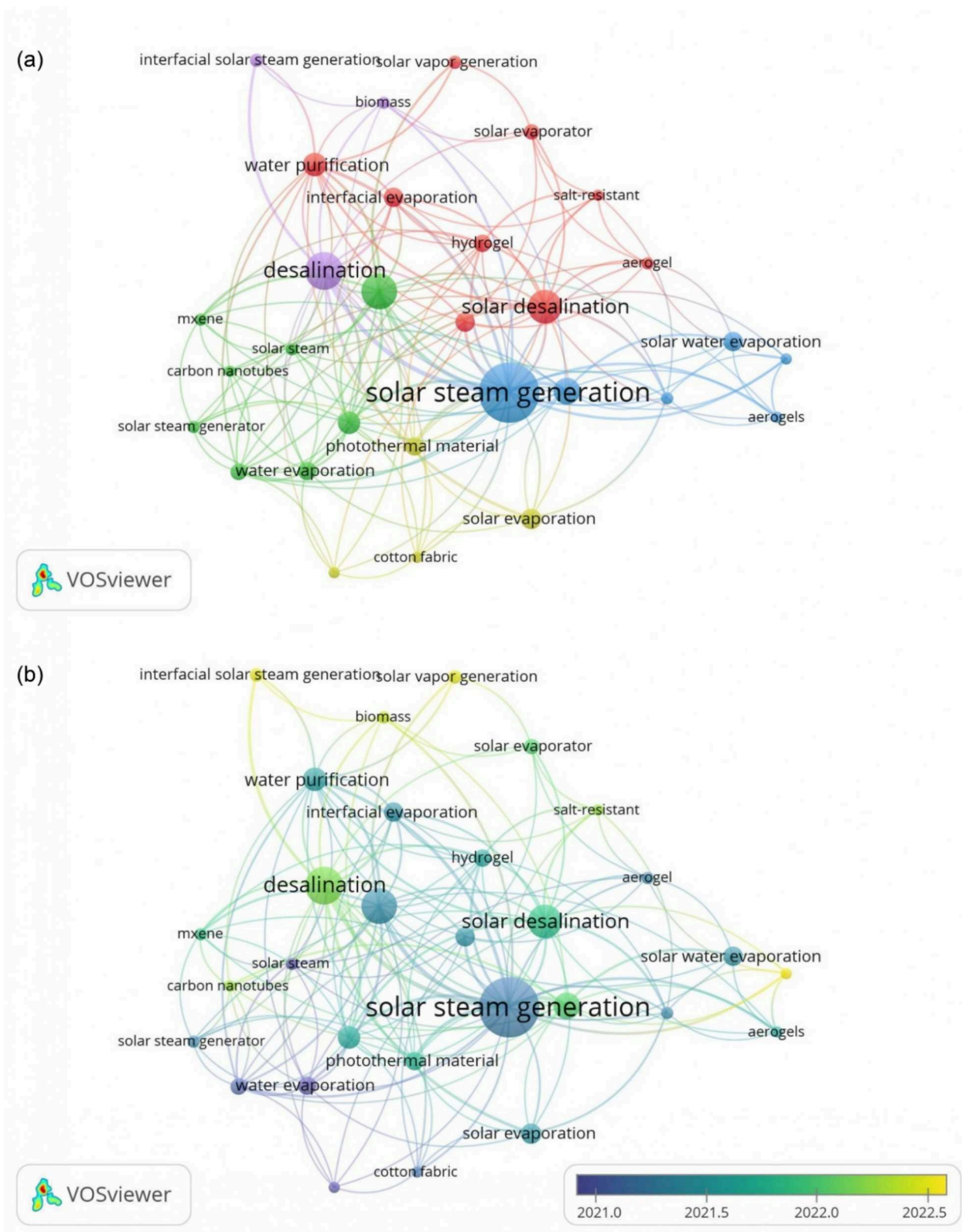


Fig. 3. Cluster of the 30 best frequent authors' keywords in the field of nano-enhanced solar evaporator. (a) Network visualization map; (b) Overlay Visualization map.

pairs. Each cluster in the visual representation reflects the total link strength of individual keywords through circle size scale indicators. The distance between the mentioned terms within the visualization reveals the strength of the relationship [17]. However, the keywords

“desalination”, “photothermal conversion”, “solar desalination”, “water purification”, and “seawater desalination” with “solar steam generation” were found to be most frequently used.

Fig. 3b shows that the study of desalination has gained interest in

recent years. The increase of interest in this field increased with the advancement of nanomaterials as photothermal absorbers for solar desalination applications to address the global freshwater shortage. Therefore, the researchers in this field are interested in optimizing the process and conditions for seawater desalination. Fig. 4 illustrates a density map of the author’s keywords in which the 30 most frequently used keywords were grouped into 5 clusters. Out of 5 clusters, 3 were more dominant. Firstly, in the red cluster the keyword “solar desalination” is surrounded by “hydrogel”, “aerogel”, “salt-resistant”, “solar evaporator”, “interfacial evaporation”, “water purification”, and “solar vapor generation”, among other keywords. Similarly, the green cluster is surrounded by keywords such as “photothermal material”, “mxene”, “solar steam”, “solar steam generator” or “water evaporation”. Lastly, the terms that represented the blue cluster are: “solar water evaporation”, and “aerogels”, among others, surrounding the main word of this group (“solar steam generation”). In Fig. 4, it can be observed that clusters established in density map visualization on VOS viewer based on their similarities in the field of nanoparticles as solar evaporators, correspond to the six groups given in Table 1.

Fig. 5 shows the thematic distribution of author keywords to indicate their importance and developmental extent in each study domain. Themes are used in bibliometric analysis to identify and categorize key research topics in a field. By analyzing themes based on their relevance (centrality) and development (density), researchers and policymakers can better understand the structure, trends, and dynamics of a research domain. The thematic map is divided into four quadrants: i) motor themes (identify core driving forces of research field with high centrality and high density, ii) basic topics (highlight foundational research topics with high centrality and low density, iii) emerging or decreasing themes (identify new, emerging research areas or declining fields with low centrality and low density) and iv) highly specialized or niche themes (recognize specialized areas of research with low centrality and high density. For the bibliometric study, the keywords on the set comprising “seawater desalination”, “solar water evaporation”, and “carbon

Table 1
Main authors keywords clusters obtained on VOS Viewer software.

Cluster	Number of items	Keywords on the VOS Viewer network
1	9	Aerogel, hydrogel, interfacial evaporation, photothermal, salt-resistant, solar desalination, solar evaporator, solar vapor generation, water purification
2	8	Carbon nanotubes, electricity generation, mxene, photothermal conversion, solar energy, solar steam, solar steam generator, water evaporation
3	6	Aerogels, photothermal materials, solar steam generation, solar water evaporation, electrospinning, seawater desalination
4	4	Cotton fabric, photothermal material, polypyrrole, solar evaporation
5	3	Biomass, desalination, interfacial solar steam generation

nanotubes” and the second set comprising “aerogels”, “electrospinning”, and “aerogel” share two quadrants; research about basic themes occupies half of the circle while motor themes make up the other half indicating their equal significance and development. The distribution of these terms indicates a need for deeper examination because their frequency falls in the middle range. These topics show the potential to become essential motivational themes as research about them continues forward. Researchers need to perform additional studies about nanoparticles in solar evaporators to discover the most efficient methods for solar desalination. The focus should intensify on improving operational conditions because they enhance efficiency while resolving the world-wide water shortage.

The keywords within highly specialized or niche themes appeared in three distinct groups even though they maintained moderate density levels. The first group comprises of “interfacial solar steam generation”, “carbonized wood” and “thermal management”, and the second group deals with “interfacial heating”, “freshwater”, and “nanomaterials”.

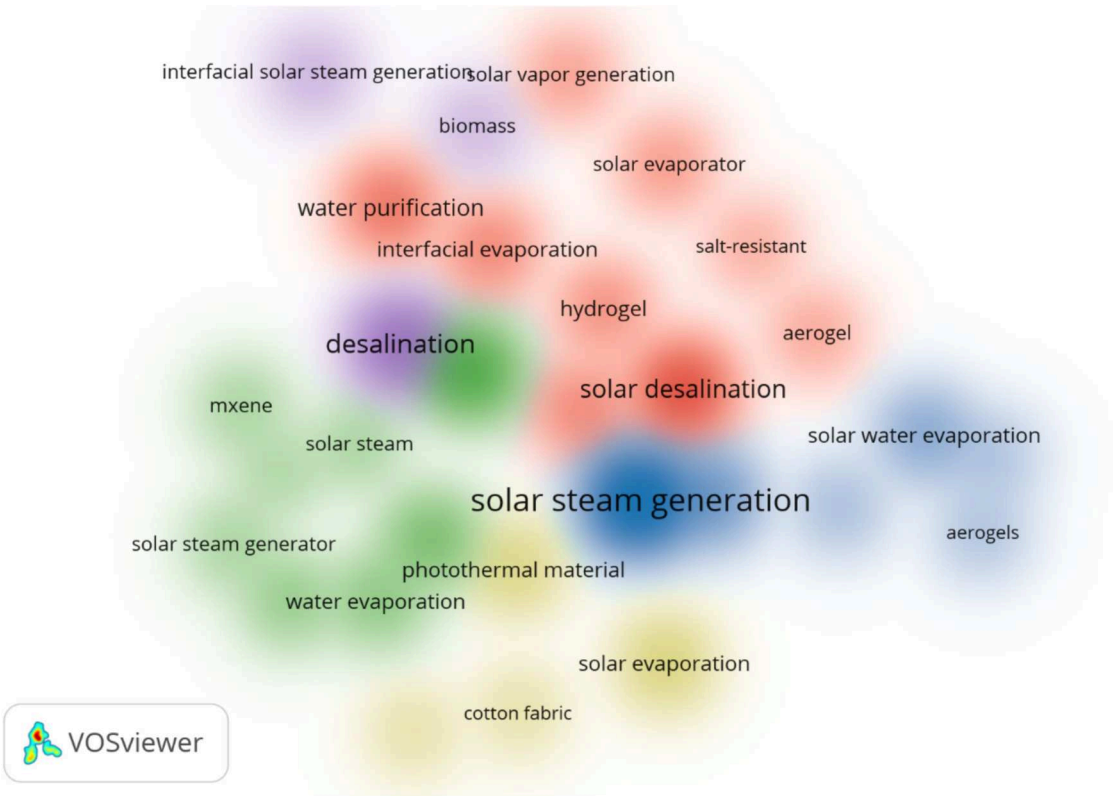


Fig. 4. Cluster of the 30 best frequent authors’ keywords in the field of nano-enhanced solar evaporator Density visualization map.

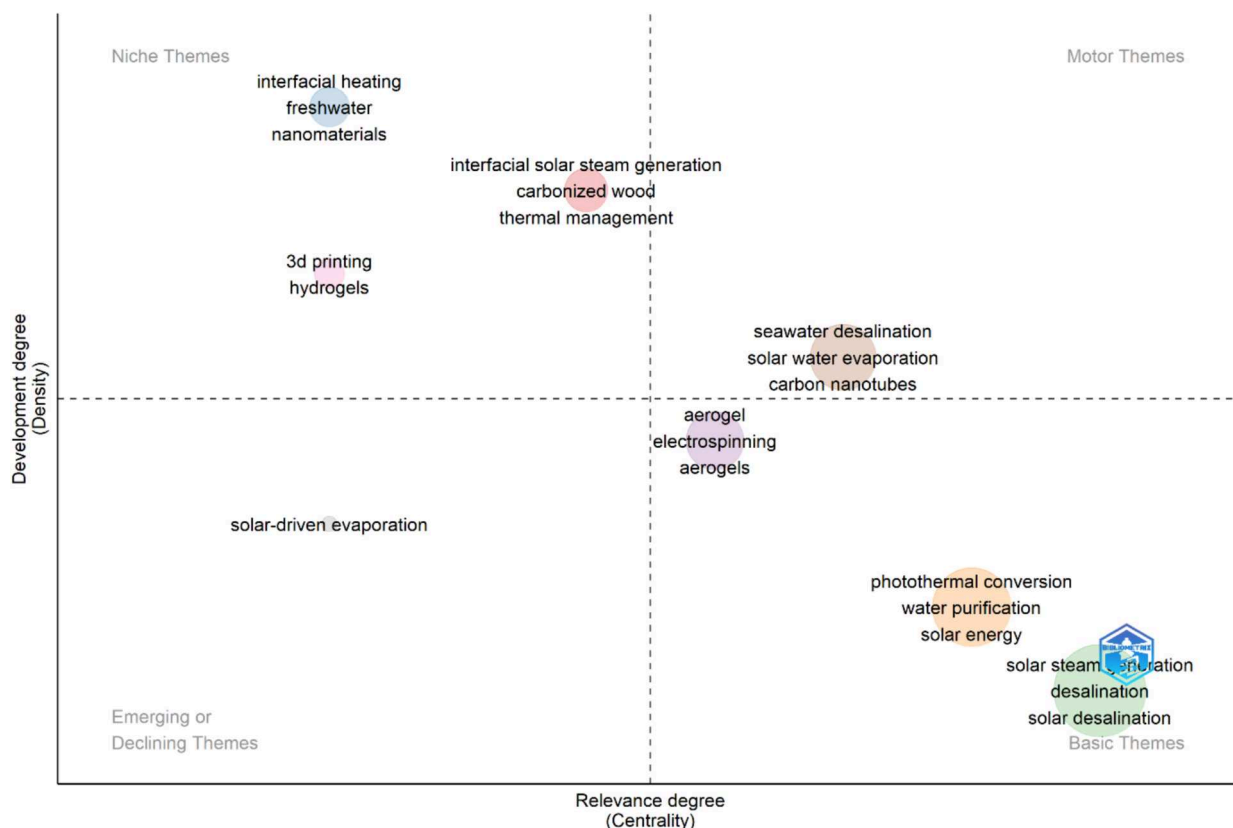


Fig. 5. Thematic map illustrating the clusters from the 60 most frequently used author's keywords in the field of nano-enhanced solar evaporator.

Similarly, the third group was composed of “3d printing”, and “hydrogels”. The results confirm the increase of interest in the use of advanced nano-based photothermal materials for solar desalination by studying their localized heating, hydrophilicity, surface temperature, and photothermal conversion for improving nanoparticle-based solar evaporator production.

Table 2 displays the summary of clusters from Fig. 6 by demonstrating their representative phrases and corresponding item counts. Fig. 6 visually presents keyword clustering into eight groups along with connecting linkages that demonstrate their relationships. The circular size within each cluster represents keyword frequency levels, and keyword placement explains their connections to other groupings in the diagram. The bibliometric analysis evaluated 638 keywords; the 20 best encountered keywords across the field are ranked in Table 3. The highly frequently utilized keywords in the research area is “solar steam generation” (79 occurrences), “desalination” (37 occurrences), “photothermal conversion” (33 occurrences), “solar desalination” (31 occurrences), “water purification” (17 occurrences), and “seawater desalination” (20 occurrences). This finding emphasizes the need to research appropriate photothermal desalination materials to produce fresh water. Research development with emerging trends can be identified through the examination of most frequently used keywords. Table 3 shows that the most often used keyword was “solar steam generation” (79 occurrences), which is the most common and environmentally friendly form of desalination.

2.3. Most cited authors

After evaluating the highly cited publications in this research topic, it was possible to determine the most cited author for the chosen study period. Table 4 reveals that 1315 writers are involved in relevant publications on the issue. There are no single-authored documents reported, and the mean total of co-authors per document is approximately 6.86.

Furthermore, the released paper contains a rather high percentage of international cooperation, approximately 16.67 %. Fig. 7 depicts the output of the top 15 writers in this scientific subject.

Fig. 7 shows authors who appeared as non-first authors in their publications and the circle size indicates publication frequency, and circle color shows annual citation counts. Visual representation of annual publication quantity appears through circle dimensions while their color denotes the annual citation count. The most common authors were Gong J, Li A, Liang WD, Niu R, Sun HX, Wang XB, and Zhu ZQ each with 9 publications, followed by Hao L, Liu N, and Mu P each with 8 publications.

2.4. Most cited papers

2.4.1. Most cited research articles

Table 5 shows the ten most cited Research articles in the field of nano-enhanced solar evaporators. The table showed that the most cited research article had 595 citations. The paper was published by Kuang et al [18] named “A high-performance self-regenerating solar evaporator for continuous water desalination” studied a solar evaporator achieved antifouling excellence through a specifically arranged artificial channel array built inside wood-based material. Research revealed this salt-rejection system to be the most efficient (75 %) when subjected to one sun irradiation while desalinating a concentrated NaCl solution (20 wt %) over extended periods [18]. The research showed that the second most cited review article received 474 citations in 2018 focused on utilizing 3D cylindrical cup-shaped mixed metal oxide structures as solar evaporators [19]. This 3D configuration exhibited excellent thermal stability, 100 % energy conversion efficiency, and a high evaporation rate of $2.04 \text{ kg m}^{-2} \text{ h}^{-1}$ under one sun irradiation [19]. Mu et al. explored monolithic carbon aerogels through conjugated microporous polymers carbonization in the article that was the third most cited with 341 citations [20]. The ammonia-based peroxydisulfate and sulfuric acid

Table 2
Clusters of main keywords obtained on Bibliometrix software.

Cluster	Main keywords	Number of items	Keywords on Bibliometrix network
1	Interfacial solar steam generation	4	Interfacial solar steam generation, carbonized wood, thermal management, antibacterial
2	Interfacial heating	4	Interfacial heating, freshwater, nanomaterials, bacterial cellulose
3	Solar steam generation	19	Solar steam generation, desalination, solar desalination, solar evaporation, interfacial evaporation, photothermal, photothermal material, hydrogel, solar evaporator, solar vapor generation, biomass, cotton fabric, polypyrrole, salt resistance, clean water production, graphene oxide, mos_2 , water treatment, adsorption
4	Aerogel	8	Aerogel, electrospinning, aerogels, photothermal materials, salt-resistant, salt rejection, wastewater purification, attapulgite,
5	Photothermal conversion	12	Photothermal conversion, water purification, solar energy, water evaporation, electricity generation, mxene, solar steam, solar steam generation, steam generation, wood, reduced graphene oxide, 2d materials
6	Seawater desalination	9	Seawater desalination, solar water evaporation, carbon nanotubes, polydopamine, molybdenum carbide, nickel foam, solar-driven, solar-driven water evaporation, solar evaporators,
7	3d printing	2	3d printing, hydrogels
8	Solar-driven evaporation	1	Solar-driven evaporation

mixture treatment of HCNT aerogels produced highly efficient and water-absorbent materials exhibiting 92 % porosity and $0.192 \text{ W m}^{-1} \text{ K}^{-1}$ thermal conductivity, and 86.8 % energy conversion rate when receiving 1 MW of sunlight for potential solar steam applications [20]. A

hydrophobic MXene membrane was presented in the fourth most cited article with its core made from salt-blocking delaminated Ti_3C_2 nanosheets that received trimethoxy (1H,1H,2H,2H-perfluorodecyl) saline treatment to harness solar energy alongside commercial filter membranes for water delivery [21]. This solar evaporator demonstrated a strong ability to evaporate water with evaporation rate of $1.31 \text{ kg m}^{-2} \text{ h}^{-1}$ with 71 % efficiency under sunshine [21]. Li et al. developed a vertical three-dimensional (3D) printing-based fabrication of a jellyfish-

Table 3
Ranking of leading 20 keywords in the research field (with rank based on the occurrences).

Ranking	Keywords	Occurrences	Total link strength
1	Solar steam generation	79	95
2	Desalination	37	53
3	Photothermal conversion	33	47
4	Solar desalination	31	32
5	Water purification	17	31
6	Seawater desalination	20	27
7	Solar energy	16	25
8	Electricity generation	9	19
9	Hydrogel	10	19
10	Photothermal material	11	19
11	Water evaporation	11	17
12	Interfacial evaporation	12	15
13	Photothermal	12	14
14	Solar evaporation	13	14
15	Electrospinning	6	13
16	Mxene	6	12
17	Aerogels	5	11
18	Photothermal materials	5	11
19	Solar steam	6	11
20	Aerogel	6	10

Table 4
Statistical insight on authors from published documents.

Criteria	Results
Number of authors	1315
International co-authorship%	16.67 %
Single-authored documents	0
Co-Authors per document	6.86

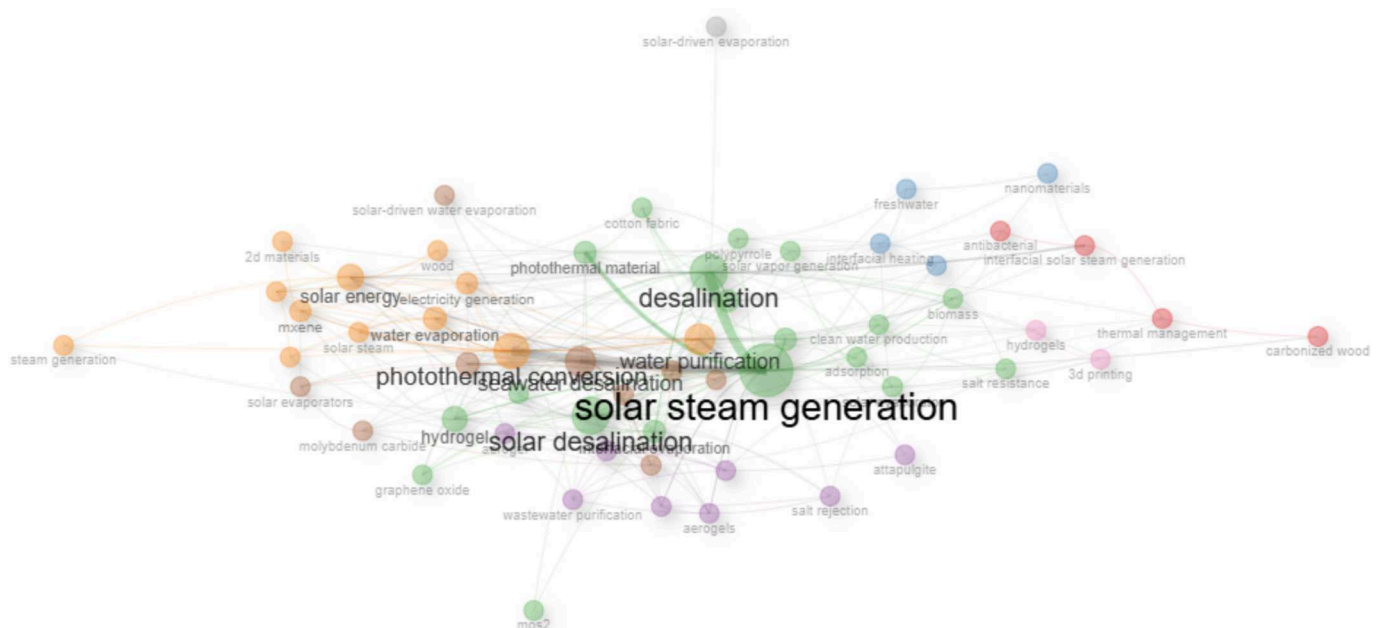


Fig. 6. Clusters from the high frequent authors keywords in the area of nano-enhanced solar evaporators.

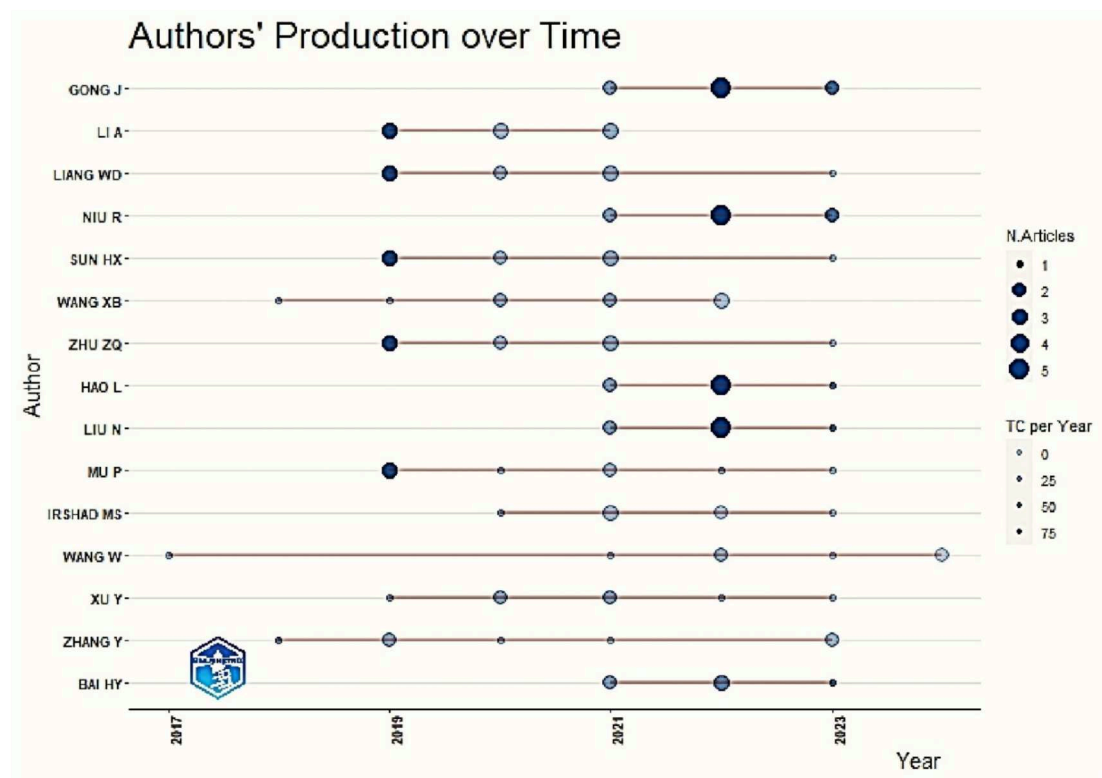


Fig. 7. Bibliometric analysis of the top 15 authors in the field of nano-enhanced solar evaporator.

Table 5
Ranking of 10 most cited research articles in the field of nano-enhanced solar evaporator.

Ranking	Title	Journal	Publication year	Total citation	Average citation per year	Reference
1 st	A high performance self-regenerating solar evaporator for continuous water desalination	Advanced Materials	2019	595	99.17	[18]
2 nd	A 3D photothermal structure toward improved energy efficiency in solar steam generation	Joule	2018	473	67.57	[19]
3 rd	Superwetting monolithic hollow-carbon nanotubes aerogels with hierarchically nanoporous structure for efficient solar steam generation	Advanced Energy Materials	2019	341	56.83	[20]
4 th	A hydrophobic surface enabled salt-blocking 2D Ti ₃ C ₂ MXene membrane for efficient and stable solar desalination	Journal of Materials Chemistry A	2018	340	48.57	[21]
5 th	Graphene oxide-based evaporator with one-dimensional water transport enabling high efficiency solar desalination	Nano Energy	2017	300	37.50	[22]
6 th	An ultrathin flexible 2D membrane based on single-walled nanotubes-MoS ₂ hybrid film for high performance solar steam generation	Advanced Functional Materials	2018	283	40.43	[23]
7 th	Flexible and salt resistant Janus absorbers by electrospinning for stable and efficient solar desalination	Advanced Energy Materials	2017	277	39.57	[24]
8 th	A plant-transpiration process inspired strategy for highly efficient solar evaporation	Advanced Sustainable Systems	2017	210	40.17	[25]
9 th	Nature-inspired, 3D origami solar steam generator toward near full utilization of solar energy	ACS Applied Materials & Interfaces	2018	197	26.25	[26]
10 th	A wood-polypyrrole composite as a photothermal conversion device for solar evaporation enhancement	Journal of Materials Chemistry A	2019	180	28.14	[27]

inspired solar evaporator designed with three main components: a body made of a porous CB/GO composite layer and the vertical GO pillars served as tentacles supplemented by the EPS matrix [22]. Water linearly passed through GO pillars to cut the interface area linking evaporation layers and mass water and decrease heat losses. Under one-sun illumination, the solar evaporator achieved an outstanding conversion efficiency of 87.5 % along with superior water desalination ability [22].

The sixth most cited research article described an ultrathin 2-dimensional porous photothermal layer constructed from MoS₂ nano-sheets and SWNT (single walled nanotubes) films. Despite its ultrathin thickness of about 120 nm, the produced SWNT-MoS₂ material absorbs

more than 82 % of the solar spectrum. Due to localized heating, it creates a strong temperature gradient, resulting in a 91.5 % evaporation efficiency [23]. Xu et al. described the synthesis of a stable solar evaporator developed by using sequential electrospinning to make a flexible Janus absorber structure [24]. This article, the seventh most cited research article with 277 citations, developed a Janus structure that divided steam generation functionality between its top hydrophobic polymethylmethacrylate (PMMA) layer coated with carbon black nanoparticles (CB) and its bottom hydrophilic polyacrylonitrile (PAN) layer. Under one-sun irradiation, the Janus absorber exhibited both excellent efficiency reaching 72 % as well as extended water production at 1.3 kg

$\text{m}^{-2}\text{h}^{-1}$ over sixteen days which outperformed multiple other absorber designs from previous studies [24]. The eighth most cited research article demonstrated how wood-polydopamine (wood-PDA) materials could be used as photothermal agents for obtaining solar steam while taking cues from plant transpiration techniques. The system applied direct water film evaporation support at bulk water surface areas to reach outstanding operational effectiveness. The material produced 87 % solar vapor generation efficiency under one-sun exposure conditions. The combination of affordability and efficiency with its basic design makes this solution suitable for wide-scale adoption as a practical solar evaporation system [25]. Hong et al. synthesized the initial deployable three-dimensional (3D) origami-based solar steam generator for capturing complete solar energy spectra. The research devoted its attention to the Miura-ori tessellation pattern because this geometric design preserves both solar energy absorption and recovers lost heat through convective and radiative mechanisms by utilizing its patterned concave structure. A combination of GO and CNTs used in the 3D solar steam system showed a clear positive connection between solar energy efficiency measurements and surface area density with almost complete solar energy conversion [26]. A research article presented a tenth-rank position in terms of citations by describing a basic pyrrole polymerization process for manufacturing polypyrrole-decorated wood (PPy-wood) [28]. The application of black PPy coating strengthened the wood's ability to absorb light by more than 90 % within a wide spectrum extending from UV to near-infrared (300–2500 nm). The harmonious grouping of wood material with PPy led to PPy-wood being an optimal solar vapor generator able to evaporate water with the rate of $1.014 \text{ kg m}^{-2}\text{h}^{-1}$ and reach 72.5 % evaporation efficiency under one-sun irradiation [27].

2.4.2. Most cited review articles

Table 6 shows the five review articles ranked based on citation over the selected investigation period. The review article “The Revival of Thermal Utilization from the Sun: Interfacial Solar Vapor Generation” is the most cited review article during the investigation period (241 citations) published in the National Science Review (Oxford Univ Press Publisher. This study analyzed the design processes and functional applications of solar steam generators constructed from wood-based materials including wood structure characteristics and device types alongside performance determinants [28]. The second most cited review article received 176 citations while examining the materials and structural characteristics of solar evaporator components consisting of solar absorbers, substrates and water collectors. The study concentrated its efforts on enhancing solar energy absorption, together with thermal regulation and water transfer mechanisms as well as surface evaporation and water accumulation [29]. The third most cited review article with 88 citations is “A review on photothermal material and its usage in the development of photothermal membrane for sustainable clean water production”. The research examined interfacial solar evaporation by defining its operation and shedding light on its mechanism as well as key performance indicators before summarizing recent material and

application progress before presenting anticipated directions [30]. The fourth most cited review article published in 2023, reviewed the wood-based solar steam generators while focusing on wood structure and properties, their types, design, applications, and factors influencing the evaporative performance [13]. Finally, the fifth most cited review article reviewed the light absorption and solar thermal conversion mechanisms of a wide variety of photothermal materials, establishing theoretical foundations for photothermal material selection and design. The most recent advances in photothermal materials for desalination, oil leakage treatment and water purification as well as the obstacles and future opportunities in photothermal material applications, were then summarized [14].

2.5. Most important countries, institutions, and journals

This section mainly focuses on the publications of documents from different countries and identifies which countries are top document producers based on the corresponding authors on nano-enhanced solar evaporators Table 7. Fig. 8a presents the data for corresponding authors as SCP (Single Country Publication) and MCP (Multi Country Publication), and the results illustrate China as the leading country with SCP and MCP factors. Fig. 8b displays the ranking of countries by the total number of published articles during the investigation period. Solar desalination is widely used across Asia, Australia, America, and Europe, and obtained results shows the top countries with the high number of publications; China (216 documents), the Iran (9 documents), Australia, India, Korea and USA (7 documents each) were the countries most

Table 7

Top ten countries and journals ranked by number of articles for bibliometric analysis.

Ranking	Countries	Number	%
1 st	China	216	80
2 nd	Iran	9	3.3
3 rd	USA	7	2.6
4 th	Australia	7	2.6
5 th	India	7	2.6
6 th	South Korea	7	2.6
7 th	Japan	4	1.5
8 th	Saudi Arabia	3	1.1
9 th	Canada	3	1.1
10 th	Indonesia	2	0.7
Ranking	Journals	Number	%
1 st	Desalination	22	8.15
2 nd	Journal of Materials Chemistry A	18	6.67
3 rd	ACS Applied Materials & Interfaces	16	5.92
4 th	Nano Energy	10	3.70
5 th	Chemical Engineering Journal	8	2.96
6 th	Separation and Purification Technology	8	2.96
7 th	Solar Energy Materials and Solar Cells	8	2.96
8 th	Solar RRL	8	2.96
9 th	ACS Sustainable Chemistry & Engineering	6	2.22
10 th	Advanced Sustainable Systems	6	2.22

Table 6

Review articles in the field of nanoparticles as solar evaporators.

Ranking	Title	Journal	Publication year	Total citation	Average citation per year	Reference
1 st	The revival of thermal utilization from Sun: interfacial solar vapor generation	National Science Review	2019	241	40.17	[28]
2 nd	Advances in solar evaporator materials for freshwater generation	Journal of Material Chemistry A	2019	176	29.33	[29]
3 rd	A review on photothermal material and its usage in the development of photothermal membrane for sustainable clean water production	Desalination	2021	88	22	[30]
4 th	Interfacial solar steam generation by wood-based devices to produce drinking water: a review	Environmental Chemistry Letters	2023	24	12	[13]
5 th	Photothermal membranes for water treatment and anti-fouling performances: A review	Journal of Cleaner Production	2023	3	1.5	[14]

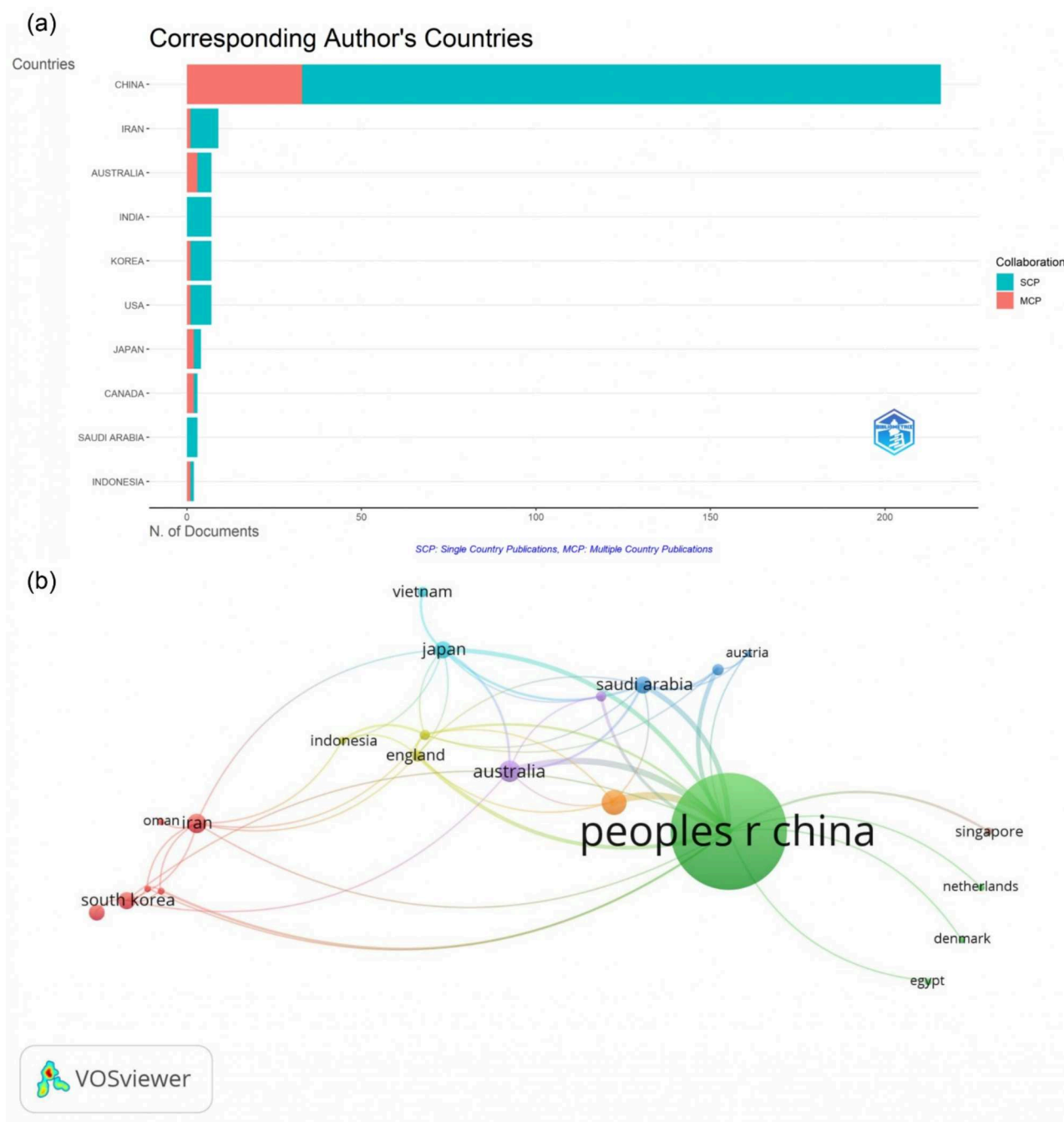


Fig. 8. A) The publications' number per country is represented graphically on the map. b) The most representing countries in the field of nanoparticles as solar evaporators.

committed to researching desalination using nano-enhanced solar evaporators. These countries have recently focused on the possible commercial applications of nanomaterials to improve the overall efficiency of solar desalination.

Fig. 9 shows the most relevant institutional affiliations of the authors in the field. The results show that the Chinese Academy of Sciences leads the total document production by about 27 and 12 publications followed by Donghua University, Hoazhong University of Science and Technology, and Husei University each with 11 publications. The results demonstrate that most publications are being produced by academic institutions in East Asia. This is explained by the availability of renewable energy sources in the area, such as solar energy, research interest working in academia, as well as the fact that nano-enhanced desalination technology is currently being used locally to address the freshwater

scarcity problem.

Fig. 10 illustrates the most relevant article sources based on the total number of articles. The journal Desalination (ELSEVIER) dominates the publications on nano-enhanced solar evaporators for desalination, with approximately 22 articles, as one might expect as it primarily focuses on desalination subjects. Other journals appropriate for publication in this field include the Journal of Materials Chemistry A (18 papers), ACS Applied Materials & Interfaces (16 articles), Nano Energy (10 articles), and so on.

Fig. 11 presents the three-field plot linking authors' keywords, authors, and journals. A Sankey diagram, which highlighted cross-field flows, helped us recognize the keywords and their relationships. Stronger links promote stronger relationships between fields [31]. The most used terms were "solar steam generation", "desalination", and

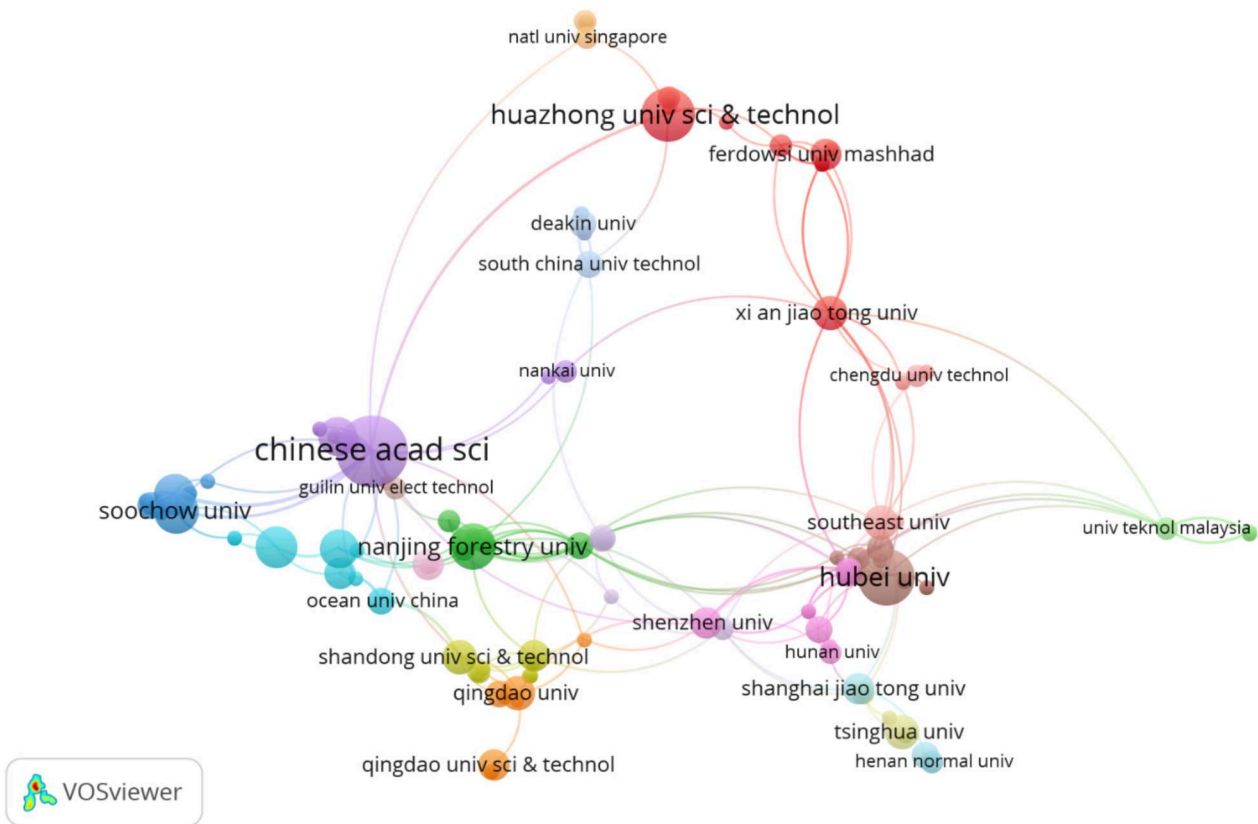


Fig. 9. Top organizations in the field.

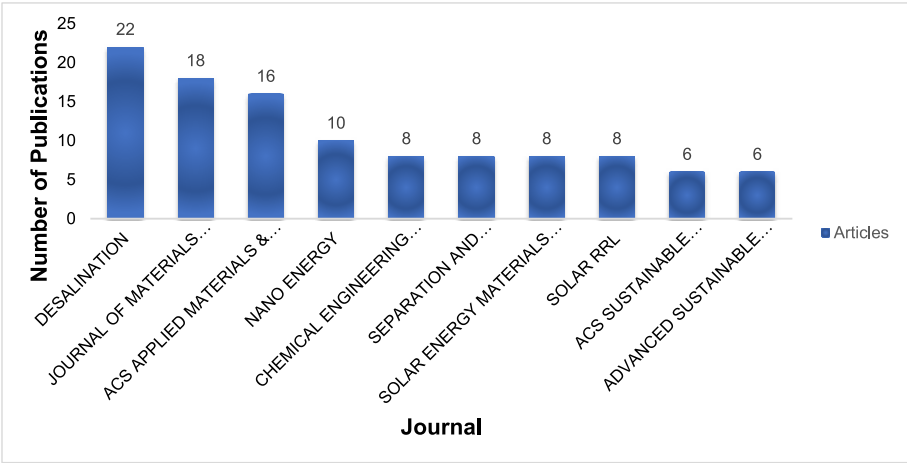


Fig. 10. Most relevant sources in terms of Publications.

“solar evaporation”, which correlate to the keywords in Table 3. The author’s Gong J, Niu R, and Hao L are closely related to the terms “solar steam generation” and “solar evaporation”. When the flow of keywords to journals was studied, it was determined that desalination-related links were the most relevant. On the other hand, the journal Separation and Purification Technology published most publications with keywords such as “solar steam generation”, “water purification”, and “photo-thermal conversion”. This three-field plot illustrates the significance of photothermal conversion during solar vapor generation for water refining.

2.6. Photothermal conversion Mechanism, Comparison, and toxicity Concerns of nano-evaporators for solar desalination

Solar energy is a bulk source of energy that can be transferred to thermal energy utilizing the photoexcitation phenomena in various kinds of materials such as plasmonic metals, semiconductors, organic molecules, and carbon-based materials. Utilizing the potential of photothermal nanostructures as nano-evaporators is a win-win solution to achieve efficient solar steam generation. Photo to thermal conversion can be achieved due to the attraction between electromagnetic radiation and matter via different mechanisms, such as localized plasma heating of metals, non-radiative semiconductor relaxation, and molecular thermal vibrations. The interaction of electromagnetic radiation with

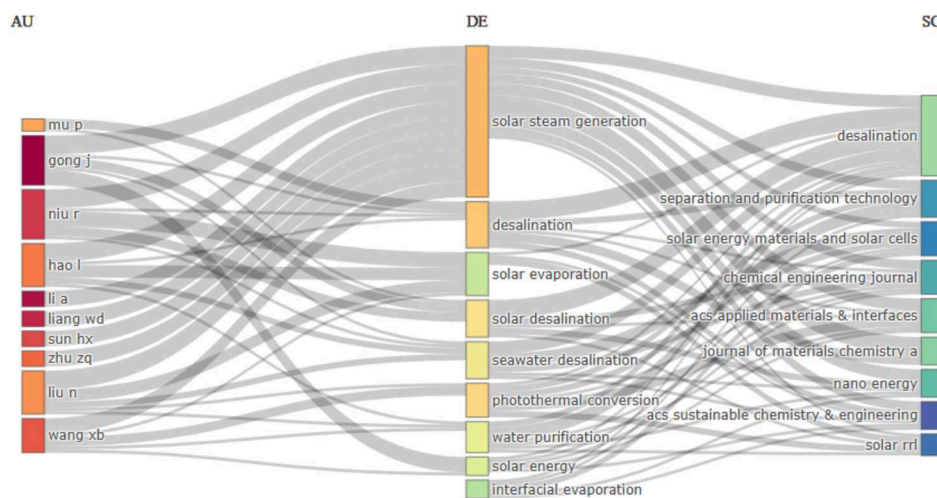


Fig. 11. Three field plot.

plasmon metallic nanostructures causes intra-band transitions, and electrons are excited to higher energy levels from the conduction band [32]. Nearby to the metal-dielectric interface, the collective electron oscillation can propagate along the interface (SPP) or be localized close to the curved surfaces of the metal nanostructures. As a result, the excited surface plasmon acts as a strong damped oscillator that could decay via electron-to-phonon, electron-to-electron, and electron-to-photon in the form of thermal energy. Electron-to-electron decay assigns the thermal electron energy, which causes the localized metal surface temperature to increase quickly, Fig. 12 (a-b) [33]. The equilibrium cooling generates towards electron-photon energy conversion due to a change in localized temperature and phonon-to-phonon transformation, resulting in heat release to the surrounding medium, Fig. 12 (c) [32,33].

In the case of a semiconductor solar absorber, the optical activity presents an obvious dependence on band gap and wavelength. The electron-hole pairs are generated according to the bandgap-like energy by irradiating the semiconductor with solar light. The excited electron reverts to the ground state by releasing energy via radiative relaxation as photons or non-radiative relaxation as phonons (heat) Fig. 12 (d). The second process entails transferring energy to impurities, defects, or dangling bonds on the material's surface. The energy loss (as phonons) is directed to localized lattice heating, which causes a temperature gradient, depending on the material's optical absorption as well as its bulk and surface recombination characteristics [34]. Nanostructures have a wide range of spectral absorption ability to demonstrate photothermal conversion; such as the work of Zhou et al shows the Au-nanoparticles in an anodized aluminum oxide (AAO) mask and transformation of transparent AAO into black material, which shows 99 % absorption (400 nm to 10 μm) [35]. However, the use of noble metals is not a reliable practice for the solar desalination process. Xu et al, investigated a cheaper nickel (Ni) nanostructure as the solar absorber that achieved $\approx 95\%$ from 200 to 1500 nm wavelength range [36]. Alternatively, the Cu-based semiconductor nano-evaporators are an excellent cost-effective candidate for solar desalination; Hussain et al., reported the CuS functionalized carbon foam, which shows the $\approx 95\%$ absorption in UV/Vis-NIR (250 to 2000 nm) [37].

The broadband absorption is a versatile feature of carbon-based materials under solar irradiation due to its natural black color. The majority of carbon-based material skeletons consist of single carbon bonds C-H, C-O, C-C that present a large energy band gap $\sigma\text{-}\sigma^*$, and they reflect an impossible $\sigma\text{-}\sigma^*$ transition under solar irradiation. Due to less strongly bonded electrons in pi (π) bonds compared to σ -bonds, the π to the π^* can be simulated with low energy. In results, the conjugated π bonds can cause a red shift and as number of π bond increased the energy

gap among lowest unoccupied molecular orbital (LUMO) and highest-occupied molecular orbital (HOMO) get smaller [34]. Under the solar irradiation the electrons are excited from the ground HOMO to excited LUMO state and relaxation of excited electron in form of electron-phonon coupling convert the light energy into vibrational modes across the atomic lattices that ultimately increased the temperature of the material Fig. 12 (e) [32]. Carbon material, such as graphene-based nanostructures and carbon black nanoparticles, has received significant attention for solar steam generation. Liu et al, investigated the role of GO as a solar absorber on bilayer-wood solar evaporator, which presents a high photothermal conversion efficiency (83 %) [38]. Xu et al. has developed a bi-layer solar steam generator in which the polyacrylonitrile (PAN) acts as a hydrophilic water pathway and upper hydrophobic carbon black nanoparticles act as light absorbers [24].

The wavelength of solar energy ranges from 280 to 2500 nm, and fifty percent of the radiation energy lies in the IR region [6]. An ideal nano-based photothermal material must absorb maximum solar radiation with low reflection and transmittance, and efficiently convert light energy to heat energy. This heat energy plays a dominant part in enhanced desalination efficiency and evaporation rate. The researchers have increased interest in the development of effective photothermal materials [7]. Carbon-based nanomaterials, metallic particles, semiconductors, and polymers are some of the nanomaterials that have been extensively studied for their broad-band light absorption across the entire spectrum [39,40,47].

Based on the comprehensive bibliometric investigation to map the research landscape of nano evaporators, highlighting key trends, persuasive contributions, and emerging directions in the nano solar steam generators. To complement these findings, a comparative analysis of numerous nanomaterial-based solar evaporators (carbon-derived, conjugated polymers, plasmonic nanomaterials, semiconductors, and composite materials) is elaborated in Table 8. This consolidative approach not only provides a map of the research trends, patterns, and impacts but also suggests valuable insights to direct future material selection for efficient solar-driven water evaporators.

Using metal-based nanostructures solar evaporators, the major problem is to ensure that the nanoparticle coatings remain stable and durable when exposed to extreme weather, like high temperatures and salt, for extended periods. Concerns exist over the possible leaking of metal content into the water stream. Excessive exposure to nanoparticles (<20 nm) might result in negative impacts on health and cause diseases [61]. A study showed that human kidneys absorb gold (Au) nanoparticles, which may cause nephrotoxicity. Adsorption of cadmium (Cd) nanoparticles in the kidneys can cause cellular damage [61]. Similarly, silver nanoparticles which are manufactured worldwide for a variety of

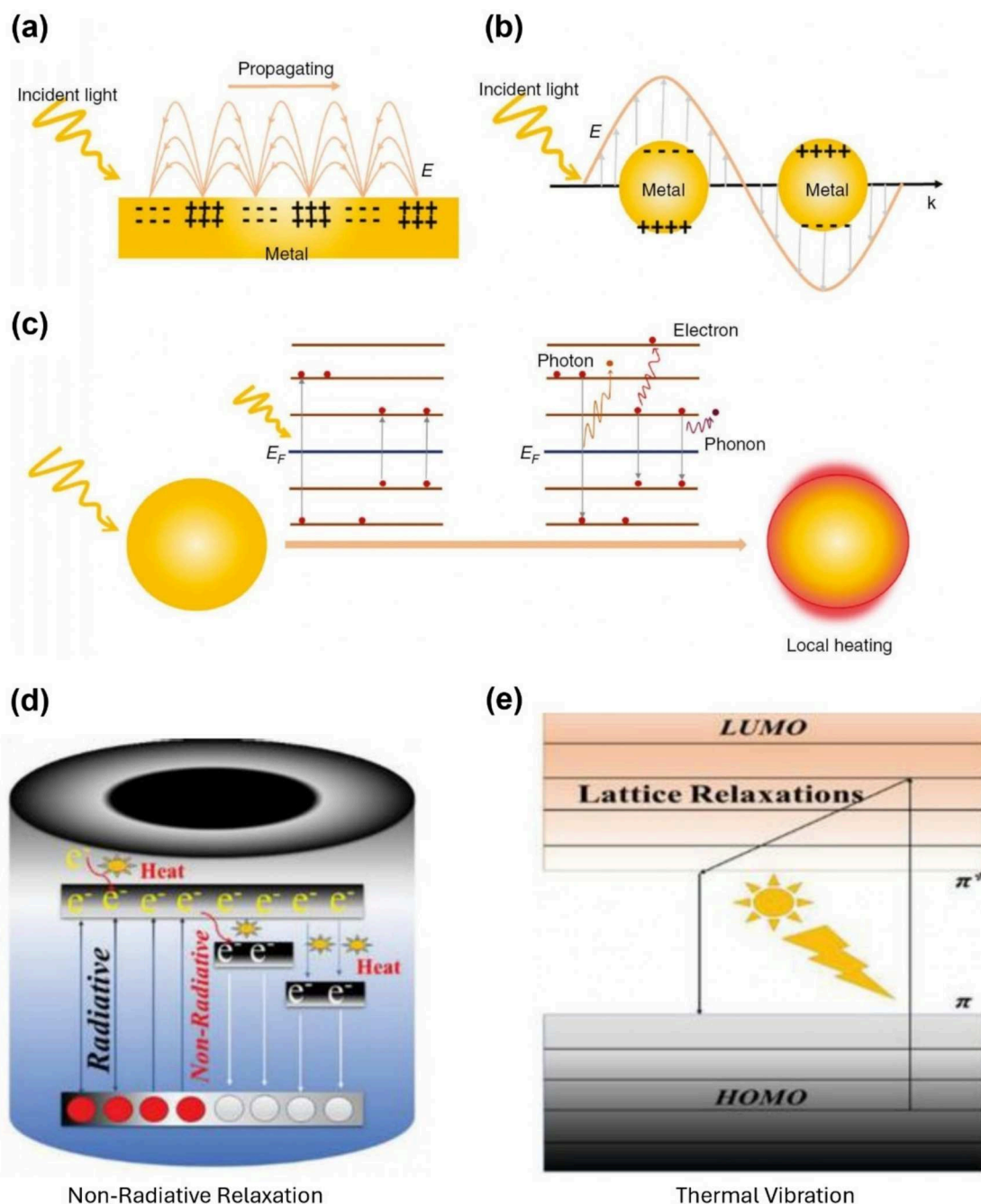


Fig. 12. Photothermal Mechanism of nano-structures; (a) Propagating surface plasmon generated (SPP) at the metal-dielectric interface, (b) localized surface plasmon resonance (LSPR) generated on the metal nanoparticles, (c) surface plasmon decays and ultimately generates local heating [33], copyright 2019, De Gruyter Brill (d) non-radiative relaxation (semiconductors), (e) π - π^* bonds transition from HOMO to LUMO band, lead towards photothermal conversion in thermally vibrated molecules [32], copyright 2021, Wiley.

industrial applications are readily absorbed by the kidneys, circulatory system, heart, and liver, resulting in major problems in humans and animals. They can reduce sperm production in mice and can cause cell death due to oxidative stress [61].

Several nanoparticles (NPs), including TiO_2 , CuO , ZnO , Fe_2O_3 , $\text{CuZnFe}_2\text{O}_4$, and Fe_3O_4 , cause DNA damage in humans, with varying doses, sizes, and forms and CuO nanoparticles cause the most DNA damage [61]. Long-term exposure to Fe_3O_4 nanoparticles inhibited root growth in *Eichhornia crassipes* (water hyacinth) [62]. Quantum dots (QDs) are increasingly used in medical applications. QDs' increased absorption in the kidneys caused nephrotoxicity [63]. Exposure to graphene nanomaterial concentrations above 200 $\mu\text{g/L}$ inhibits metabolic

activity in human kidney cells after 10 days. Engineered nanoparticles, such as QDs and CNTs, can interact with fibroblasts and epidermal keratinocytes. SWCNTs can cause cutaneous toxicity in humans [64].

2.7. Techno-economic analysis

As the purpose of solar steam generation is cost-effective production of fresh water and for this reason it is important to estimate the cost of material and process used for water treatment Ni et al used material costs to calculate the cost of water production by various solar evaporators and finding concluded that the production of floating solar still can produce water at $2.5 \text{ L m}^{-2} \text{ day}^{-1}$ with the estimated cost of $\$3 \text{ m}^{-1}$.

Table 8
Comparison of nano-enhanced solar evaporator for desalination.

	Material	Light absorption (%)	Surface temperature (°C)	Evaporation rate (kg m ⁻² h ⁻¹)	Conversion Efficiency (%)	References
C-based nanomaterials	Graphene/GO-Polyvinyl (GGOP)	94.5	38	1.44	86	[41]
	Carbonized corn straw(CSMC)	96.5	54.4	1.42	89.3	[71]
	Porous carbon nano-foam (PCN)	88	40.2	1.68	88	[42]
	PVA-activated carbon/PSS	>95	33	3.86	92	[72]
	Nano-fibrous-hydrogel-rGO	90	40	1.85	95.4	[73]
	Carbonized daikon	93.5	32.6	1.57	85.9	[74]
	Candle soot nanoparticle-decorated wood	89	34.7	0.95	67.9	[75]
Plasmonic	Carbonized lotus seapod	98 %	44.8	1.3	86.5	[76]
	Ti ₃ C ₂	—	39	1.31	71	[21]
	ce-MoS ₂ /BNC bilayer aerogel	96	37	0.81	76	[43]
	Reduced (WO _{2.72} /PLA) fiber membrane	—	75.3	3.81	81.39	[44]
	CuS/polyethylene (CuS/PE)	93	52	4.03	63.9	[45]
	Cu ₇ S ₄ /Cu mesh	95.7	43.5	1.41	88.1	[46]
	Ag@PAN membrane	92.8	41.3	1.34	76	[77]
	Tungsten trioxide (WO ₃)/wood	94	42	1.28	82.5	[78]
	Cu _{1.8} SnSe ₃ /Cu ₂ ZnSnSe ₄ -polyurethane foam	97/95.5	40	1.657	86.6	[79]
	CuS/polyvinylidene fluoride membrane (PVDFM)	96	38.5	1.43	90.4	[80]
	Cu _{1.8} S/PVDFM	91.7	36.1	1.173	80.2	[81]
	TiAlON-modified NiO (M–NiO)	98	41	1.13	73	[82]
Semiconductor	Bi ₂ S ₃ /Pd composite	95	38	1.61	97	[50]
	Co ₃ S ₄ /NF	97 %	39.7	1.56	94.18	[49]
	Cu _{2-x} S nanowires (NWs)	—	—	~0.95	~67	[48]
	Al ₂ O ₃ -coated Cu-Si nanowire	93	65.1	1.37	86	[83]
	TiO ₂ nanorods/glassy carbon foam	90	41.4	2.23	67.1	[84]
	Black TiO ₂ /polystyrene foam	..	45.4	1.16	77.14	[85]
	Nanofibrous aerogels (PTCNFAs)	95	—	2.89	90.3	[52]
Polymeric	Wood-derived aerogel (C-WA)	95	92.7	1.40	83.4	[53]
	glass capillary array (GCA) coated with Pd nanoparticle (PDN) (PDN-GCA)	99	31.7	1.5390	89.8	[54]
	PVA/PPy gel membrane	90	28	3.64	96	[86]
	PPy/FeCl ₃ -coated melamine foam	98.1	65.7	2	90	[87]
	PPy/FeCl ₃ coated pomelo peel	99	50.8	1.22	76.61	[88]
	Polydopamine nanofibrils/polystyrene foam	75	45	1.72	90	[89]
	SWNT–MoS ₂	82	—	0.9	91.5	[23]
Composite material	Monolithic carbon aerogels consisting of hollow carbon nanotubes (HCNTs)	99	40.1	1.44	86.8	[20]
	MoS ₂ /bio-carbon foam composites (MBCF).	96	35	1.49	88.3	[55]
	Sea urchin-like metal–organic frameworks (MOFs) wrapped around Ni nanoparticles (Ni-MOF@W)	98	51.3	2.07	91.5	[56]
	Activated carbon-carbon black (CF-ACB)	—	30.5	1.70	91.8	[57]
	BiVO ₄ @CNT	96	40.08	2.36	94	[58]
	CuCo ₂ S ₄ -decorated carbon foam	96	74.4	2.4	—	[59]
	PDA@Co ₃ O ₄ -SnO ₂	99	40.6	2.26	118.3	[60]

[65,66]. Polymeric nanomaterials such as hydrogels are economically feasible but have low solar absorption capacity and low stability. Guo et al combined konjac glucomannan, readily available biomass, to fabricate Fe-based metal–organic framework-derived nanomaterials into polyvinyl alcohol networks to construct cost-effective hybrid hydrogel evaporators (\$ 14.9 m⁻² of total materials cost) [51]. Metallic nanoparticles, such as gold nanoshells at \$395 per mg [67], is a significant barrier to large-scale applications. Carbon-based nanomaterials such as wood, polyethylene terephthalate, and carbon dots (CD) are cost-effective as compared to metallic nanomaterials. Rahmawati et al described that carbon dots (CDs) are promising solar water evaporators because to their low cost, non-toxicity, high solubility, and tunable optical features. However, their low absorption in the visible zone impedes their functionality. Despite this, CDs exhibit amazing evaporation efficiency (up to 70 %) and stability [68].Solar evaporation efficiency for water collection decreased from 56 % to 24 % as a result of optical loss caused by water droplets on transparent windows [66]. Research on solar steam generation focuses mostly on sun evaporation efficiency and does not consider water collection. A single distillation cycle which includes vaporization and condensation with heat dissipation to the environment needs more than 640 kWh m⁻³ thermal energy regardless of photothermal efficiency reaching 100 % [69].

A variety of factors impacting both capital (CAPEX) and operating

(OPEX) expenditures influence the cost of producing desalinated water. Certain technologies require a large amount of capital expenditures (CAPEX) (land, engineering, unit acquisition, transportation, installation, etc. whereas other technologies have a higher OPEX (labor, energy, and chemicals). The \$/m³ of water produced unit of measurement is used. Variations in fuel costs, building, and material costs, feed water parameters (turbidity and salinity), and cost calculation techniques can all be blamed for the disparities in water cost estimates found in the literature [70]. Although modern solar evaporators showed more than 90 % evaporation efficiency, the efficient collection of water remains the primary obstacle for ongoing advancements. A thorough evaluation between material expenses and operational efficiency will determine the optimal expense-to-benefit relationship for every scenario [29].

3. Conclusion

The present study focuses on examining the global interest in the development of nano-evaporators for solar steam generation. A scientometric-based review approach was applied to gain an understanding of the current state of research in this field worldwide. This study reviewed the nano-enhanced solar evaporator for desalination from 2017 until April 2024, a total of 270 publications (Research articles: 265 and Review articles: 5) were found. The following are key

results achieved from bibliometric analysis.

The analyzed research period for the publication of articles shows a consistent growth in the number of published articles in the prior five years (14.63 % annually) due to an increase in interest in advanced nanostructured-based photothermal evaporators for solar desalination.

Bibliometric analysis evaluated 638 keywords; The highly frequently utilized keywords in the research area is “solar steam generation” (79 occurrences), “desalination” (37 occurrences), “photothermal conversion” (33 occurrences).

The obtained results presented China as the leading country for research publication using nano-enhanced solar evaporators, corresponding authors, and academic institutions.

The bibliometric review highlights a trend in using nanomaterials to enhance desalination efficiency by providing a detailed comparison/examination of carbon, metal-based, semiconductors, polymer-based, and composite nanomaterials as critical components in solar evaporators for the desalination of saline water to overcome the freshwater shortage problems.

Nanomaterial-based solar evaporator has its distinct properties, and performance depends on light to heat conversion, morphology, and device design Scalability of these materials is still a major challenge in terms of cost, and stability under harsh conditions.

In short, present bibliometric investigation pools the knowledge and drives the field forward, guiding contributors to more sustainable and eco-friendly methods that could be a viable solution for addressing the global water crisis to achieve sustainability goals, concisely focusing on SDG-6, SDG-7, and SDG-13. Advances in material selection and engineering are critical for moving these technologies from the lab to real-world applications.

CRediT authorship contribution statement

Ansa Shahzadi: Writing – original draft, Formal analysis. **Muzamil Hussain:** Writing – review & editing, Writing – original draft. **Ijaz Ahmad:** Writing – original draft, Visualization. **Kiran Aftab:** Investigation, Conceptualization. **Elisa Moretti:** Writing – review & editing. **Alberto Vomiero:** Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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RESEARCH ARTICLE OPEN ACCESS

Decoration of Two-Dimensional CuS Nanoflakes on Graphitic Carbon Foam Derived from Waste Plastic for Interfacial Solar Desalination

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ABSTRACT

Interfacial solar desalination using plasmonic metal semiconductors is a valuable process for freshwater production. However, the design of a sustainable and efficient photothermal evaporator is still challenging. In the present research, polyethylene terephthalate waste bottles were upcycled into carbon foam (CF) and further functionalized with CuS nanoflakes as a photothermal layer. Analytical characterizations (X-ray diffraction, Fourier transform infrared spectroscopy, Scanning electron microscopy, and scanning transmission electron microscopy-high-angle annular dark field) demonstrated the successful decoration of two-dimensional Covellite CuS nanoflakes on graphitic CF having microporous channels. UV/vis spectroscopy measurements show enhanced optical absorption with CuS/CF of up to 95% compared to bare CF (72%). The photothermal desalination experiment displayed an improved evaporation rate of $1.90 \text{ kg m}^{-2} \text{ h}^{-1}$ for the CuS-CF compared to $1.58 \text{ kg m}^{-2} \text{ h}^{-1}$ for the bare CF and CuS $1.41 \text{ kg m}^{-2} \text{ h}^{-1}$, revealing the excellent water evaporation efficiency of 91%. The obtained results suggested that the design of CuS-functionalized CF derived from waste plastic for solar desalination is a useful strategy to produce fresh water from the upcycling of waste materials and a good example of circular economy through the development of engineered composite systems.

1 | Introduction

Considering waste as a resource is a vital strategy for the transition from a linear economy to a circular economy and can be implemented in various ways such as durable design, maintenance, repair, reuse, and remanufacturing [1, 2]. Due to high dependence on plastic products, the end life of post-consumed

plastic is a huge obstacle. Plastics can be recycled into various products, but recycling is mostly downcycling toward less recyclable or low-quality products [3]. The inappropriate management of waste plastics has adverse effects on the environment and affects human health by entering the food chain in the form of micro and nanoplastic. Polyethylene terephthalate (PET) belongs to a class of polyesters and is widely used in textiles,

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packaging, carpets, and single-use beverage bottles [4]. By the end of 21st century, it is estimated that in the European Union on land plastic disposal will increase from 4.73×10^5 to 9.1×10^5 tons, and in the ocean approximately from 2.5×10^7 to 1.3×10^8 tons [5]. To mitigate this urgency, the reduction of plastic waste is strongly needed. Plastic disposal in landfills or its incineration can cause severe environmental issues; alternatively, great intention was paid to its conversion into value-added products such as fuels, carbon-based materials, and fine chemicals. Interestingly, plastic wastes contain carbon materials and can be upcycled into a series of C-based structures such as carbon nanotubes (CNTs), carbon nanosheets, graphene, carbon dots, and porous carbon foams (CFs). Utilizing techniques such as flash Joule heating, microwave heating, catalytic carbonization, carbonization, and hydrothermal carbonization, it is possible to tune the functionality of the synthesized carbon materials [6]. Plastic-derived carbon materials provide great environmental and economic benefits and can have diverse applications in the broad field of renewable energy such as in supercapacitors, batteries, hydrogen production, or sustainable environmental practices for pollutant adsorption/degradation, solar evaporation, and CO₂ capture [7–12].

On the other hand, water pollution is a serious and persistent problem due to the rapid increase in urbanization [13]. Water scarcity can be mitigated by treating seawater resources that are widely available on earth, but saline water treatment is very complex. Numerous technologies are available to treat saline water such as the use of membranes, thermal technique, electrochemical processes, advanced oxidation, coagulation–floculation, and ion exchange process [14]. Recently, a new concept of solar desalination has been introduced, to exploit solar light, because solar energy is the most abundant and cost-effective renewable energy and provides energy equivalent to five million tons of coal when solar radiation irradiates on the earth in 1 s [15]. An ideal solar evaporator must consist of an efficient photothermal layer and a matrix material with a hydrophilic porous channel that not only provides a water channel, but also prevents heat loss [6, 16]. In the literature, some studies are reported on low-cost solar evaporators such as CNTs, graphene, graphene oxide hydrogel, and wood-based material for solar evaporation [17–20]. But these materials could not meet the significant requirements of ideal solar evaporator such as high UV/vis absorption to the infrared (IR) region [12], low thermal conductivity [21], high surface temperature, [22, 23] and high hydrophilicity [12] for an enhanced evaporation rate. Recently, CF-based material has attracted great attention for solar evaporator devices due to various advantages such as meso/microporous channels, maximum light absorption from UV/vis to near-IR (NIR), highly reduced heat loss, and lightweight [21–24]. The architecture of the CF includes the sp² strips of graphene and the sp³ carbon atom junction which leads to the porous 3D structure. This architecture owing to the properties of lightness, high specific surface area, and porosity is a good substrate for decoration with metallic nanostructures in 3D pores with high chemical and thermal stability, resulting in an excellent composite system for energy application [25].

Due to large thermal conversion, plasmonic metals such as gold, silver, and platinum nanoparticles are extensively studied for solar desalination to harvest solar energy and transform it into heat [26–28]. However, their high cost and scarcity have limited

their application in solar evaporation. In this framework, copper-based materials can provide significant advantages due to their low cost over precious metals, environment-friendly behavior, excellent LSPR, and photothermal properties [29, 30]. All these features guarantee the harvesting of solar radiation with increased optical absorption toward near-IR (NIR) region [31].

Due to the high versatility of CF for solar desalination process, ongoing research has been reported while the combination with nanostructured such as plasmonic metals is rarely reported. The development of composites for efficient solar evaporator devices is still challenging, but these systems are expected to provide a high solar evaporation rate due to high-temperature surface and morphological advantages. Capitalizing on this concept, we upcycled waste PET into CF to achieve micropores that function as water channels and further decorate the CF for the first time with hydrophilic Covellite CuS that is expected to harvest more solar radiation to enhance the evaporation rate. The CuS nanoflakes decorated CF presented enhanced absorption to harvest solar radiation with an enhanced evaporation rate. The obtained results will assist researches focusing on the rational development of low-cost narrow bandgap energy material from waste plastic for interfacial solar desalination to produce fresh, promoting sustainable circular economy practices. In addition, the presently suggested strategy avoids the use of cobalt, which was previously applied in our research, but which is a harmful solution for the risk of cobalt contamination both in the environment and in the fresh water obtained at the end of the desalination process.

2 | Results and Discussion

The Covellite phase of CuS was decorated on CF (derived from the carbonization of waste PET bottle) using the hydrothermal method (Figure 1). X-ray diffraction (XRD) analyses of synthesized CF, CuS, and CuS–CF were performed in the angular range 20°–80° to investigate the phase and crystal structure (Figure 2). The XRD pattern of the CF shows the broad Bragg peak at $2\theta = 18^\circ\text{--}32^\circ$, attributed to the graphitic (002) plane (JCPDS no. 41–1487), in agreement with previous results from the literature [21, 32]. CuS grown on CF exhibits the Covellite phase with diffraction peaks at 2θ values of 27.1, 31.7, and 47.7° corresponding to the three crystal planes (100), (103), and (107) of Covellite CuS (JCPDS no. 06–0464). A similar XRD pattern with the relative intensity of the (103) and (101) peaks was reported for the pure Covellite structure [33, 34].

Scanning electron microscopy (SEM) was performed to analyze the surface morphology of synthesized CF and the CuS growth on the CF (Figures 3 and S1 and S2, Supporting Information). The SEM images of CF present an apparent open-cell pores structure (Figure 3a), which is due to the physical templating effect of molten salt and foaming features that occurred due to small molecules such as H₂O and CO₂ during degradation that leads to the development open cell pores [21]. The SEM images of the CF present flat sheets which reflect the existence of multilayer graphitic sheets corresponding to the recently reported morphology of CF [32, 35]. In the literature, a similar surface morphology is reported for the occurrence of micropores on the flat sheets of CF due to aggregation of eutectic salts ZnCl₂/NaCl [24]. The SEM

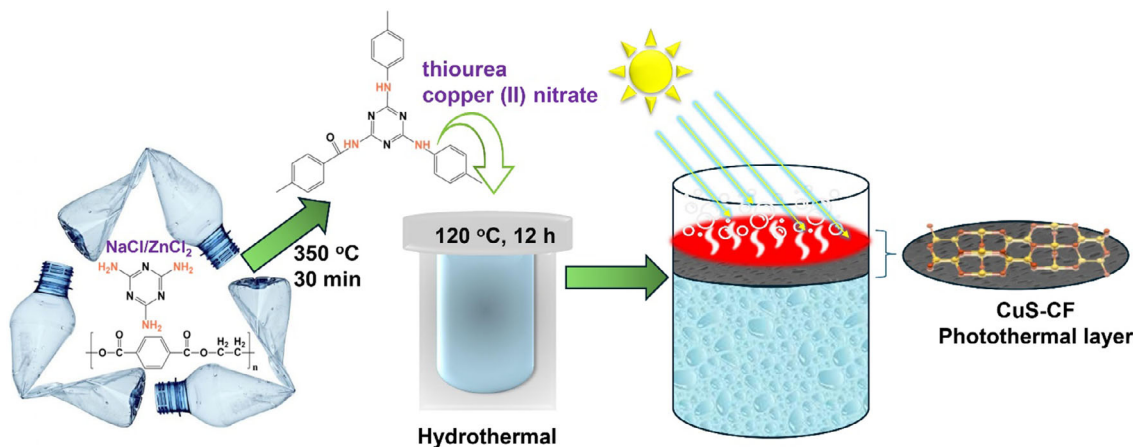


FIGURE 1 | Graphical illustration of carbon foam synthesis and functionalization of CuS nanoflakes on carbon foam powder for interfacial solar desalination experiment.

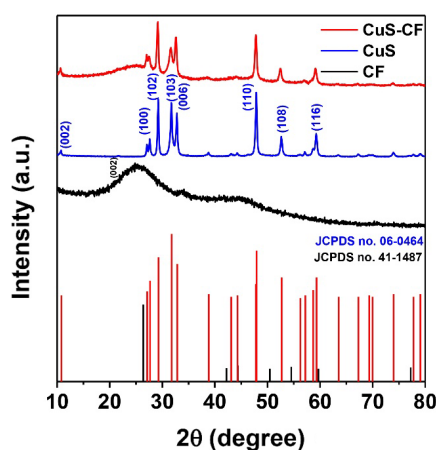


FIGURE 2 | X-ray diffraction patterns of CF-, CuS-, and CuS-decorated CF. CF = carbon foam.

images in Figure 3b,c present the successful decoration of CuS nanoflakes that are randomly distributed in CF surface, and the nanoflake's morphology well matches well with the recently reported study Shifa et al. [34] The elemental compositions of the samples were investigated with energy-dispersive X-ray spectroscopy (EDX). Elemental mapping of CuS-CF evidences the uniform distribution of Cu and S on the CF surface (Figure 3d,e). The transmission electron microscope (TEM) analysis was performed for a more detailed nanoscale analysis, particularly of copper-based crystals. Detailed results are presented in Figure 3g-i and Figure S2, Supporting Information. TEM analysis confirms the successful growth of nanoflakes with varying dimensions of flakes. High-magnification TEM micrographs for the thinner crystal investigation have confirmed the polycrystalline Covellite phase of CuS and the overlap of several layers (Figure 3g-i). The obtained d-spacing values of 0.33, 0.19, and 0.28 nm were successfully matched the corresponding XRD patterns with the crystal planes (100), (103), and (107) for the Covellite phase of CuS. Furthermore, high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) images show how the flakes are randomly placed, resulting in highly different contrast. This observation can be explained by differences in density, not chemical composition. Electrons

passing through a multilayer flake placed on the short side must go through thicker material due to the single layer being almost two-dimensional, as shown by the yellow arrow (Figure 3f). To confirm these observations, EDS analyses of the CuS flakes were carried out, taking into account the STEM micrograph in Figure S2 g,h, Supporting Information, as a reference, to better define the atomic ratio between Cu and S, taking advantage of the higher spatial resolution guaranteed by STEM mode. The S/Cu atomic percentage ratio matches perfectly with the 1:1 of CuS in both cases, confirming all structural observation made by XRD, SEM-EDS, and high-resolution TEM (HR-TEM) (S/Cu = 1.05 for point 1 and 0.91 for point 2).

The survey of X-ray photo-electron spectroscopy (XPS) spectrum shows that the bare CF consists of C, N, and O, as is evident in Figure S3, Supporting Information, and the survey that of CuS-functionalized CF comprising C, N, O, Cu, and S (Figure 4a). The high-resolution C 1s core-level spectrum can be deconvoluted into three contributions, ascribed to C=N (288 eV), C-N (286.3 eV), and graphitic carbon C-C (284.8 eV). The O 1s core-level spectrum can be fitted with two contributions COOH (531.5 eV) and C-O (533.01 eV). The high-resolution N 1s spectrum is deconvoluted into two peaks, ascribed to graphitic N (400.2 eV) and pyridinic N (398.7 eV) species (Figure S3, Supporting Information). The obtained binding energies of C 1s, O 1s, and N 1s peaks are well matched with the reported results [21]. The high-resolution Cu 2p spectrum in Figure 4e exhibits the doublet $2p_{3/2}$ and $2p_{1/2}$ at 932.6 and 952 eV, respectively. Figure 4f displays the S 2p core-level spectrum which exhibits two doublet with the $2p_{3/2}$ at 162.3 and 164.2 eV, assigned to sulfide of Covellite CuS nanocrystals and S(0), respectively [34]. In the case of CuS-CF, the high-resolution C 1s, O 1s, and N 1s spectra are almost the same as the spectra obtained from the CF, clearly indicating that the functionalization of CF with CuS does not affect the graphitic character of CF. The CuS-CF sample is rich in C, N, and O content confirming its graphitic nature, which enables its hydrophilic characteristics.

Fourier transform infrared spectroscopy (FTIR) analysis was performed to identify the functional groups present on the CF and to confirm the CuS nanoflake's growth (Figure 5a). A broad peak at 3420 cm^{-1} is observed for the stretching vibration of -OH and

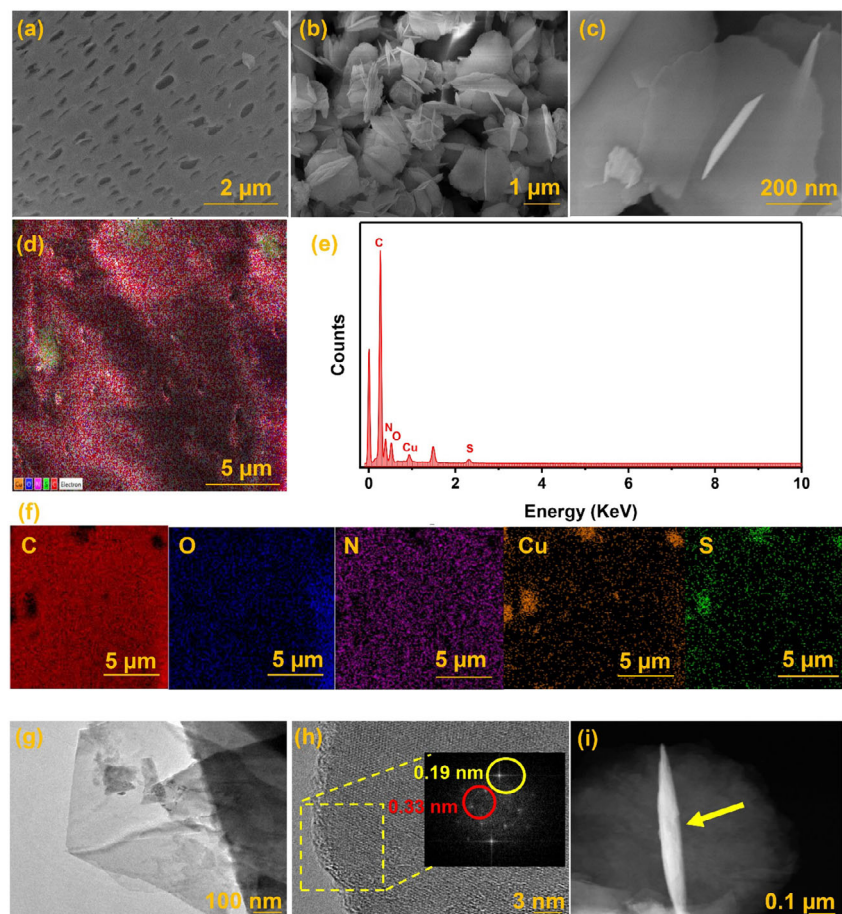


FIGURE 3 | (a) SEM image of CF. (b,c) SEM images of CuS nanoflakes on CF. (d–f) SEM–EDS mass sum spectrum and elemental mapping of CuS–CF. (g,h) TEM and HR-TEM of CuS nanoflakes. (i) STEM–HAADF of CuS nanoflakes. CF = carbon foam; EDX = energy-dispersive X-ray spectroscopy; HAADF = high-angle annular dark field; HR-TEM = high-resolution transmission electron microscope; SEM = scanning electron microscope; STEM = scanning transmission electron microscope; TEM = transmission electron microscope.

the asymmetric stretching vibration of —NH . The peak for the stretching vibration of COOH is observed at 1720 cm^{-1} , while the graphitic structure is confirmed by the presence of C=N stretching and benzene vibration. Furthermore, the presence of oxygen in the graphitic CF skeleton is also confirmed by the presence of small peaks related to C—O bonds at 1114 and 1280 cm^{-1} . The functional groups in CF matched well with the reported studies on CF [21, 32]. Interestingly, FTIR analysis of the CuS–CF sample shows the advent of new peaks absent in pure CF. The additional peak at 617 cm^{-1} ascertains the successful growth of CuS nanoflakes (Figure 5a). Wang and coworkers reported the growth of CuS on a graphene scaffold and reported similar peak observations for CuS [36, 37]. Moreover, there is no major distortion in the functional groups of graphitic CF after functionalization with CuS nanocrystals, suggesting that the growth of CuS did not alter the structure of the CF platform.

An efficient solar steam generator must have the following characteristics: high light absorption, low thermal conductivity, and porous channel morphology to facilitate the escape of vapors. Almost half of the solar radiation energy lies in the IR region, and IR absorbing material should have an enhanced capacity to harvest radiation in the IR region for photothermal application [37]. Focusing on the basic principle for good performance of synthesized CF and CuS–CF, the light absorption properties of

the CF, CuS, and the CuS–CF composite were measured (Figure 5b). The obtained results showed the excellent light absorption of CF powder in the UV–vis region (more than 95%) while a decrease in absorption toward the NIR region (from 95% to 72%, Figure 5b) was reported. Similar optical absorption has been reported for CF powder for solar steam generation [21]. The CF-functionalized with the CuS Covellite phase exhibited more than 95% steady light harvesting from UV–vis toward NIR region, indicating the successful enhancement of light absorption due to the CF functionalization with CuS. Bumping of material efficiency for enhanced optical absorption of CuS–CF was achieved due to the local surface plasmon resonance (LSPR) of the Covellite phase of CuS which leads to free carrier. The conductive oscillation of conduction electrons generated the LSPRs effect after interaction with photon radiation. Our result here agrees with the report of Tao et al. who stated that Covellite CuS shows optical absorption in the visible region (maximum around 650 nm) due to the LSPRs of the free carrier (holes) [33]. Covellite CuS is a p-type semiconductor that shows localized surface plasmonic absorption in the NIR region [38]. The nanoflakes of Covellite CuS generate the free holes, which are directly attributed to the cation vacancies due to copper deficiency. The other phases Anilite ($\text{Cu}_{1.75}\text{S}$), Digenite ($\text{Cu}_{1.8}\text{S}$), Djuleite ($\text{Cu}_{1.96}\text{S}$), and Chalcocite (Cu_2S) do not present LSPRs effect due to the high copper concentration [33, 39].

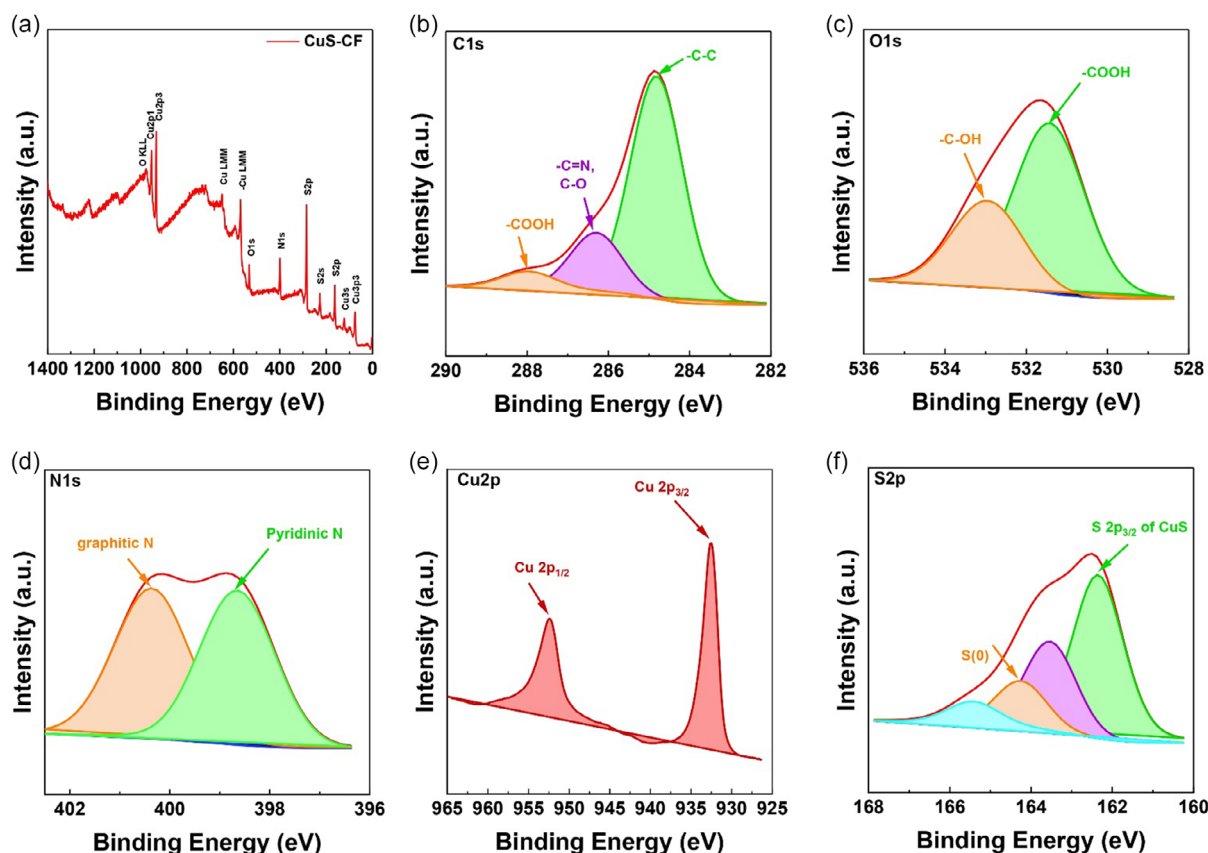


FIGURE 4 | (a) XPS spectrum of CuS-CF. High-resolution (b) C1s, (c) O1s (d)N1s (e) S2p and (f) Cu2p spectrum of CF. CF = carbon foam.

The solar thermal desalination experiment was conducted under simulated solar light (AM 1.5G 1 Sun irradiation) by depositing the synthesized CF powder, CuS, and CuS-CF on the glass micro-fiber membrane. The evaporation rate of solar evaporators (CF, CuS, and CuS-CF) and glass microfiber under 1 Sun irradiation and in the dark is presented in Figure 6. Before running the solar desalination experiment, the surface temperatures of photothermal membranes were measured under dry conditions under 1 Sun irradiation using a photothermal camera. A steady temperature is reached after less than 5 min of irradiation for investigated samples. The maximum surface temperature of 75.1°C was achieved in the case of CuS-CF sample compared to CF

powder and CuS (68°C and 62.8°C) Figure 6a,b. The results are presented in Figure 6b and illustrate the continuous and rapid increase in surface temperature to an asymptotic level reached after less than 5 min of irradiation. In the case of the CuS-CF sample, the rapid increase of the temperature can be attributed to the LSPRs effect of the CuS Covellite phase and the architecture of CF that prevented loss of heat. The obtained dry surface temperature 75.1°C was achieved higher than that recently reported cobalt and nickel selenite hydrates (67 and 57°C) [23]. The wet surface temperatures of CF, CuS, CuS-CF materials were also presented in Figure S4, Supporting Information. The surface temperature during photothermal

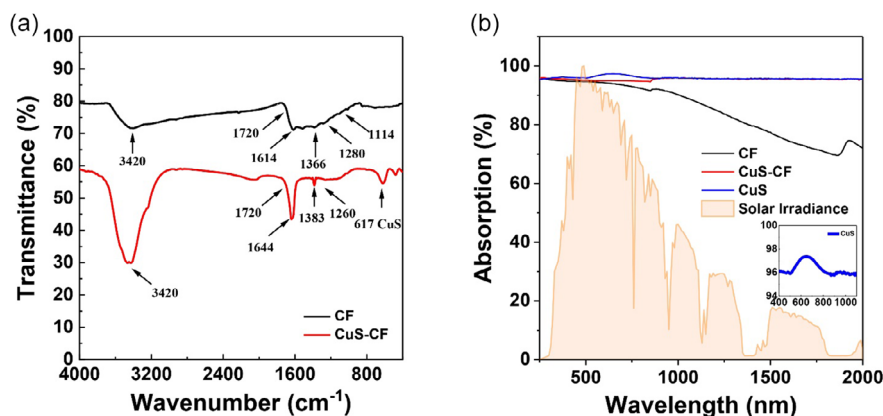


FIGURE 5 | (a) FTIR and (b) UV-vis absorption spectra of CF- and CuS-functionalized CF. CF = carbon foam and FTIR = Fourier transform infrared spectroscopy.

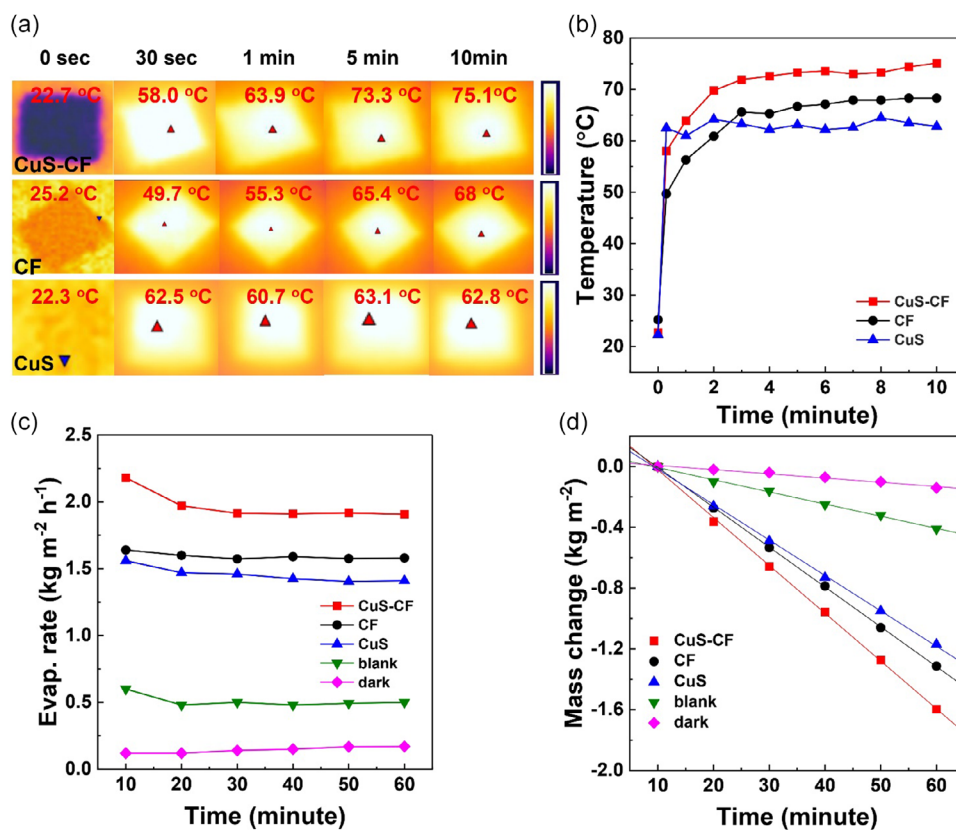


FIGURE 6 | (a,b) Thermal images and rise in the dry surface temperature of the membranes, (c) evaporation rate, and (d) change in mass of CF, CuS, and CuS-CF membrane under 1 Sun radiation during photothermal desalination process. CF = carbon foam.

desalination was significantly higher for CuS-CF (41.4°C) compared to the literature reported for CuS membranes (35.2°C) under 1 Sun radiation [33].

The solar thermal experimental results presented an excellent average evaporation rate for CF (1.58 kg m⁻² h⁻¹) and an even further enhanced evaporation rate for CuS-CF (1.90 kg m⁻² h⁻¹, Figure 6c) compared to CuS (1.41 kg m⁻² h⁻¹). The excellent water evaporation rate was achieved due to the existence of pores in the CF shown in surface morphology images obtained with SEM (Figure 3a), enhancing the capillary movement of water. Moreover, the presence of hydrophilic oxygen and nitrogen groups helps to boost water transport toward the photothermal layer along with capillary action through the pores in CF to allow water vapors escape during interfacial evaporation. A similar mechanism has been reported in the literature for CF powder on polyvinylidene fluoride (PVDF) membrane which demonstrated an evaporation rate of 1.62 kg m⁻² h⁻¹ [24]. The present study revealed a promising average evaporation rate of 1.58 kg m⁻² h⁻¹ for bare CF powder on glass wool membrane compared to the recently reported evaporation rate of 1.27 kg m⁻² h⁻¹ for CF powder on PVDF membrane [21]. An enhanced evaporation rate of 1.90 kg m⁻² h⁻¹ has been achieved for CuS-CF compared to CF due to hydrophilic nanoflakes decoration which provides an LSPRs effect. The change in mass (kg m⁻²) of water during the desalination experiment was recorded and presented a continuous reduction in mass (Figure 6d). This effect demonstrated the salt resistance efficiency of a synthesized photothermal generator with the capacity of

pores capability in CF to facilitate water transport [21]. The present investigation shows a remarkable enhancement in the evaporation rate of CuS-CF (1.90 kg m⁻² h⁻¹) compared to the previously reported evaporation rate of CuS nanoflowers on semipermeable colloidal membranes that reported evaporation rate as 1.09 kg m⁻² h⁻¹ under 1 Sun radiation. The hydrophilicity of the solar evaporator plays a significant role in the evaporation rate [33]. The contact angle measurements presented in Figure 7a show the rapid absorption of water droplet in less than a second for both CF and CuS-CF. This experimental evidence indicates that the Covellite CuS semiconductor has a hydrophilic character and does not negatively affect the hydrophilicity of the CF. The high hydrophilicity of the material was achieved due to the presence of oxygen and nitrogen in the graphitic skeleton of CF.

The experiment for the sample CF and CuS-CF was repeated three times and the mean evaporation rate with standard error bar is presented in Figure 7b. Moreover, the DSC analysis was carried out to calculate the water vaporization enthalpy to evaluate the energy consumption of water (heat flow versus temperature) that is required to investigate the reason underlying the evaporation efficiency of the best-performing sample CuS-CF. The analysis was carried out at 5°C/min and it gives water vaporization enthalpy of 1897 J/g. Evaporation efficiency (η) is calculated by using the following equation

$$\eta = \frac{\dot{m}h_{lv}}{C_{opt}q_i} \quad (1)$$

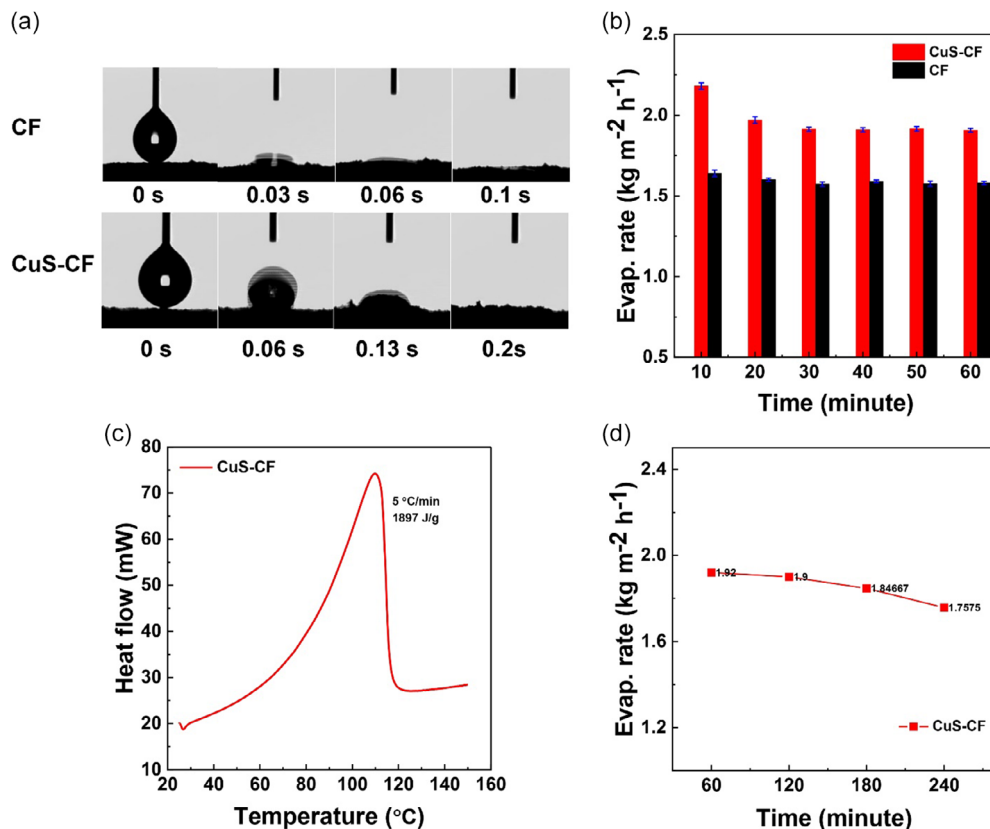


FIGURE 7 | (a) Contact angle measurements, (b) average evaporation rate of CF and CuS-CF with error bar, (c) DSC analysis of CuS-CF, and (d) stability test of CuS-CF. CF = carbon foam and DSC = differential scanning calorimetry.

where $\dot{m}$ is the mass flux $\text{kg m}^{-2} \text{s}^{-1}$, h_{lv} is enthalpy of liquid to vapor phase change, and C_{opt} is optimal concentration and q_i is solar radiation (1 KW/m^2). The results revealed an excellent evaporation efficiency of 91% proving the performance of CuS-CF as the solar evaporator. The CuS-CF solar evaporator ascribed excellent evaporation efficiency of 91.17% compared to literature reported efficiency of CF/PVDF 53% and CuS/SCM 68.6% [19, 31]. Stability tests of CuS-CF were performed to investigate the effect of salt accumulation on evaporation rate. The schematic diagram of the experimental setup and real photos of the experiment are presented in Figure S5a,b, Supporting Information. The photographs of solar evaporators before and after the desalination experiment presented in Figure S5c, Supporting Information,

show that there is no salt crystal present on the surface of solar evaporators but slight decrease in evaporation rate is noted that might have occurred due to salt accumulation in cotton sponge that works as a water transport channel. By comparing the obtained results from the CuS-CF sample with the recently reported carbon- and copper-based solar evaporators, the present study provides a significantly higher evaporation rate, as reported in Table 1. The successful enhancement of the evaporation rate can be ascribed to the combined effect of the hydrophilic graphitic CF micropores, which facilitate water transport, preventing heat losses due to the low thermal conductivity of CF, along with the photothermal properties of Covellite CuS-CF, which lead to strong solar light absorption and enhanced evaporation rate.

TABLE 1 | Comparison of present study evaporation rate with recently reported solar evaporators.

Photothermal material	Evaporation rate ($\text{kg m}^{-2} \text{h}^{-1}$)	Surface temperature (dry, °C)	Reference
Carbon foam/PVDF	1.27	75	[21]
CuS nanoflowers	1.09	35	[33]
Chitin/CuS composite	1.52	84.1	[31]
Cu_2SnSe_3	1.62	40.1	[40]
Wood CNT	0.95	36.2	[41]
Fe_3O_4 at polydopamine	1.002	47	[42]
Graphene oxide aerogel	1.39	40	[19]
CuS nanoflakes/carbon foam	1.90	75.1	Present study

3 | Conclusion

Interfacial solar desalination is an appealing technology to produce freshwater. In this study, we upcycled the waste PET plastic into graphitic CF and we further functionalized it with 2D Covellite CuS nanoflakes to enhance the evaporation rate. The morphology and structure of the material produced have been clearly defined using techniques such as XRD, SEM, HR-TEM, STEM, XPS, and EDS. The LSPRs effect on Covellite CuS remarkably enhanced the capacity of CF to harvest solar radiation, reaching more than 95% absorption from the UV/vis to NIR region. The CuS/CF showed an enhanced evaporation rate of $1.90 \text{ kg m}^{-2} \text{ h}^{-1}$ compared to the bare CF ($1.58 \text{ kg m}^{-2} \text{ h}^{-1}$) with an evaporation efficiency of 91.17%. This work suggests a very promising sustainable development of new photothermal materials from waste plastic, combined with functionalization with low-cost plasmonic metals for freshwater production via interfacial solar desalination. This strategy may help to mitigate the water and plastic crises, enabling the upcycling of plastic wastes in a circular economy model.

4 | Experimental Section

4.1 | Reagent and Chemicals

All the chemicals and reagents that are used in this study were purchased from Sigma Aldrich, NaCl, ZnCl_2 , melamine, HCL, $\text{CuNO}_3 \cdot 3\text{H}_2\text{O}$, and thiourea.

4.2 | Synthesis of CuS-CF

Initially, the CF (yield = 35.95%) was prepared by the already reported method, 1.5 g of the waste PET bottle sheets was mixed with 3 g $\text{ZnCl}_2/\text{NaCl}$ (58/42 wt%) and 0.75 g of melamine, the mixture was pyrolyzed in a muffle furnace at 340°C for 30 min with a heating rate of 10°C . After that, the obtained black foam was washed using dilute 0.5 M HCl and deionized water until pH neutral. Finally, the obtained CF was dried in an oven at 50°C overnight, packed, and labeled as CF. After the successful synthesis of CF, the CuS was decorated by following the already reported method, 0.2 mmol of $\text{CuNO}_3 \cdot 3\text{H}_2\text{O}$, 2 mmol of thiourea and 0.15 g of CF powder were stirred in 80 ml of deionized water for 20 min. Then, the prepared mixture was added to a Teflon-autoclaved for hydrothermal treatment for 12 h at 120°C , with a filling ratio 3:1. Finally, the obtained black powder was centrifuged and washed with deionized water and ethanol, and the powder material dried at 50°C overnight and labeled as CuS-CF. The same procedure was used for the synthesis of CuS without the addition of CF.

4.3 | Characterization

The XRD analysis for synthesized samples was performed using on a Philips PW1050/37 diffractometer. XPS measurements were carried out on a PHI Versa Probe II Scanning XPS Microprobe spectrometer using a monochromatic Al $K\alpha$ radiation as the excitation source (200 μm diameter, 25.0 W, 15 kV, 1486.6 eV).

The SEM-EDX analysis was performed with a Zeiss SUPRA 35VP field-emission SEM with acceleration voltage 5–20 kV coupled with an EDS (Oxford Instruments, INCA) at 20 kV. HR-TEM and high-angle annular dark field (HAADF)-STEM micrographs were recorded via Tecnai F20T TEM FEI equipped with a 200 kV Schottky emitter. The TEM is equipped with a MSC794 Gatan CCD camera, a Fischione HAADF-STEM detector, and a double-tilt sample holder. The elemental analysis was carried out by EDS, coupled with STEM-HAADF to map elemental distribution. The IR spectrum was recorded with an FTIR spectrometer (Nicolet 6700 FT-IR Spectrometer). The UV/vis spectroscopy measurements were carried out using ultraviolet-visible spectrophotometer LAMBDA 1050⁺, Perkin Elmer, with an integrating sphere. The contact angle measurements was carried out using the FTA 1000 Analyzer System with $1 \times 1 \text{ cm}$ piece from the already prepared membrane for the photothermal desalination experiment. Differential scanning calorimetry (DSC) analysis was performed using a 1020 Series DSC 7 thermal analysis system and the temperature range was selected as $20\text{--}150^\circ\text{C}$ at $5^\circ\text{C}/\text{min}$.

4.4 | Solar Evaporation Test

The solar evaporation experiment for CF and CuS-CF powder was conducted under 1 Sun radiation separately with a relative humidity 34.8%; the 0.1 g of synthesized material was sonicated for 10 min and deposited on a glass microfiber membrane using vacuum filtration and the membrane was dried in the oven at 60°C . The 45 ml of brine solution in a 50 ml beaker was taken along with a cotton sponge that facilitated saline water transport and the beaker was covered with polyethylene foam as a thermal insulator. A piece of membrane $1 \times 1 \text{ cm}$ was placed on a cotton sponge and the experiment was carried out to measure the dry and wet surface temperature and evaporation rate for 1 h under 1 Sun radiation using the solar simulator. The change in mass was calculated by using an analytical balance and solar evaporation was calculated with the following equation:

$$\text{Evaporation rate} = \Delta m / S \times \tau \quad (2)$$

where Δm is the mass loss of water (kg), S is the area of the evaporation (m^2), and τ is the evaporation time (h).

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The authors have nothing to report.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Table of Content**Decoration of Two-Dimensional CuS Nanoflakes on Graphitic Carbon Foam Derived from Waste Plastic for Interfacial Solar Desalination**

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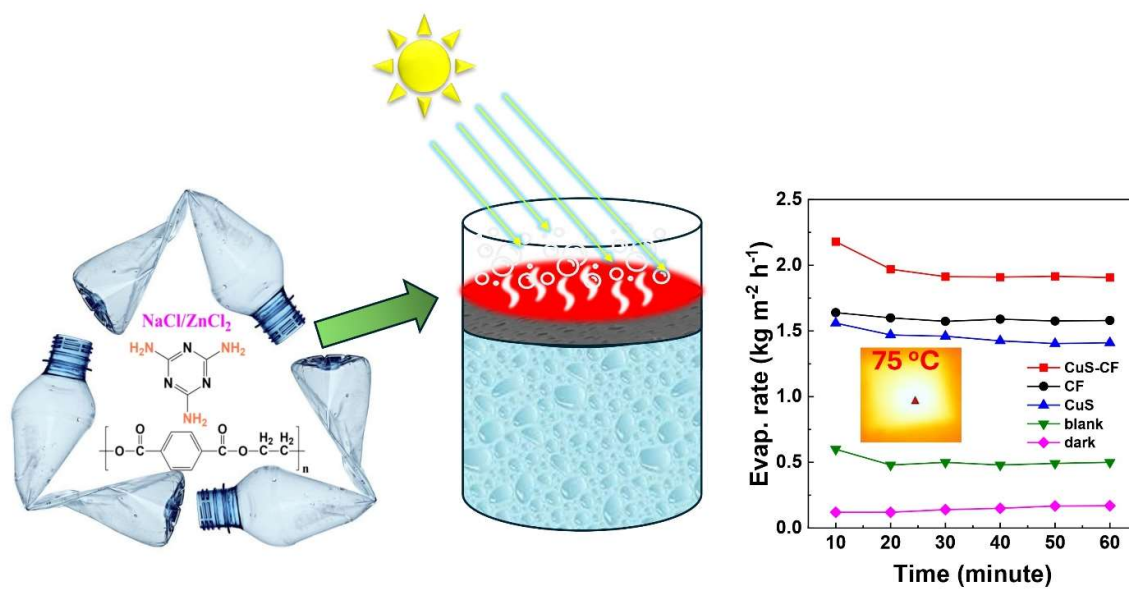
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Supporting Information

Decoration of Two-Dimensional CuS Nanoflakes on Graphitic Carbon Foam Derived from Waste Plastic for Interfacial Solar Desalination

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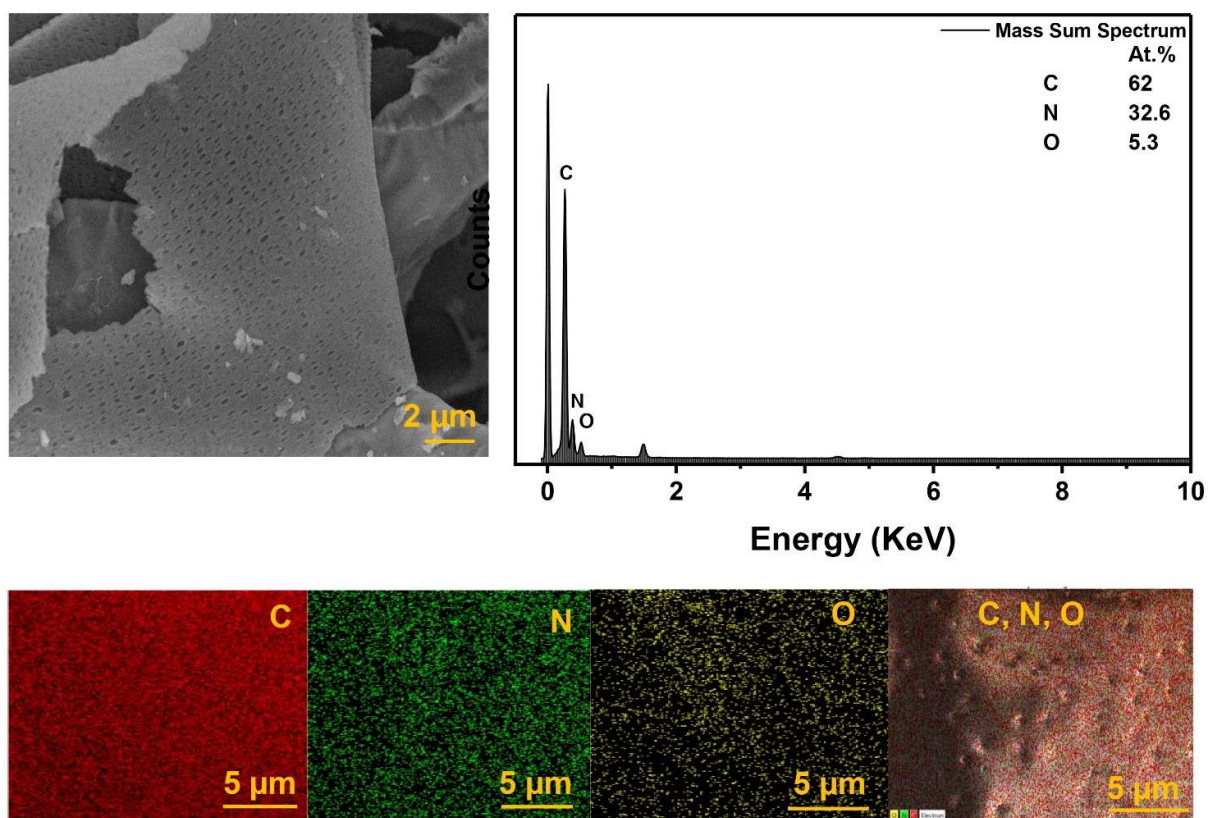


Figure S1. FE-SEM images, EDS spectra and elemental mapping of carbon foam

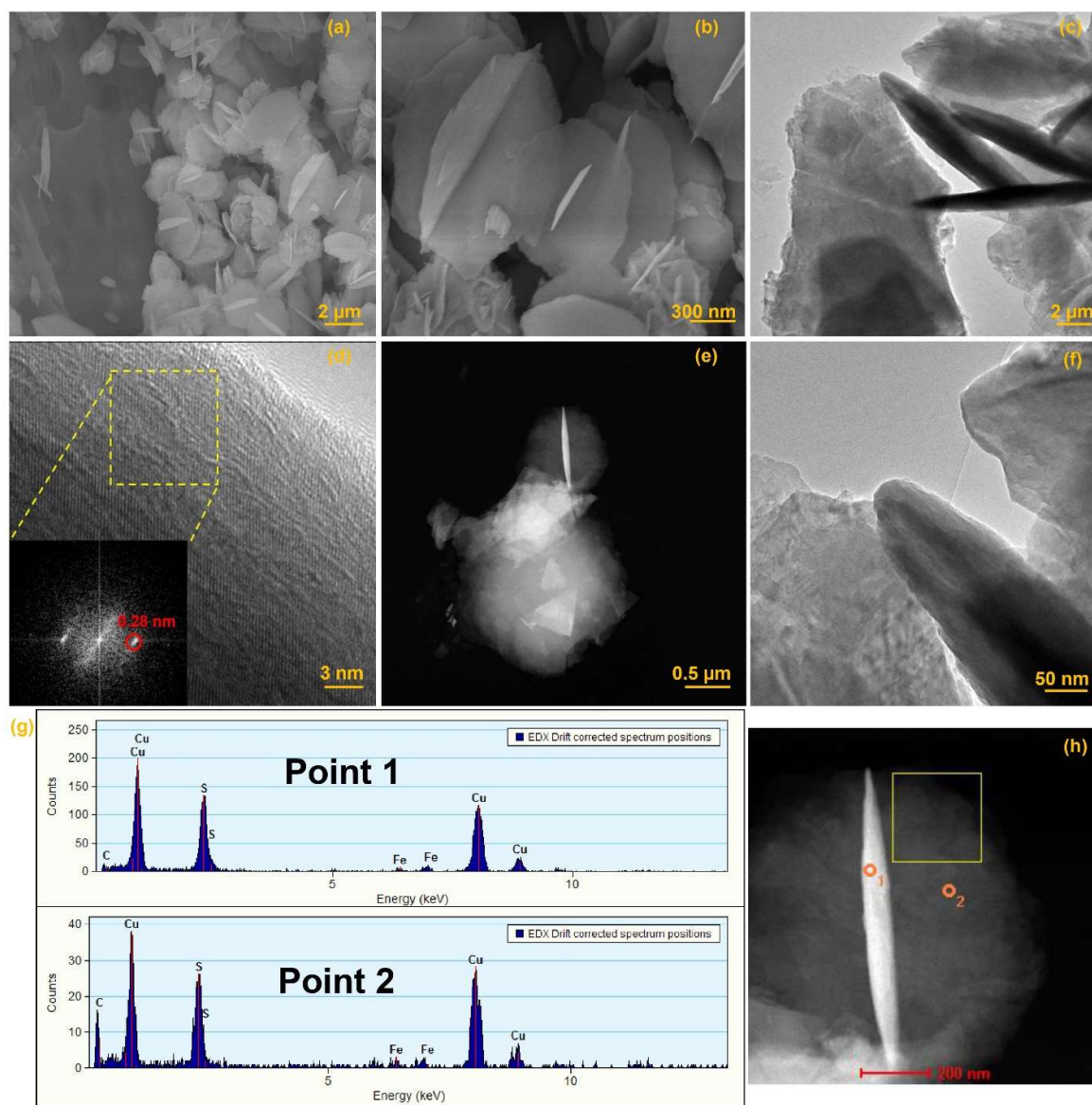


Figure S2. SEM, TEM, HM-TEM , HAADF -STEM, EDS analysis CuS nanoflakes functionalized carbon foam

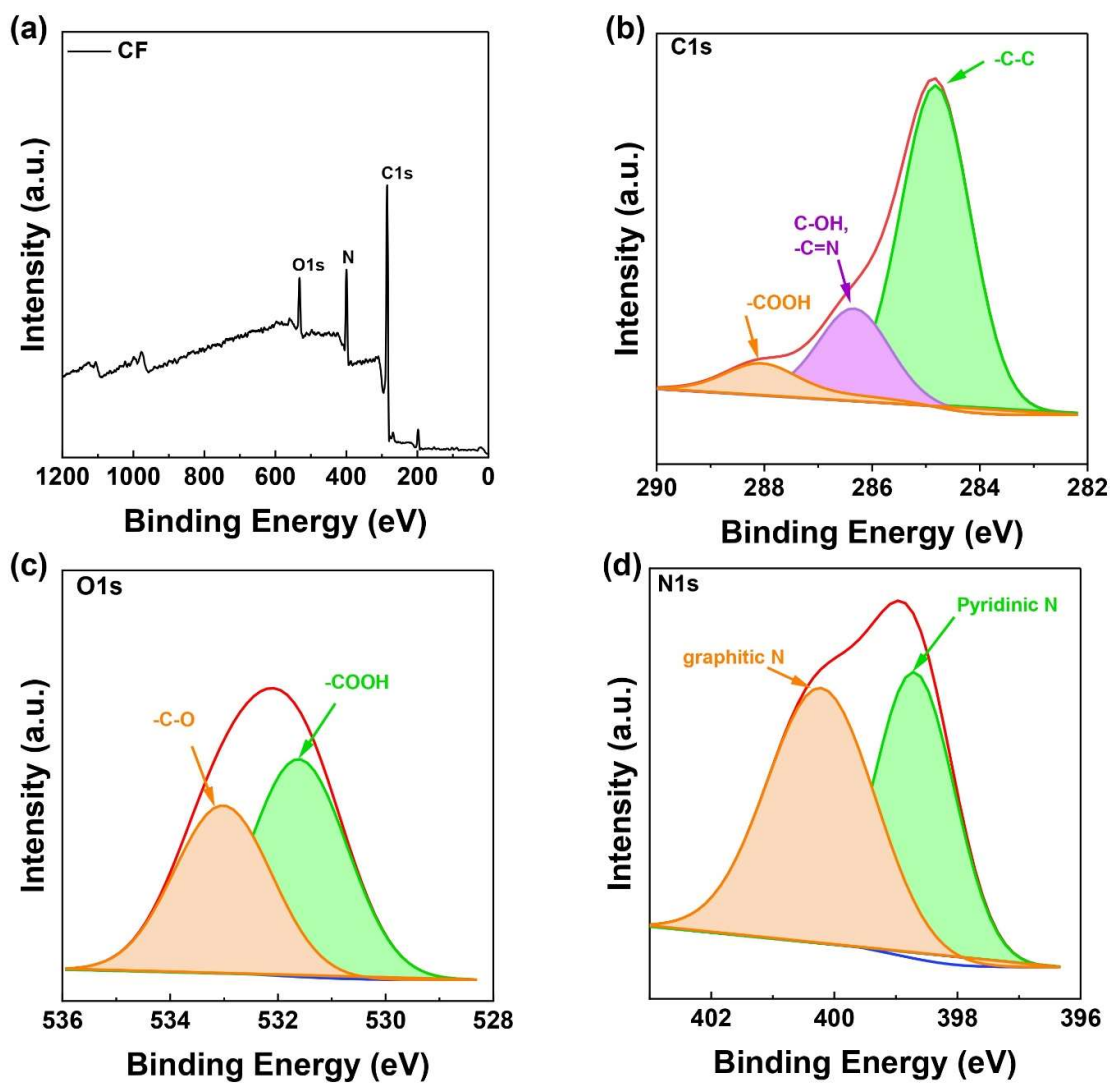


Figure S3. (a) XPS spectrum of CF. High-resolution (b) C1s, (c) O1s, and (d) N1s XPS spectrum of CF

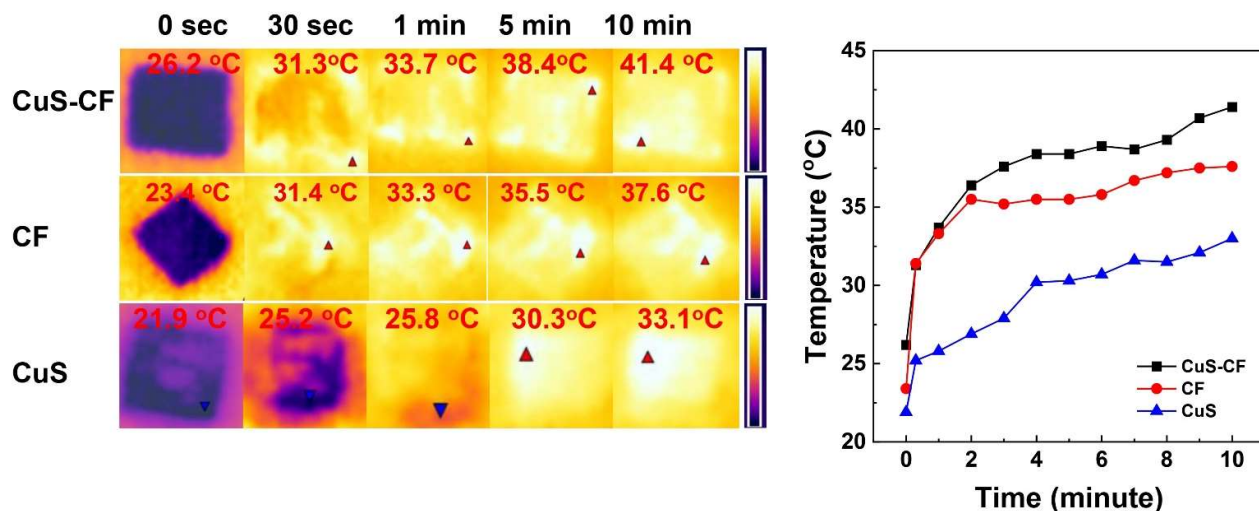


Figure S4. Wet surface temperature of carbon foam CuS and CuS functionalized carbon foam membrane under one sun radiation during the desalination process.

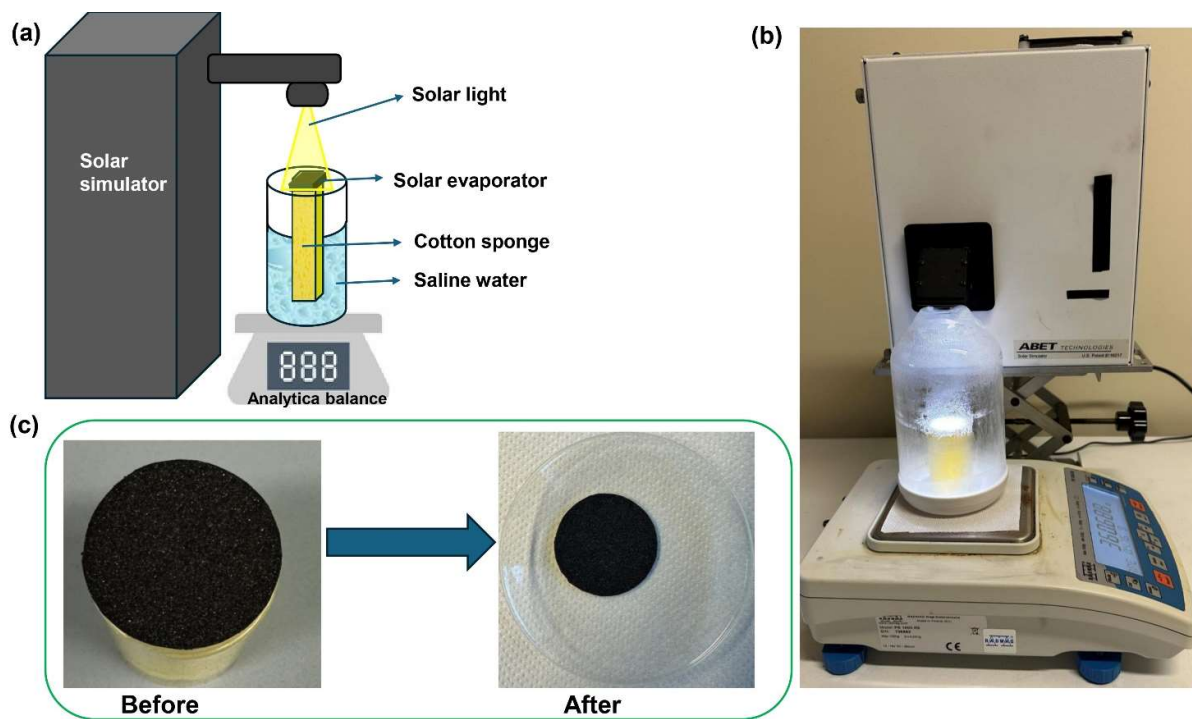


Figure S5: (a) Schematic diagram of solar evaporator and experimental setup (b) and (c) experimental setup for salt accumulation experiment and solar evaporator surface images before and after solar desalination.

Enhanced Solar Water Desalination by CuCo_2S_4 -decorated Carbon Foam Derived from Waste Plastics

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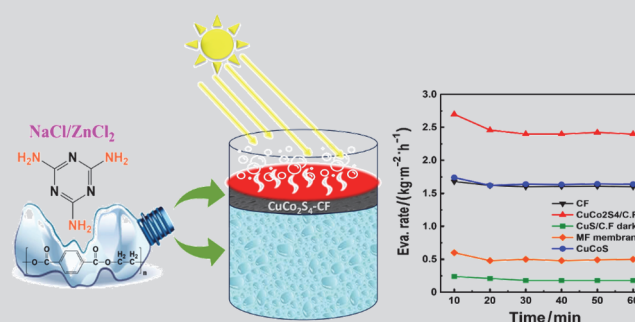
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Interfacial solar desalination is an emerging technology for freshwater production, but the finding of novel solar evaporators is still challenging. In the present research, graphitic carbon foam (CF) was synthesized from the upcycling of waste plastic polyethylene terephthalate (PET) waste bottles functionalized with carrollite CuCo_2S_4 as a photothermal layer. Analytical characterization [X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), and scanning electron microscopy-energy dispersive spectroscopy (SEM-EDS)] confirms the functionalization of carrollite CuCo_2S_4 on graphitic carbon foam. The UV-Vis spectroscopy analysis showed an enhanced optical absorption in the UV-Vis-near IR region (>96%) for functionalized CuCo_2S_4 -CF foam compared to carbon foam (67%). The interfacial solar desalination experiment presented a significantly enhanced evaporation rate of $2.4 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ for CuCo_2S_4 -CF compared to that of CF ($1.60 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) and that of CuCo_2S_4 ($1.60 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$).

The obtained results proved that the newly synthesized CuCo_2S_4 -CF from the upcycled plastic into new material for the photothermal desalination process can enhance the practice of a circular economy to produce fresh water.



Keywords Photothermal desalination; Cobalt; Copper; Chalcogenide; Waste upcycling; Circular economy

1 Introduction

Water is the most essential need for all living organisms, but with the limited resources of freshwater and increasing commercial and industrial sectors, freshwater availability is under high threat. Water desalination of widely available seawater resources will significantly help to fill the gap of water shortage with techniques, such as membrane desalination, thermal desalination, and emerging desalination. However, these techniques are still not favorable due to energy consumption and environmental impact.^[1] Solar energy is the most cost-effective source of renewable energy, and interfacial solar desalination has

gained much attention in water management.

To enhance the evaporation rate, the engineering of the interfacial solar evaporators relies on two major factors: a solar absorber and a substrate.^[2] For enhanced evaporation rate, the ideal solar absorber should absorb maximum solar radiation and convert it into thermal energy, and an efficient substrate should be highly hydrophilic and prevent thermal energy loss.^[3,4] Moreover, a material for interfacial solar desalination should be cost-effective with as low as possible environmental impact. For this reason, recently some carbon-based materials, such as graphene oxide,^[5,6] graphene aerogel,^[7] and carbon nanotubes (CNTs)^[8] have been reported for solar desalination. Unfortunately, these materials are not very efficient due to low solar-to-thermal conversion, low evaporation rate, and high cost of production for materials, such as graphene aerogel.

Therefore, considering the sustainability goals, waste plastics can be a good raw material to upcycle into new viable material and to enable the circular economy.^[9] In fact, it is one of the major causes of the global white pollution crisis, because most of the plastics end up as waste, polluting the environment. According to a recent environmental survey, global greenhouse gas emissions would grow by 31% from 2015 to the end of 2030.^[10] To deal with this ever-increasing environmental issue, various strategies, such

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as landfill, mechanical, and chemical recycling, and incineration were adopted. However, landfill and incineration faced much criticism due to production of secondary pollutants, while mechanical and chemical recycling got much attention for reducing greenhouse gases. Recently some studies have been reported for the upcycling of waste plastic into carbon foam (CF) for interfacial solar desalination that provided a significantly enhanced evaporation rate,^[11–13] compared to other carbon-based materials, such as graphene, carbon nanotube (CNT) and carbonized carbon black. Carbon foam has appealing characteristics, such as porous structure and rough morphology, low thermal conductivity, and high water transport due to porous microchannels.^[11]

In the past decades, the semiconductor functionalized carbon materials have been intensively studied for photocatalytic, photovoltage, and synergetic functions of photothermal applications.^[14] Recently, cobalt and copper-based nanostructures, such as $\text{Co}_3\text{O}_4/\text{PDA-rGO}$ (GO: graphene oxide), CoSb_3 , Co@C/NCNT (NCNT: nitrogen-doped carbon nanotube), cuprous telluride, and Cu-GO , gained much attention for photothermal applications due to localized surface plasmonic resonance.^[15–19] Furthermore, sulfide-based materials are extensively studied for numerous energy and environmental applications, where the engineering of nanostructures plays a key role in catalyst performance.^[20–23] The ternary cobalt copper sulfide (Co_2CuS_4), a thiospinel nanostructure, has been recently studied for its excellent performance for supercapacitors, solar cells, lithium-ion batteries. The appealing thermal stability, and controllable morphology of CuCo_2S_4 makes it an excellent candidate for photocatalytic applications in dye degradation and hydrogen evolution.^[24–27]

In the present research work (Fig. 1), we upcycled the waste polyethylene terephthalate (PET) material into graphitic CF and further functionalized it with carrollite CuCo_2S_4 . The rationale for focusing on carrollite is due to its excellent track record in photocatalytic pollutant degradation,^[26] hydrogen evolution,^[27] and photothermal

application.^[28] Despite these applications, it has not yet been reported as an active material for interfacial solar desalination. Accordingly, we controllably synthesized CuCo_2S_4 and integrated it with CF upcycled from environmental plastic wastes and obtained an excellent result that can be substantiated by the enhanced evaporation rate and surface temperature. This work aligns with the global circular economy and gives a fresh insight into the sustainable development of photo-active material for interfacial solar desalination to produce clean water.

2 Experimental

2.1 Reagent and Chemicals

All the chemicals and reagents used in this research work, such as $\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$, $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, NH_4OH , NaCl , ZnCl_2 , melamine, HCl , and thiourea were purchased from Sigma Aldrich.

2.2 Synthesis of CuCo₂S₄-CF

Initially, CF was synthesized by following the already reported procedure:^[11] 1.5 g of waste PET bottle sheets were mixed with 3 g of eutectic salt [ZnCl₂/NaCl (58/42, mass ratio)], and 0.75 g of melamine. Then the mixture was placed in the muffle furnace and calcined at 340 °C for 30 min with a heating rate of 10 °C/min. After cooling to room temperature, the obtained black foam was mashed and washed using dilute HCl and deionized water repeatedly till neutral pH. Finally, the obtained carbon foam powder was dried in an oven at 50 °C overnight, packed, and labeled as CF. The solvothermal method was used to grow CuCo₂S₄ on the CF powder: in detail, 0.75 mmol of Cu(NO₃)₂·3H₂O and 1.5 mmol of Co(NO₃)₂·6H₂O were dissolved in 10 mL of distilled water followed by the addition of 0.15 g of CF powder, and then 25 mL of ethanol was added and sonicated

for 20 min. Then the mixture solution (pH 9) was maintained using ammonium hydroxide at room temperature with continuous stirring, as the mixture attained greenish color, 0.228 g of thiourea was added and the reaction continued for 12 h at 80 °C. The suspension mixture was transferred into a Teflon-lined stainless-steel autoclave and heated at 180 °C for 6 h. Finally, the obtained black powder was centrifuged and

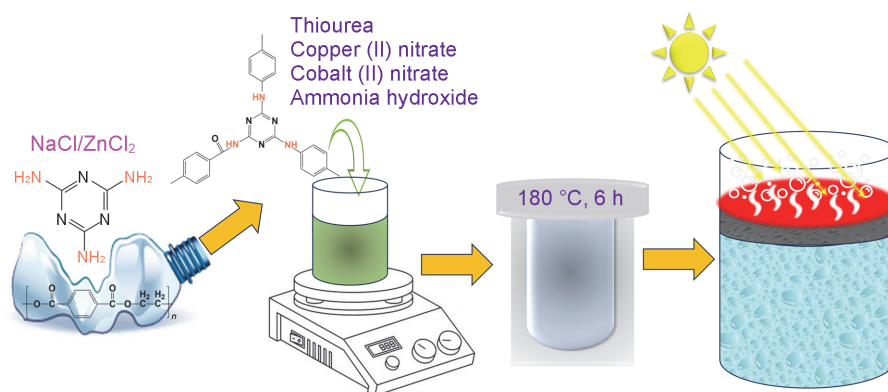


Fig. 1 Graphical synthesis illustration of CF and functionalization with carrollite CuCo_2S_4 on CF powder for interfacial solar desalination

washed with deionized water and ethanol, and the powder material was dried at 60 °C overnight. The pure CuCo_2S_4 was also prepared by using the same methodology without the addition of CF powder.

2.3 Characterization

The X-ray diffraction (XRD) analysis was performed using a Philips PW1050/37 diffractometer. The UV-Vis absorption spectroscopy measurements were carried out with an ultraviolet-visible spectrophotometer LAMBDA 1050⁺, Perkin Elmer with an integrating sphere. The scanning electron microscopy-energy dispersive spectroscopy (SEM-EDS) analysis was carried out using an FEI Magellan 400 FEG-SEM with an EDS detector (X-Max 80 mm² SDD, Oxford Instrument). The IR absorption spectrum was recorded with an Fourier transform infrared spectroscopy (FTIR) spectrometer (Nicolet 6700 FTIR Spectrometer) in transmission mode. The contact angle measurements were performed using an FTA 1000 Analyzer System. X-Ray photoelectron spectroscopy (XPS) was performed using an ESCALAB 250 (ThermoFisher Scientific, USA) with X-ray source monochromated Al K α , 150 W, 1486.6 eV, and energy pass of 200 eV for the survey and 30 eV for high-resolution scans.

2.4 Interfacial Solar Evaporation

For the interfacial solar desalination experiment, 0.1 g of powdered material of CF powder, CuCo_2S_4 , and CuCo_2S_4 -CF was sonicated for 5 min in 20 mL of deionized water and deposited separately on a glass microfiber filter (Whatman GF/F, CAT No. 1825-047) using vacuum filtration assembly. The membrane after the deposition of the material was dried at 60 °C. Then 40 mL of brine solution [0.6 mol/L NaCl solution in the deionized water that is 3.5% (mass fraction) average global seawater salinity] in a 50 mL beaker with a cotton sponge that facilitated saline water transport and polyethylene foam as a thermal insulator was used to cover beaker. Finally, the experiment for evaporation rate was conducted under one sun radiation (air mass 1.5 global, AM1.5G, 100 W/cm²) by placing a 1 cm×1 cm prepared membrane on a carbon sponge. The surface temperature of the membrane was recorded using a thermal camera (FLIR C3-X) for both the dry and wet stages. The change in mass was calculated by using an analytical balance and the

solar evaporation rate was calculated with the following equation:

$$\text{Evaporation rate} = \frac{\Delta m}{S} \times \tau$$

where Δm is the mass loss of water (kg), S is the area of the evaporation (m²), and τ is the evaporation time (h).

3 Results and Discussion

3.1 Characterization

3.1.1 XRD Analysis

The as-synthesized graphitic CF, CuCo_2S_4 , and CuCo_2S_4 -CF decorated CF powder were characterized by XRD over the angular range (10°–80°) to examine their phase and crystal structure. The diffraction peaks for CF (Fig. 2A) show the corresponding diffraction plane (002) (JCPDS: 41-1487) that indicated the graphitic structure of synthesized CF. The broad peak in the 2θ range of 18°–32° pertains to reflection from (002) plane.^[11] The XRD patterns of CuCo_2S_4 and CuCo_2S_4 -CF exhibit peaks at $2\theta=16.1^\circ$, 26.5° , 31.27° , 37.96° , 46.99° , and 49.96° , corresponding to crystal planes (111), (022), (113), (004), (224), and (115) of carrolite (JCPDS: 42-1450) (Fig. 2B). It is important to note that both CuCo_2S_4 and CuCo_2S_4 -CF resulted in a similar XRD pattern, suggesting that CF as matrix does not affect the growth of carrolite CuCo_2S_4 .

3.1.2 SEM Analysis

The surface morphologies of the synthesized graphitic CF powder, CuCo_2S_4 , and CuCo_2S_4 -CF were analyzed at different magnifications. The SEM images of graphitic CF present the open-cell interconnected pores on the surface that were generated due to the physical template of molten salt (Fig. 3). Similar surface morphology has been reported in a recent investigation for waste plastic-derived CF.^[13]

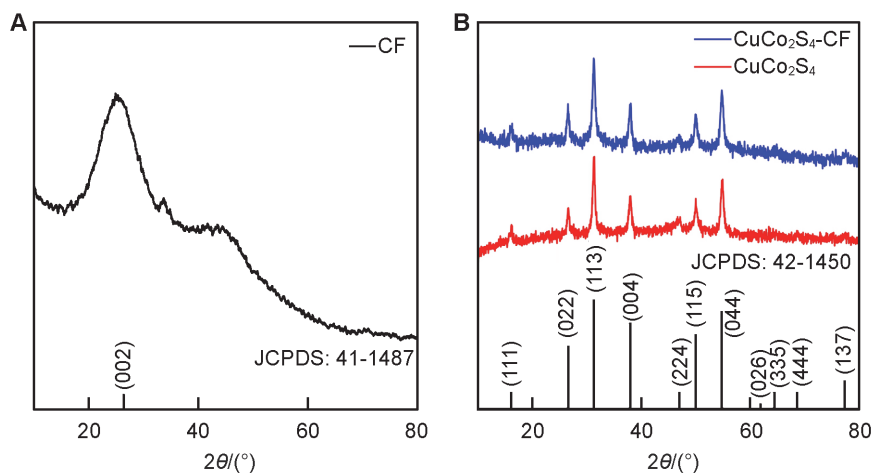


Fig. 2 XRD patterns of graphitic CF (A), and CuCo_2S_4 and CuCo_2S_4 -CF (B)

Moreover, the flat sheet presents the existence of multilayer graphitic sheets in the architecture of CF and these results show good agreement with the reported morphology of CF.^[12,29] The SEM images for the CuCo_2S_4 show the agglomerated nanobeads like morphology (Fig. S1, in the Electronic Supplementary Information, ESI) and similar nanobeads were illustrated for CuCo_2S_4 -CF that clearly present the no effect on morphology with functionalization of CuCo_2S_4 on CF matrix (Fig. 3). The elemental compositions of CF, CuCo_2S_4 , and CuCo_2S_4 -CF were investigated using EDS equipped with FE-SEM. EDS spectra show the elemental composition of sample CF (Fig. 3, carbon, nitrogen, oxygen), CuCo_2S_4 (Fig. S1, copper, cobalt, sulfur), CuCo_2S_4 -CF (Fig. 4, carbon, nitrogen, oxygen, copper, cobalt, sulfur) and elemental mapping shows the uniformity of elemental distribution on CF matrix.

3.1.3 FTIR Analysis

The FTIR analysis was performed to analyze the functional group/bonding nature of the as-synthesized CF and CuCo_2S_4 -CF (Fig. 5A). The stretching vibration of $-\text{OH}$ and the asymmetric stretching vibration peaks are observed at 3430 cm^{-1} . The stretching vibration of $\text{C}-\text{H}$ and COOH is responsible for the peaks at 3200 and 1720 cm^{-1} , respectively. The peaks appearing at 1630 and 1380 cm^{-1} correspond to $\text{C}=\text{N}$ stretching vibration and benzene stretching vibration. The obtained FTIR spectrum for the synthesized CF agrees with the recently reported spectrum of carbon foam.^[11] In the case of functionalized CF with CuCo_2S_4 ,

the additional peaks at 617 and 475 cm^{-1} correspond to symmetric and asymmetric stretching vibrations of $\text{Cu}-\text{S}$, and $\text{Co}-\text{S}$ and similar observation has already been

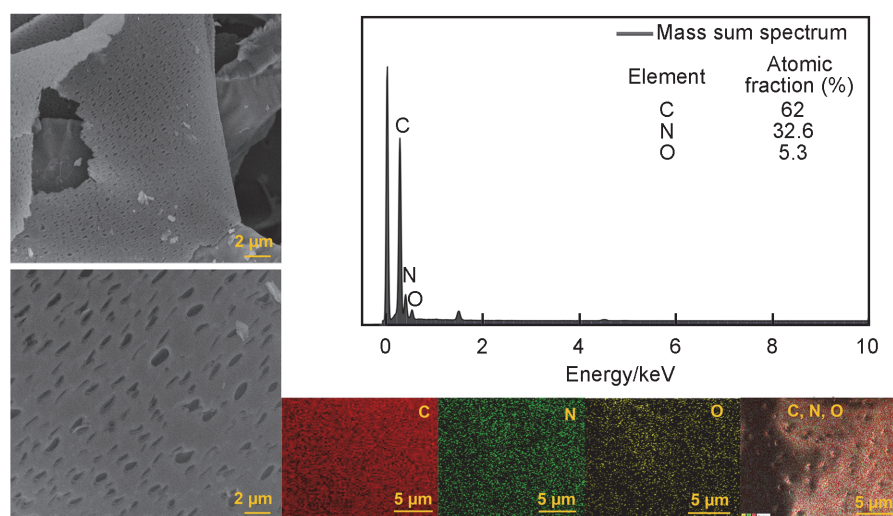


Fig. 3 SEM-EDS analysis of CF

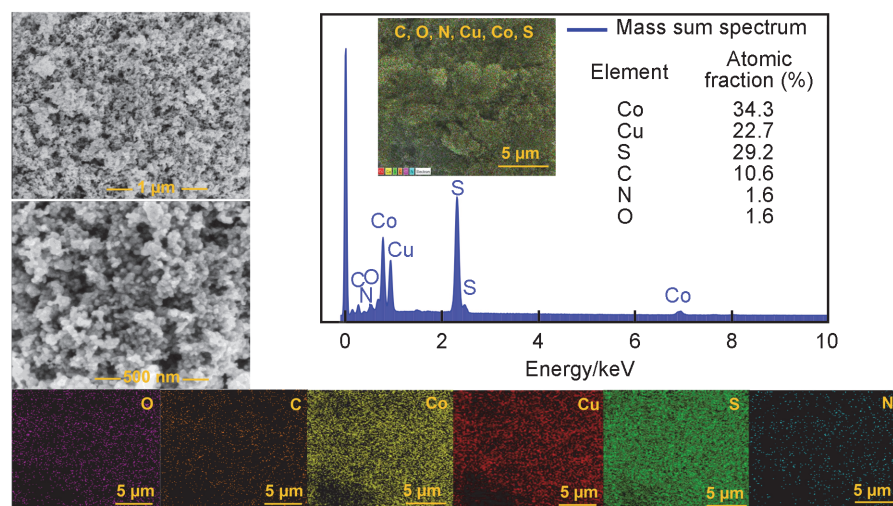


Fig. 4 SEM-EDS analysis of CuCo_2S_4 -CF

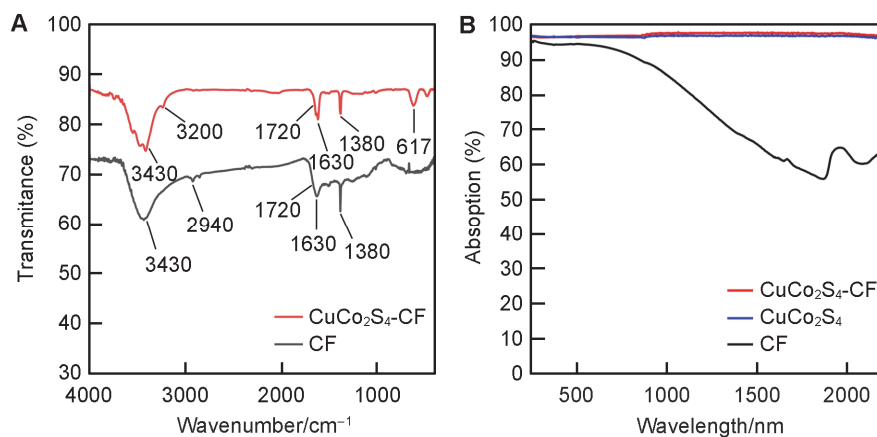


Fig. 5 FTIR spectra of CF and CuCo_2S_4 -CF (A) and absorption spectra of CF, CuCo_2S_4 , and CuCo_2S_4 -CF (B)

3.1.4 XPS Analysis

XPS was performed to analyze the chemical composition of the synthesized CF, CuCo_2S_4 , and $\text{CuCo}_2\text{S}_4\text{-CF}$. The XPS survey indicates the presence of C, N, and O in sample CF (Fig. S2, A and E in the ESI). The obtained binding energies of C 1s (deconvoluted peaks: C—N 288 eV, C=N 286.3 eV, and graphitic carbon C—C 284.8 eV), N 1s (graphitic N 400.2 eV and pyridinic N 398.7 eV), and O 1s (COOH 533 eV, and C—O 531.5 eV) confirmed the graphitic character of CF (Fig. S2, B—D). The obtained results matched well with the reported binding energies of C 1s, N 1s and O 1s for CF.^[11]

The XPS spectrum in Fig. S2E shows the presence of Cu, Co, and S for the carrolite CuCo_2S_4 . The XPS survey spectrum for the CuCo_2S_4 functionalized CF indicates the presence of C, N, O, Cu, Co, and S (Fig. 6A). The obtained binding energies for the deconvoluted peaks of C 1s, N 1s, and O 1s are the same as those in the bare CF sample. The binding energies for the Cu [$2p_{2/3}$ (932.7 eV) and $2p_{1/2}$ (952.2 eV)], Co [$2p_{1/2}$ (793.8 eV) and $2p_{2/3}$ (779.6 eV)] and S [$2p_{3/2}$ (161.7 eV) and $2p_{1/2}$ (162.8)] are similar as those in the pristine sample in Fig. 6, B—G. The obtained results confirm that the functionalization of CF with carrolite CuCo_2S_4 does not affect the graphitic structure of CF and CF does not affect the phase purity of carrolite CuCo_2S_4 .

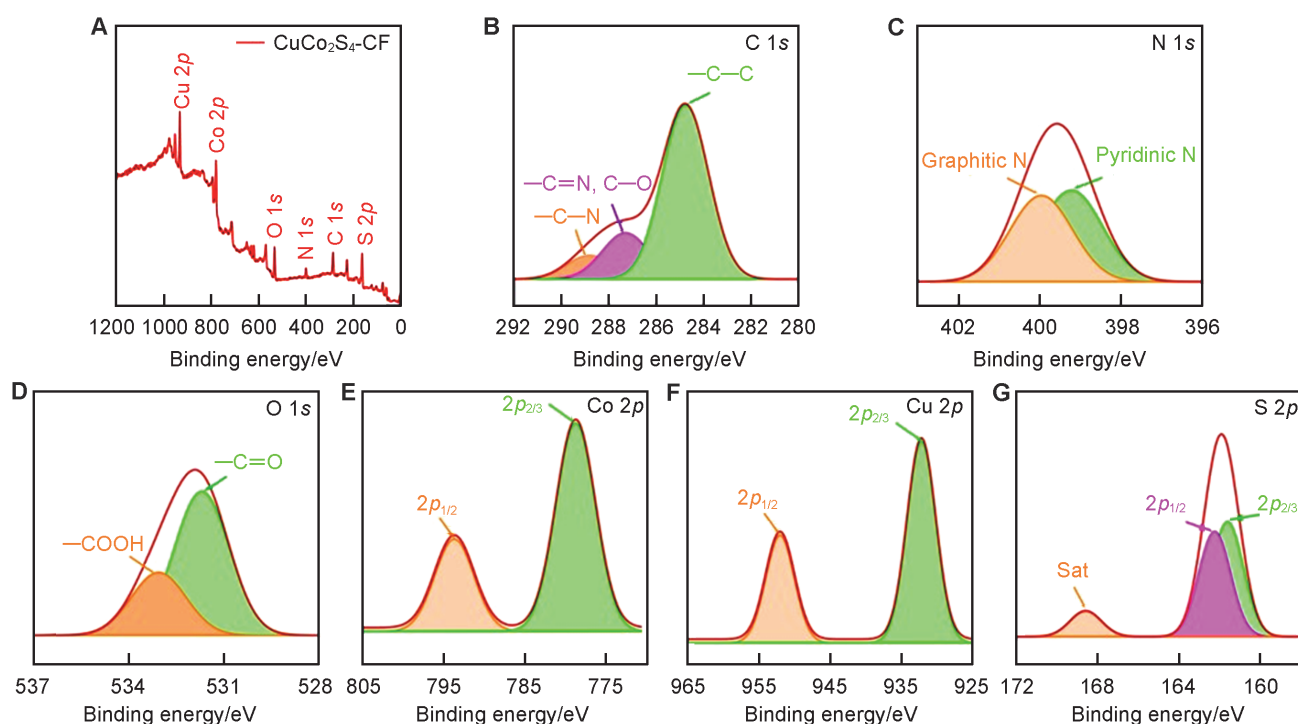


Fig. 6 XPS analysis of $\text{CuCo}_2\text{S}_4\text{-CF}$

(A) Survey XPS spectrum of $\text{CuCo}_2\text{S}_4\text{-CF}$; (B) C 1s; (C) N 1s; (D) O 1s; (E) Co 2p; (F) Cu 2p; (G) S 2p. Spectra were corrected for changing effect.

3.2 Optical Properties of $\text{CuCo}_2\text{S}_4\text{-CF}$

To monitor the potentiality of the material as solar evaporator, UV-Vis absorption spectroscopy was applied in the spectral range of 250–2200 nm. Fig. 5B shows the absorption for all the samples. For the bare CF, absorbance is equal to 95% in the UV-Vis region. However, moving from the Vis to the near IR and IR regions, the solar absorption decreased down to 55% at 1800 nm. This trend is in accordance with other reported studies on CF powder.^[12] To enhance the evaporation rate for the interfacial solar desalination process, the solar evaporators should absorb maximum solar radiation in the near IR region. A recent study shows that ternary CuCo_2S_4 has excellent

photothermal activity, giving rise to strong absorption that ranges from UV-Vis to near IR.^[28] Based on these findings, we functionalized the CF with CuCo_2S_4 to realize enhanced light absorption that extends to the IR region. To this end, the obtained material presents excellent absorption above 96% in the UV-Vis-IR region (Fig. 5B). Based on the obtained characterization results, CF shows micropores with a graphitic structure that may facilitate water transport, and functionalization with CuCo_2S_4 nanoparticles, which may enhance the optical absorption of the system to harvest maximum solar energy. For these reasons, it is expected that $\text{CuCo}_2\text{S}_4\text{-CF}$ can work as an excellent solar evaporator.

3.3 Interfacial Solar Desalination

The solar evaporation experiment was conducted to measure the evaporation rate of CuCo_2S_4 -CF. For comparison, the pure CuCo_2S_4 , CF, and microfiber membrane (Whatman glass microfiber filter: 47 mm) were also reported separately. The dry surface temperatures of CF, CuCo_2S_4 , and CuCo_2S_4 -CF are reported in Fig. 7, resulting in 68 °C for CF, 70.6 °C for CuCo_2S_4 , and 74.4 °C for CuCo_2S_4 -CF. The wet surface temperatures were recorded as 41, 39 and 43.8 °C for CF, CuCo_2S_4 , and CuCo_2S_4 -CF, respectively (Fig. S3 in the ESI). The comparison of the dry and wet surface temperature of the samples is presented in Fig. S4 in the ESI. It is observed that, in both cases, the temperature under dry and wet conditions of the CuCo_2S_4 -CF sample is higher than that of the other samples, most likely due to the photothermal effect of CuCo_2S_4 and low thermal conductivity of carbon foam that prevents heat losses. The interfacial solar desalination experiment shows the enhanced evaporation rate ($2.40 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) for the CuCo_2S_4 functionalized CF compared to CF ($1.6 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) and CuCo_2S_4 ($1.6 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) (Fig. 8B). The evaporation rate of CuCo_2S_4 -CF under dark conditions (no solar irradiation) shows an evaporation rate of $0.18 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ that is even lower than the evaporation rate for microfiber membrane ($0.5 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$). For enhanced evaporation rate, the morphology of the material plays a key role. The SEM analysis shows the carbon surface with micropores that facilitate the capillary action of water transport towards the photothermal layer. The 3D connected graphitic structure can prevent heat loss. The continuous change in mass reduction (kg/m^2) shows the hydrophilicity of synthesized CuCo_2S_4 -CF due to the faster movement of water toward the photothermal layer (Fig. 8A), and the investigation of CF for interfacial solar desalination showed excellent salt-resistant property.^[11] Fig. 9 shows the

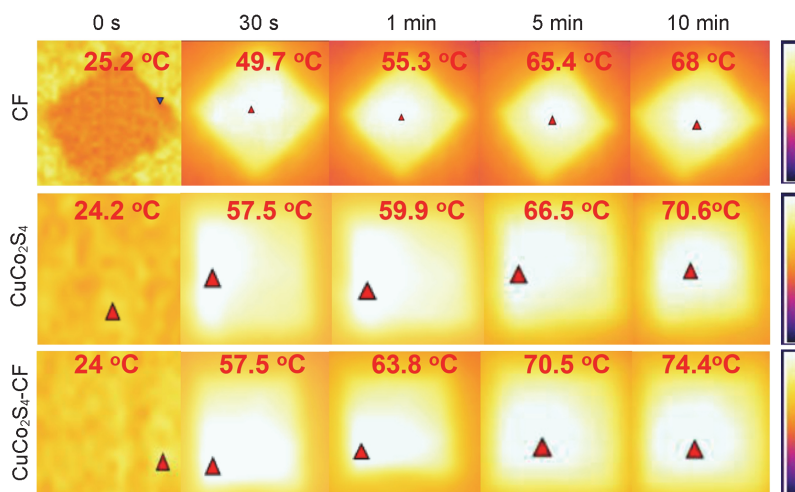


Fig. 7 Comparison of the dry surface temperature of CF, CuCo_2S_4 , and CuCo_2S_4 -CF

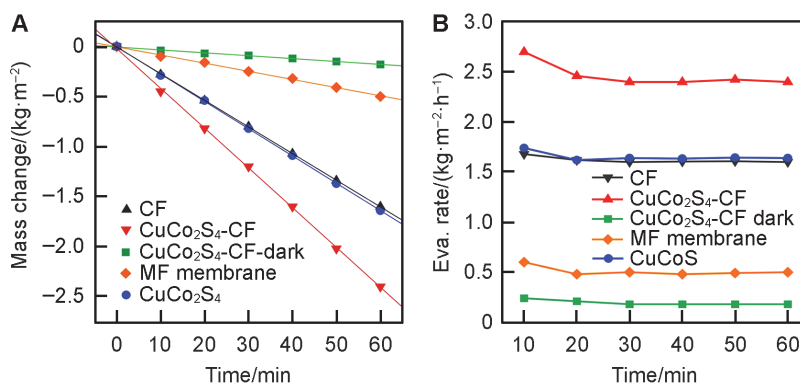


Fig. 8 Change in mass (A) and evaporation rate (B) of CF, CuCo_2S_4 , and CuCo_2S_4 -CF

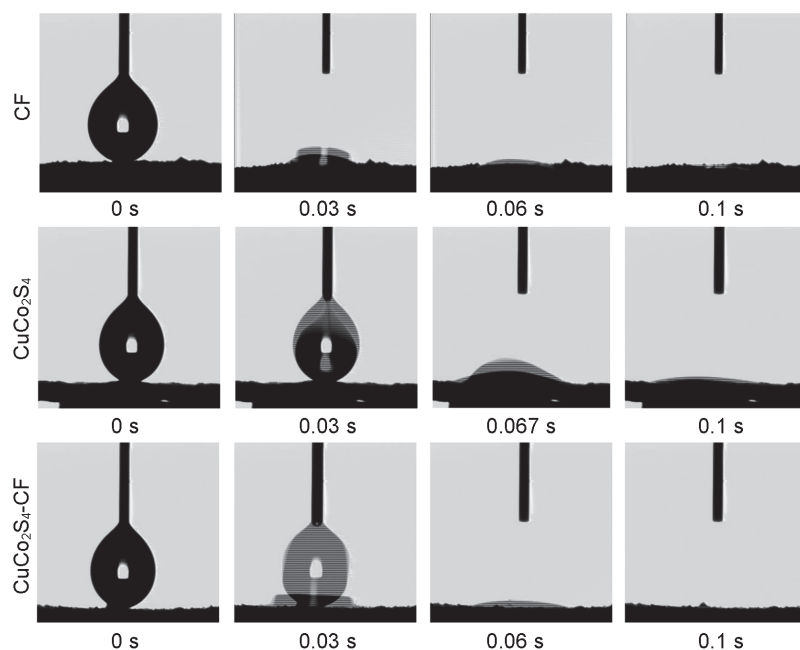


Fig. 9 Contact angle measurements of CF, CuCo_2S_4 and CuCo_2S_4 -CF

hydrophilicity of synthesized CF, CuCo_2S_4 , and $\text{CuCo}_2\text{S}_4\text{-CF}$, which was analyzed with contact angle measurements and it shows very high hydrophilicity of CuCo_2S_4 functionalized CF. The water drop absorbs within 0.1 s in the case of both CF and $\text{CuCo}_2\text{S}_4\text{-CF}$, proving the super hydrophilicity of material due to the presence of O-, N-containing functional groups in graphitic CF. The functionalization with CuCo_2S_4 does not affect the hydrophilicity of the material.

The evaporation rate of CF ($1.60 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) well matched with a reported evaporation rate of carbon foam.^[13] the evaporation rates for CuCo_2S_4 ($1.62 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) and $\text{CuCo}_2\text{S}_4\text{-CF}$ ($2.40 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$) have never been investigated before, except in the present research work. The evaporation rate for $\text{CuCo}_2\text{S}_4\text{-CF}$ has achieved a significantly higher value, compared to recently reported studies on carbon-based, copper, and cobalt-based nano photothermal evaporators (Table 1).^[13,16,31–36] The mechanism behind the enhanced evaporation seems being the combined effect of graphitic CF with porous channels that facilitate fast water transport, preventing at the same time heat losses, and the solar absorption in a broadband, thanks to the narrow band gap of the $\text{CuCo}_2\text{S}_4\text{-CF}$ photothermal layer.

Table 1 Comparison of the evaporation rate for $\text{CuCo}_2\text{S}_4\text{-CF}$ with different C-, Cu-, and Co-based solar evaporators

Photothermal material	Evaporation rate/ ($\text{kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$)	Surface temperature/ $^{\circ}\text{C}$	Ref.
CF/PVDF	1.27	75	[13]
CoSb_x	1.4	101	[16]
CuS nanoflower	1.09	35	[31]
Chitin/CuS composite	1.52	84.1	[32]
Cu_2SnSe_3	1.62	40.1	[33]
Wood CNT	0.95	36.2	[34]
Co_3S_4	1.26	38	[35]
$\text{Co}_3\text{S}_4\text{/NF}$	1.56	40	[36]
$\text{CuCo}_2\text{S}_4\text{-CF}$	2.40	74.4	This work

4 Conclusions

In the present research work, the newly combined nanostructure of $\text{CuCo}_2\text{S}_4\text{-CF}$ was synthesized by upcycling the waste plastic into graphitic CF, and CuCo_2S_4 was functionalized on the CF powder using solvothermal techniques. Carrollite CuCo_2S_4 functionalized CF showed excellent solar absorption (>96 % in the 250–2250 nm range). Due to the combined effect of CF morphology and enhanced optical absorption of CuCo_2S_4 , excellent evaporation rate was achieved, equal to $2.4 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$, compared to that of CF ($1.6 \text{ kg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$). This work presents the sustainable

development of new low-bandgap energy materials from waste plastic and functionalization with carrollite CuCo_2S_4 photothermal layer for freshwater production *via* interfacial solar desalination to mitigate the water and plastic crises, thereby enabling the circular economy.

Electronic Supplementary Information

Supplementary material is available in the online version of this article at <http://dx.doi.org/10.1007/s40242-024-4091-8>.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Enhanced Solar-Water Desalination by CuCo₂S₄-Decorated Carbon Foam Derived from Waste Plastic

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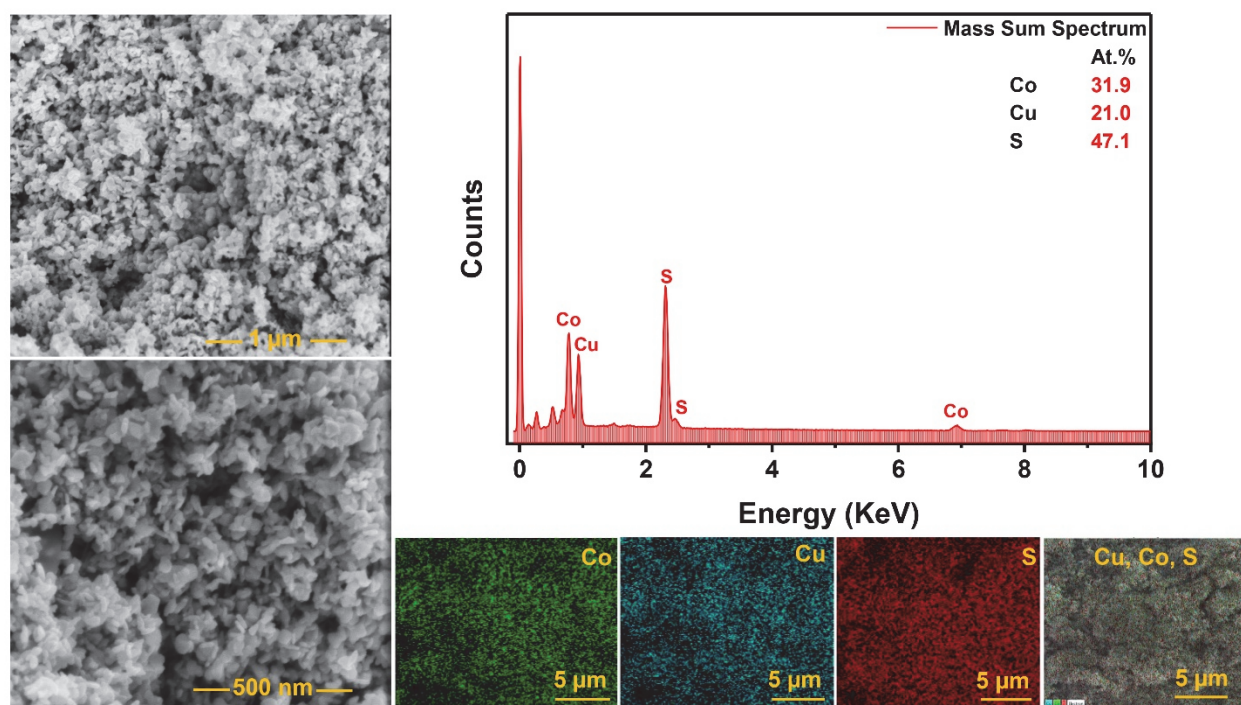


Fig. S-1 SEM-EDS analysis of CuCo_2S_4

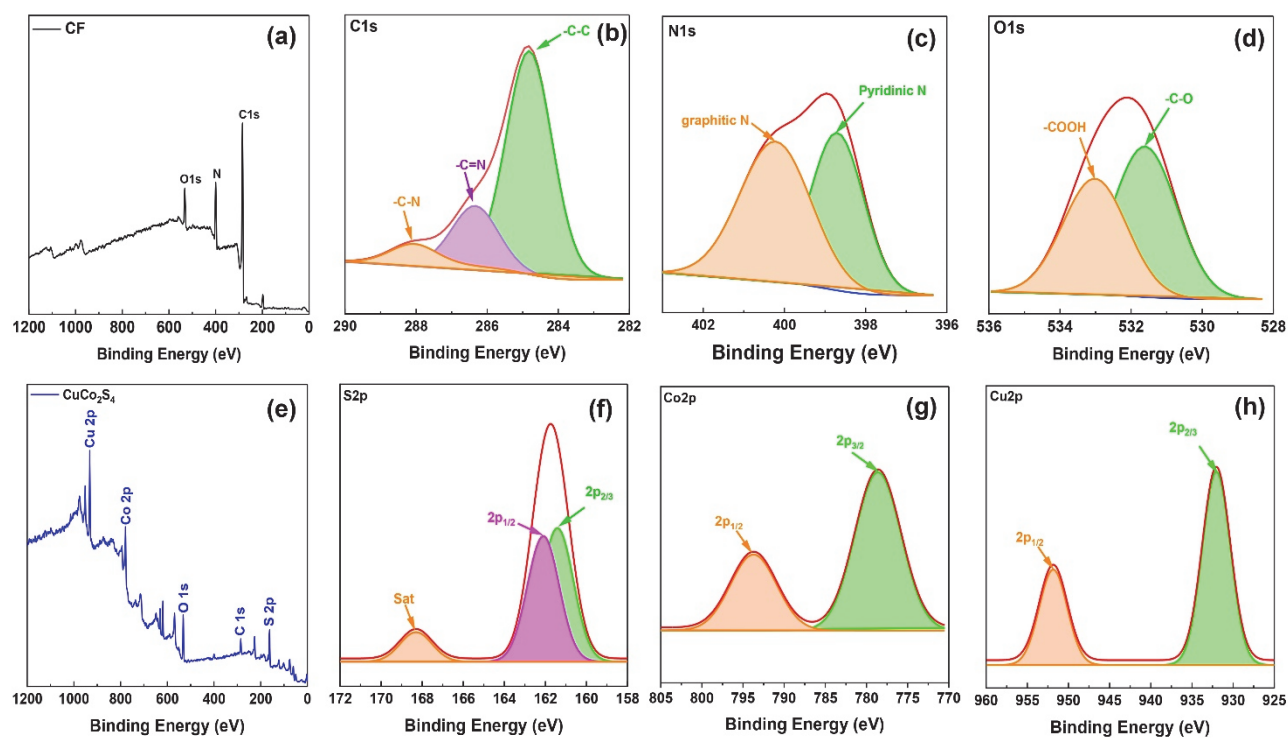


Fig. S-2 XPS analysis of CF (a-d) and CuCo_2S_4 (e-h)

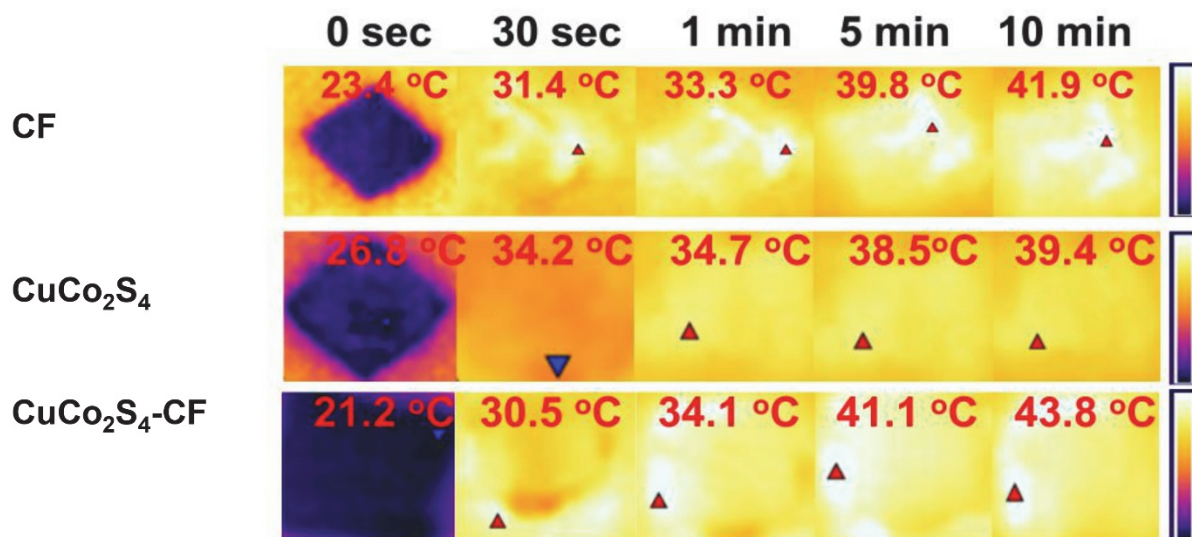


Fig. S-3 Comparison of the wet surface temperature of CF, CuCo₂S₄, and CuCo₂S₄-CF during solar desalination

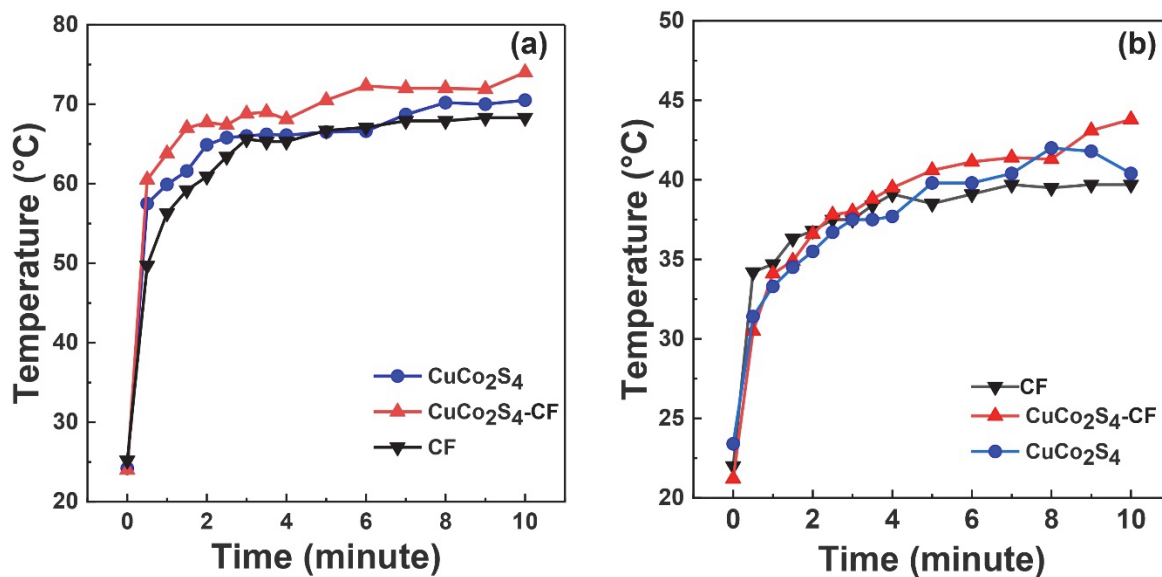


Fig. S-4 Comparison of the (a) dry and (b) wet surface temperature of CF, CuCo₂S₄, and CuCo₂S₄-CF during solar desalination

Upcycled PET-Derived Carbon Foam Functionalized with $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3$ Heterostructures for Efficient Interfacial Solar Desalination

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Solar desalination is an emerging technique to produce fresh water utilizing renewable solar energy. However, the engineering of efficient photothermal material is a significant obstacle. In the present study, a carbon foam is synthesized from the upcycling of waste PET and hydrothermally functionalized with a heterostructure composed of Cu_3SbS_4 and Sb_2S_3 . Material characterizations demonstrated the successful decoration of nanochannels on graphitic carbon foam (CF). The analysis of the optical properties in the UV/Vis-NIR spectral range demonstrated excellent absorption properties of 96% for $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3/\text{CF}$ compared to $\text{Sb}_2\text{S}_3/\text{CF}$ (48%) and CF (68%) in near-IR. Photothermal desalination results reveal the evaporation rate of $2.82 \text{ kg m}^{-2} \text{ h}^{-1}$ for $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3/\text{CF}$ compared to $1.4 \text{ kg m}^{-2} \text{ h}^{-1}$ for $\text{Sb}_2\text{S}_3/\text{CF}$ and $1.58 \text{ kg m}^{-2} \text{ h}^{-1}$ for CF, with 99% salt removal in condensed water. The formation of the composite leads to a high surface temperature and enhanced evaporation rate. The contact angle analysis confirmed the hydrophilic nature of the material that plays a crucial role in the solar desalination process. These findings elucidate the effective photothermal performance achieved through chalcogenide heterostructure engineering supported on upcycled carbon foam derived from waste PET, demonstrating a practical application aligned with circular economy principles in solar desalination.

1. Introduction

Fresh and clean water is a basic need of humans and is highly associated with human survival. However, due to the blooming in industrialization and urban development, the water resources are highly affected.^[1–3] The utilization of seawater for drinking and energy production has consistently raised concerns, prompting the development of various strategies for desalinating seawater. A series of energy-intensive methods with complex technologies are used for water desalination, including electrodialysis (ED), forward osmosis (FO), multiple-effect distillation, reverse osmosis (RO), thermal desalination, solar desalination, and multi-stage flash distillation.^[4] Among them, solar desalination is one of the emerging methods to treat seawater using renewable solar energy. Interfacial solar steam generation using solar energy is not only a cost-effective and straightforward technology, but it also

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harnesses a free and clean energy source.^[5] In photothermal material for desalination, the solar energy can be transformed into thermal energy that increases the water evaporation rate and makes the process more efficient and greener under sunlight irradiation.^[4,6]

Material development for solar steam generators plays a significant role in enhancing the solar absorption and evaporation rate. Considering these concerns, in recent years various carbon materials have been investigated, such as graphite, graphene oxide, CNTs, biomass, and wood-derived carbonized carbon.^[7–11] These carbon-based materials have similar properties, such as good light absorption and lightweight.^[5] On the other side, carbon-based systems are missing some key features that are required for high solar desalination, they may have high synthesis cost (graphene oxide and biochar), low water transport and light reflection due to the layered structure (graphene oxide), and hydrophobic nature (CNTs /graphene), which reduces the water evaporation rate.^[12,13] Furthermore, the high thermal conductivity of these carbon materials reduces the surface thermal properties, favoring heat dispersion in the water reservoir, reducing an efficient interfacial solar desalination.^[14] The development of cost-effective carbon materials with low thermal conductivity, hydrophilicity, and high solar absorption, such as PET (polyethylene terephthalate) upcycled carbon foam, could be an appealing solution. Waste PET upcycled carbon foam is an excellent carbon material owing to the essential characteristics of solar evaporators, such as high hydrophilicity and low thermal conductivity, which prevent the surface heat loss and boost the evaporation rate.^[15]

Semiconductors, plasmonic and hydrated transition metal chalcogenides, based nano-evaporators play a crucial role in the solar steam generation.^[16–20] A bibliometric analysis shows that in recent years the nanoevaporators have attracted significant interest from the research community, as evidenced by a substantial increase in related publications.^[6] Efficient solar steam generator design requires high solar absorption from UV/Vis to the Near Infrared region to guarantee absorbance of the full Sun spectrum, and a series of advanced materials is intensively investigated to obtain solar evaporation rates above $3 \text{ kg m}^{-2} \text{ h}^{-1}$.^[21] In this context, sulfide-based materials attract strong interest in harvesting solar energy to produce thermal energy. Recently, copper-based sulfide nanostructures have proved their excellent potential as solar steam generators.^[22–26] Sulfide-based nanostructures are characterized by their narrow band gaps (usually ranging from 1.0 to 2.4 eV), and this electronic property permits them to absorb a broad spectrum (UV/Vis-NIR) of solar radiation, which underlines the potential of sulfide-based nanostructures in advancing efficient and sustainable solar desalination processes.^[27] Recently, ternary chalcogenides of copper-antimony-sulfide have attracted significant attention for solar cell applications due to their earth-abundance and low toxicity.^[28–30] They have demonstrated promising achievements due to their high optical activity, catalytic surface properties, and tunable morphologies, with encouraging performances in areas such as dye degradation and CO_2 reduction.^[31–33] However, despite their intriguing optical and thermal characteristics, their potential as photothermal materials for interfacial solar desalination remains largely unexplored. Interfacial solar desalination demands a highly efficient combination of materials that, at least, meet three essential criteria: high hydrophilicity coupled with low thermal conductiv-

ity, suitable wettability, and excellent solar light absorption^[34]. Herein, we report a rationally designed heterostructure composed of Cu_3SbS_4 and Sb_2S_3 (Stibnite) on carbon foam (CF). The CF is derived from the upcycling of waste PET. The engineered copper-antimony sulfide-based heterostructure grown onto CF offers several key advantages for solar water desalination, including enhanced light absorption across a broad spectrum, improved photothermal conversion efficiency, and effective interfacial heat localization (due to the low thermal conductivity, porous and hydrophilic nature of the material which guarantee effective interfacial heat exchange between the evaporator and the absorbed water, resulting in a high evaporation rate). These features collectively make it an excellent candidate for achieving a high water evaporation rate under solar illumination. The obtained results prove that the heterojunction of Cu_3SbS_4 and Sb_2S_3 with CF successfully engineers the morphology of the hybrid material and enhances the surface thermal property as compared to $\text{Sb}_2\text{S}_3/\text{CF}$ and the bare CF. In general, the combination of waste plastic-derived graphitic carbon with sulfide material for the rational design of an efficient solar steam generator promotes circular economy practices while enabling clean water production.

2. Results and Discussion

Initially, the carbon foam (yield = 35.95%) was synthesized from PET of waste plastic bottles using eutectic salt of NaCl and ZnCl_2 and melamine by carbonization in an air environment. To synthesize an efficient photothermal layer, the carbon foam was further functionalized hydrothermally by copper-antimony sulfide-based materials and investigated for interfacial solar desalination, see **Figure 1a**. The conversion mechanism of PET to carbon foam is illustrated in **Figure 1b**, which starts with the degradation of the PET chain by random scission at the ester linkage (beta-hydrogen transfer), which creates two chain fragments (1-carboxyl-terminated chain and 2-vinyl-terminated chain). The vinyl-terminated fragment (2) decomposes into a carboxyl-terminated fragment (1) by eliminating acetylene. During the first crosslinking, the amide reaction of the carboxyl group of the carboxyl-terminated chain and the amino group of melamine causes carboxyl-terminated PET degradation intermediate (5). The crosslinking of melamine with a carboxylic group suppresses the formation of aromatic ring-terminated fragments (4) from the carboxyl-terminated chain (2) and (3), and during the carbonization process, the decarboxylation and dehydration result in the formation of a stable framework due to the catalytic action of molten salt by owing to the Lewis acidity of ZnCl_2 . The compound (3) from vinyl-terminated chain fragments undergoes intermolecular condensation to ease the self-crosslinking structure (6). Zinc chloride not only promotes the decarboxylation but also removes the weak bonds of the crosslinked structure, which yields a more stable crosslinking structure (7). During the degradation and crosslinking process, the physical template effect of NaCl and in situ formed small molecular compounds such as CO_2 and H_2O causes a foaming effect. X-ray diffraction analyses were performed to investigate the crystal structure of the synthesized materials (namely: CF, SbS/CF , and $\text{Cu}_3\text{Sb}_{1.5}\text{S}/\text{CF}$) in the angular range of 10° – 80° . **Figure 2** shows the broad Bragg peak at $2\theta = 18^\circ$ – 32° , attributed to the (002)

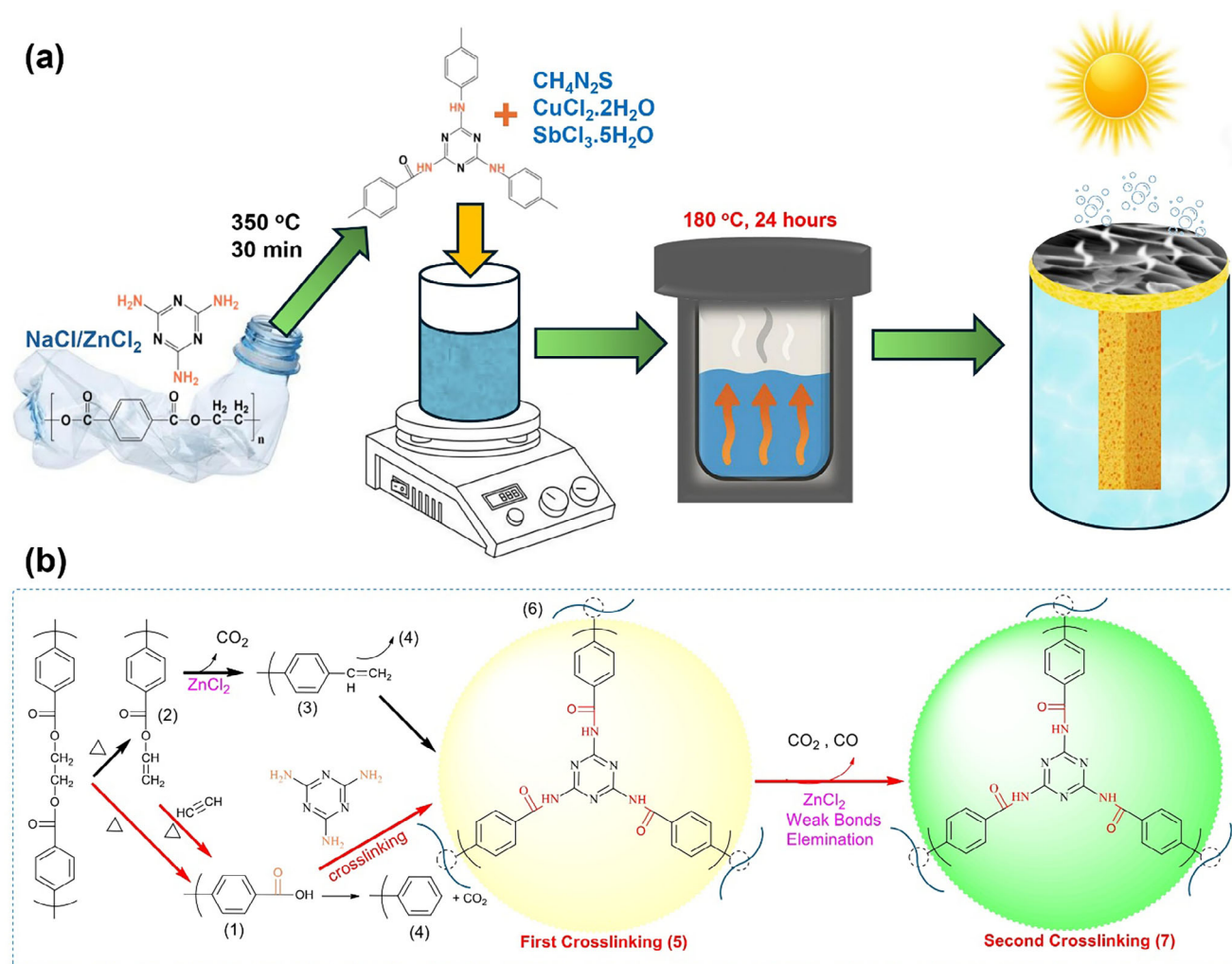


Figure 1. a) Graphic presentation of CF production and decoration of $\text{Cu}_1\text{Sb}_{1.5}\text{S}$ on CF for interfacial solar desalination, b) Carbonization mechanism for CF formation.

diffraction by graphitic carbon of CF (JCPDS no. 41-1487). The Sb_2S_3 grown on CF exhibits diffraction peaks at 2θ values of $11.1, 15.7, 17.5, 22.2, 24.8, 25.7, 28.4, 29.2, 35.5, 39.9, 40.3, 42.9, 46.7, 48.7, 52.9, 60.6$ and 71.9° the crystal planes (110), (200), (120), (220), (130), (111), (230), (211), (221), (340), (141), (421), (501), (112), (351), (422), and (811) of stibnite (JCPDS no. 42-1393). The addition of Cu precursor during the hydrothermal synthesis induces the advent of another phase in addition to stibnite. The Cu/Sb ratio of 1:1.5 mm resulted in a heterostructure in which two different phases, stibnite (Sb_2S_3) and famatinite (Cu_3SbS_4) co-exist. As illustrated in Figure 2, the $\text{Cu}_1\text{Sb}_{1.5}\text{S}/\text{CF}$ sample exhibits the diffraction peaks at 2θ values of $18.4, 28.6, 29.9, 33.2, 47.7, 56.6, 59.4, 77.2$ and 89.1° that can be indexed to Cu_3SbS_4 (JCPDS no. 35-0581), with crystal planes of (101), (112), (103), (200), (204), (312), (224), (316), and (228), respectively. It is also evident from the Figure 2 that the peaks at 2θ value of $15.6, 17.5, 24.8, 32.3$ and 48.7° can be indexed to Sb_2S_3 (JCPDS no. 42-1393) with crystal plans of (020), (120), (130), (221), and (112) respectively. Moreover, the XRD patterns of samples with varied concentrations of Cu and Sb are pre-

sented in Figure S1a (Supporting Information). It is noteworthy that the CF did not induce any major crystal changes on the growth of the materials. This can be evidenced from Figure S1b (Supporting Information) where there is no significant alteration in the XRD pattern of $\text{Cu}_1\text{Sb}_{1.5}\text{S}$ as compared to that of Cu_3SbS_4 in Figure 2. Furthermore, the Rietveld Refinement was performed to determine the phase contents of the Cu_3SbS_4 – Sb_2S_3 heterostructure. The refinement was performed using (X'pert High Score Plus), and structural models were based on standard crystallographic data (Cu_3SbS_4 : JCPDS no. 35-0581 and Sb_2S_3 : JCPDS no. 42-1393). The refined pattern exhibited good agreement with the experimental data, with a χ^2 value of 5.28, indicating a reliable fit. Quantitative phase analysis revealed that the sample consists of ≈ 58 wt.% Cu_3SbS_4 and 42 wt.% Sb_2S_3 Figure S1c (Supporting Information). These results prove the structural integrity of the biphasic heterostructure (Cu_3SbS_4 – Sb_2S_3).

X-ray Photoelectron Spectroscopy (XPS) analyses were conducted to check the elemental composition and chemical state of CF and nanostructure functionalized CF. The XPS survey

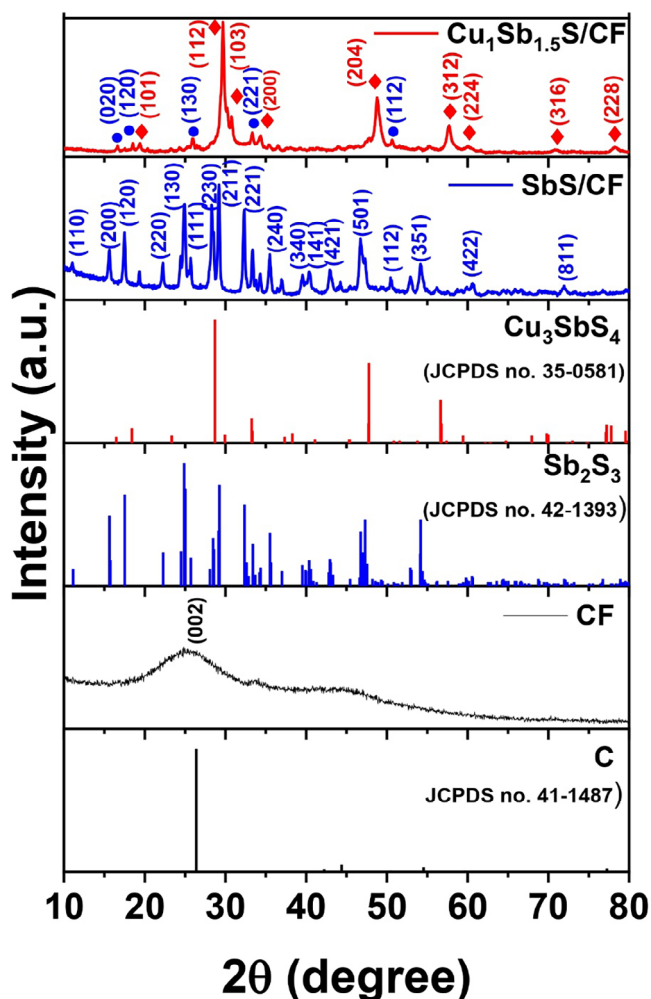


Figure 2. X-ray diffraction patterns of CF, SbS/CF, and $\text{Cu}_1\text{Sb}_{1.5}\text{S}$ (a), and $\text{Cu}_1\text{Sb}_{1.5}\text{S}$ /CF and JCPDS cards for C, Sb_2S_3 , and Cu_3SbS_4 are also reported for direct comparison with the experiments.

spectrum in Figure S2a (Supporting Information) shows surface chemical composition (in atomic concentration%) was: C: 74.0%, N: 13.0%, O: 5.6% and Cl: 1.1%. The high resolution C 1s core level spectrum of CF (Figure S2b, Supporting Information) shows four contributions at 284.8 eV (69%), 286.1 eV (18%), 287.2 eV (7%) and 288.6 eV (7%), assigned to adventitious carbon/ $-\text{C}-\text{C}-/-\text{C}=\text{C}-$, $\text{C}-\text{OH}/-\text{C}=\text{N}$, $\text{C}=\text{O}$, and $-\text{COOH}$, respectively. The high-resolution O 1s core level spectrum (Figure S2c, Supporting Information) shows three contributions at 530.8 eV (10%), 532.0 eV (51%), and 533.4 eV (39%), assigned to $\text{C}=\text{O}/-\text{COOH}$ and $\text{C}-\text{OH}$, respectively. The N 1s spectrum has two contributions with similar relative intensities at 398.6 and 400.2 eV, assigned to pyridinic N and graphitic N. In addition, this sample presents a small amount of chlorine at the surface with a Cl $2p_{3/2}$ signal at 197.3 eV, typical of chloride from final washing with HCl. Figure S3a (Supporting Information) presents the surface chemical composition of sample SbS/CF Figure S3b (Supporting Information) shows the C 1s core level spectra of the sample SbS/CF shows three contributions at 284.76, 286.2, and 288 eV assigned to $-\text{C}-\text{C}-/-\text{C}=\text{C}-$, $\text{C}-\text{OH}/-\text{C}=\text{N}$, and

$-\text{COOH}/-\text{COO}^-$. The N 1s in Figure S3c (Supporting Information) present similar information as observed in CF, with two deconvoluted peaks at 398.6 and 400.2 eV corresponding to pyridinic and graphitic carbon. The O 1s core level shows overlapping with Sb $3d_{5/2}$, which presents two contributions at 529.9 and 539.2 eV corresponding to Sb $3d_{5/2}$ and the peak at 531.7 eV for $\text{C}=\text{O}/-\text{COOH}$ (Figure S3d, Supporting Information). Figure S3e (Supporting Information) shows the deconvoluted peaks for the S $2p$ core level spectrum that presents two doublets S $2p_{3/2}-\text{S } 2p_{1/2}$, with S $2p_{3/2}$ binding energy values at 162.6 and 168.01 eV corresponding to sulfide and sulfate.

Figure 3a presents the surface chemical composition observed as: C: 23.9%, N: 5.1%, O: 5.6%, S: 15.1%, Cu: 17.1%, and Sb: 33.1%. The high resolution C 1s core level spectrum of sample $\text{Cu}_1\text{Sb}_{1.5}\text{S}$ /CF (Figure 3b) can be deconvoluted into three contributions at 284.8 eV (74%), 286.2 eV (19%), and 288.0 eV (7%), assigned to adventitious carbon/ $-\text{C}-\text{C}-/-\text{C}=\text{C}-$, $\text{C}-\text{OH}/-\text{C}=\text{N}$, and $-\text{COOH}/-\text{COO}^-$, respectively. The contribution due to $\text{C}=\text{O}$, observed in the case of sample CF, is not observed. The N 1s spectrum shows a broad peak centered at 400.1 eV (Figure 3c assigned to $-\text{C}=\text{N}$). The O 1s signal cannot be analyzed because it is fully overlapped with the Sb $3d_{5/2}$ signal. For this reason, we used the Sb $3d_{3/2}$ (Figure 3d) that appears at 539.5 eV, typical of Sb(III). This confirms the co-existence of two chemical states of Sb^{5+} in Cu_3SbS_4 and Sb^{3+} in Sb_2S_3 . The high-resolution Cu $2p$ core level spectrum (Figure 3e) presents a Cu $2p_{3/2}$ at 932.0 eV without satellite. This binding energy value is typical of copper sulfide. Finally, Figure 3f shows the $2p$ core level spectrum presents two doublets S $2p_{3/2}-\text{S } 2p_{1/2}$ with S $2p_{3/2}$ binding energy values at 161.8 and 168.3 eV, assigned to sulfide and sulfate, respectively, being the former the predominant. These findings demonstrate that the hydrothermal growth of Sb_2S_3 and Cu_3SbS_4 - Sb_2S_3 on CF does not affect the elemental states/electronic structure of CF.

Scanning electron microscopy (SEM) analyses was performed to investigate the surface morphology of bare CF, SbS/CF, and $\text{Cu}_1\text{Sb}_{1.5}\text{S}$ /CF. In Figure S4a,b (Supporting Information), the as-synthesized CF surface presents the open cell pores developed due to the physical templating effect of molten salt and the foaming feature occurred as a result of carbon dioxide and water molecules released during degradation of PET.^[15] In literature, some recent studies present a similar morphology of carbon foam with tiny open pores and flat sheets of CF, indicating its graphitic nature.^[35] The surface morphology of the stibnite phase of Sb_2S_3 on CF shows the elongated, densely packed nanorods that cover the CF surface, as shown in Figure S5a,b (Supporting Information). The nanorods present a good resemblance to literature-reported hydrothermally grown nanorods of stibnite Sb_2S_3 .^[36] Upon introducing Cu into the reaction system (representing the heterostructure of Cu_3SbS_4 - Sb_2S_3 on CF), a significant morphological transformation is observed. The nanorods evolve into vertically aligned nanosheets as shown in Figure 4a–c with different magnifications. Interestingly, it exhibits interconnected layers, forming abundant open channels that can facilitate mass transfer which is an advantageous feature for interfacial solar steam generation. Surface morphology plays a crucial role in the efficient performance of solar evaporators, and the aligned nanochannels in nanostructures facilitate directional water transport by reducing the vapor escape resistance and heat localization at the evaporation surface due to enhanced light

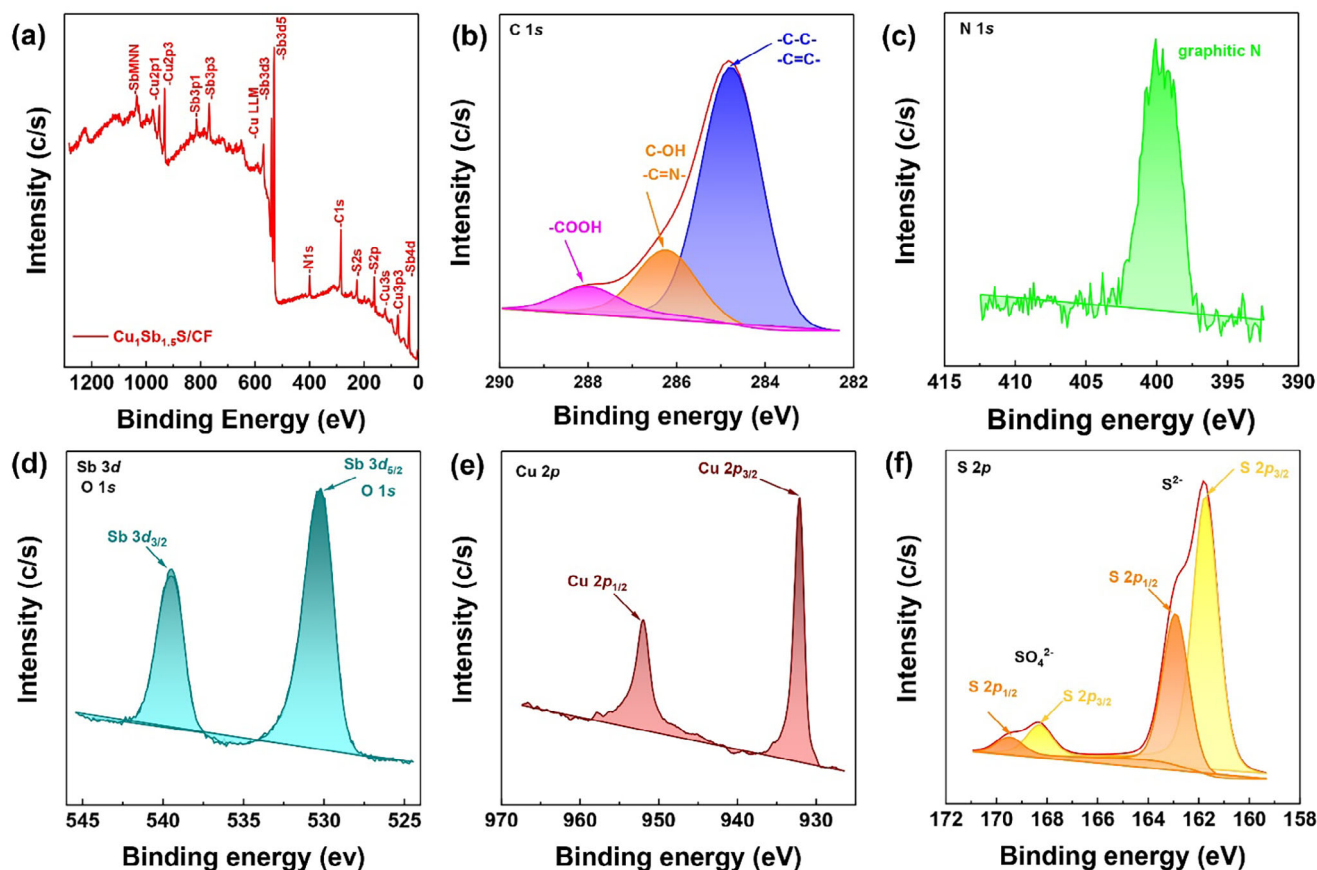


Figure 3. a) XPS survey spectrum of $\text{Cu}_1\text{Sb}_{1.5}\text{S}/\text{CF}$, high-resolution b) C 1s, c) N 1s, d) O 1s and Sb 3d, e) Cu 2p, f) S 2p.

absorption. The elemental compositions of the samples were investigated through energy-dispersive X-ray spectroscopy (EDS), and the results are presented in Figure S4 (Supporting Information), Figure 4, and Figure S5 (Supporting Information), respectively. The elemental mapping shows the uniform distribution of elements in each respective sample. The TEM image in Figure 4d further confirms the nanosheet morphology seen in SEM. The thin, wrinkled edges in the TEM image indicate the presence of ultrathin sheet-like domains, consistent with the SEM observation. The contrast variations suggest a heterogeneous structure, possibly due to the coexistence of Cu_3SbS_4 and Sb_2S_3 phases within the nanosheets. The existence of the two phases is further corroborated by the HRTEM analysis (Figure 4e), which reveals the distinct lattice fringes that are consistent with the crystal planes of Cu_3SbS_4 and Sb_2S_3 . The obtained d-spacing (SAED) values of 0.48, 0.32, and 0.16 nm, were successfully matched to the corresponding XRD crystal planes of Cu_3SbS_4 (101), (112), and (312); and the d-spacing 0.503 nm corresponds to Sb_2S_3 crystal planes (020), (120). These observations confirmed the successful synthesis of the heterostructure with retained crystallinity.

Efficient photothermal conversion relies critically on the ability of materials to absorb a broad spectrum of solar radiation, particularly spanning the ultraviolet (UV), visible (Vis), and near-infrared (NIR) regions, where the majority of solar energy is concentrated.^[37,38] To understand the fundamental optical prop-

erties, the absorption spectra of the synthesized samples were recorded across the UV/Vis to Near-IR range. Figure S6 (Supporting Information) shows the results of bare CF, SbS, and SbS/CF, and various composites with different Cu/Sb ratio (1:1, 0.5:1, 1.5:1, 1:0.5, and 1:1.5). The selected sample demonstrate optimum ratio $\text{Cu}_1\text{Sb}_{1.5}\text{S}/\text{CF}$ (i.e. equivalent to $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3/\text{CF}$) that delivers the highest absorption is also depicted in Figure 5a. The sample $\text{Cu}_1\text{Sb}_{1.5}\text{S}/\text{CF}$ exhibits an almost constant absorption ranging between 94% and 96% in the full 300–2000 nm spectral range. Bare CF and SbS/CF samples exhibit a significant drop in absorbance in the NIR region. Specifically, the Sb_2S_3 functionalized CF shows a dramatic decrease in absorption from 90% in UV/Vis region down to 48% (at 2000 nm) in the near-IR region, most likely due to the wide band gap of stibnite Sb_2S_3 . Although Sb_2S_3 presents excellent absorption in UV/Vis region, but declined in absorption activity in NIR is because of higher wavelength (>800 nm) and the photon with lower energy does not absorb well due to integration of Sb_2S_3 with CF, the Sb_2S_3 layer partially masks the highly NIR-absorptive carbon surface with a material that performs poorly in NIR region. The uniform coating of Sb_2S_3 nanocrystals can increase the surface reflectance of the material that interferes with the CF. Both factors, the spectral mismatch and structural interference, explain why SbS/CF shows lower overall light absorption than bare CF. The enhanced absorption of $\text{Cu}_1\text{Sb}_{1.5}\text{S}/\text{CF}$ is achieved due to the heterojunction of famatnite (Cu_3SbS_4) and stibnite (Sb_2S_3). Such a

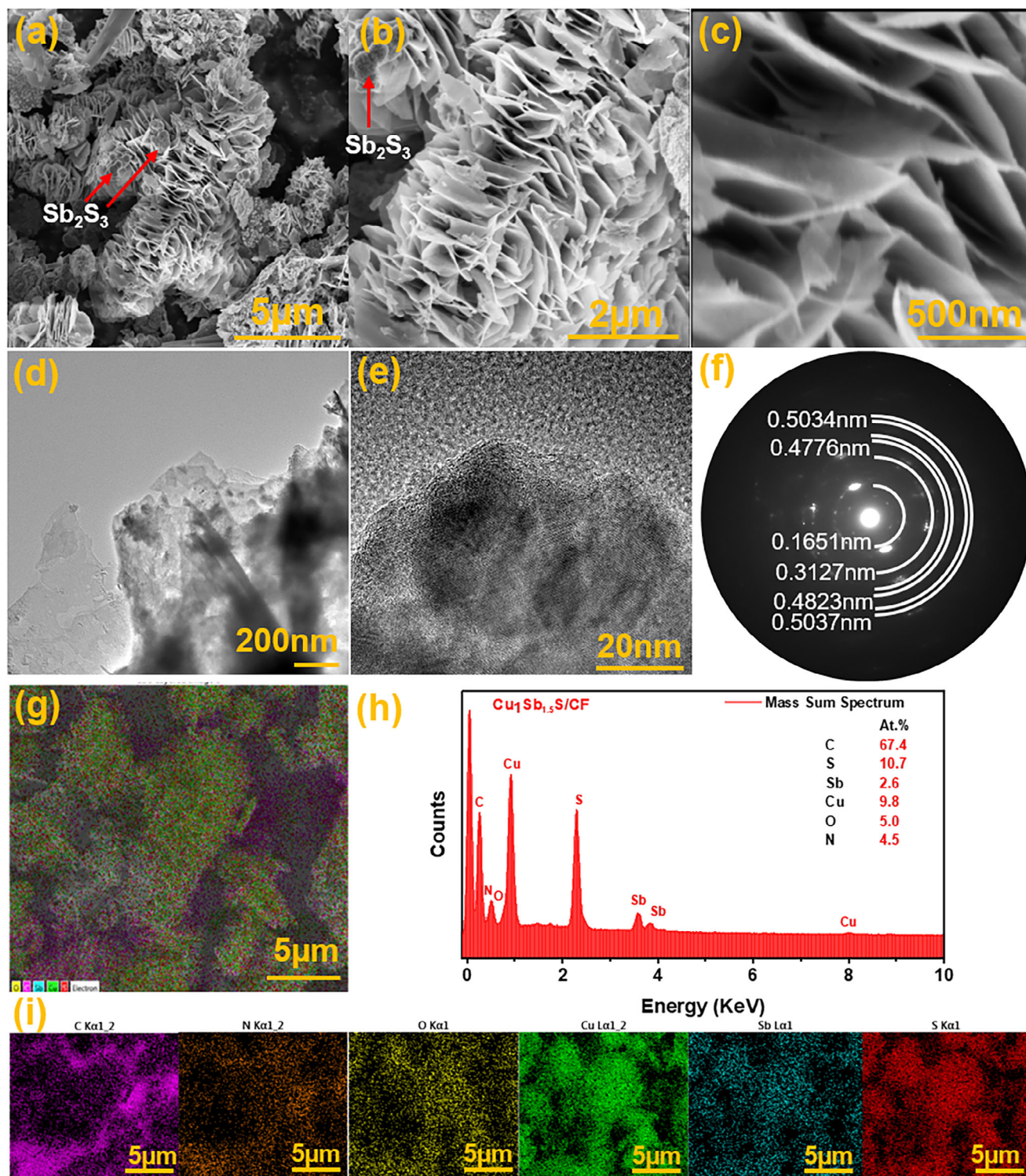


Figure 4. a–c) SEM image of $\text{Cu}_1\text{Sb}_{1.5}\text{S}/\text{CF}$, d–f) HR-TEM of $\text{Cu}_1\text{Sb}_{1.5}\text{S}/\text{CF}$, g–i) elemental mapping and EDS mass sum spectrum of $\text{Cu}_1\text{Sb}_{1.5}\text{S}/\text{CF}$.

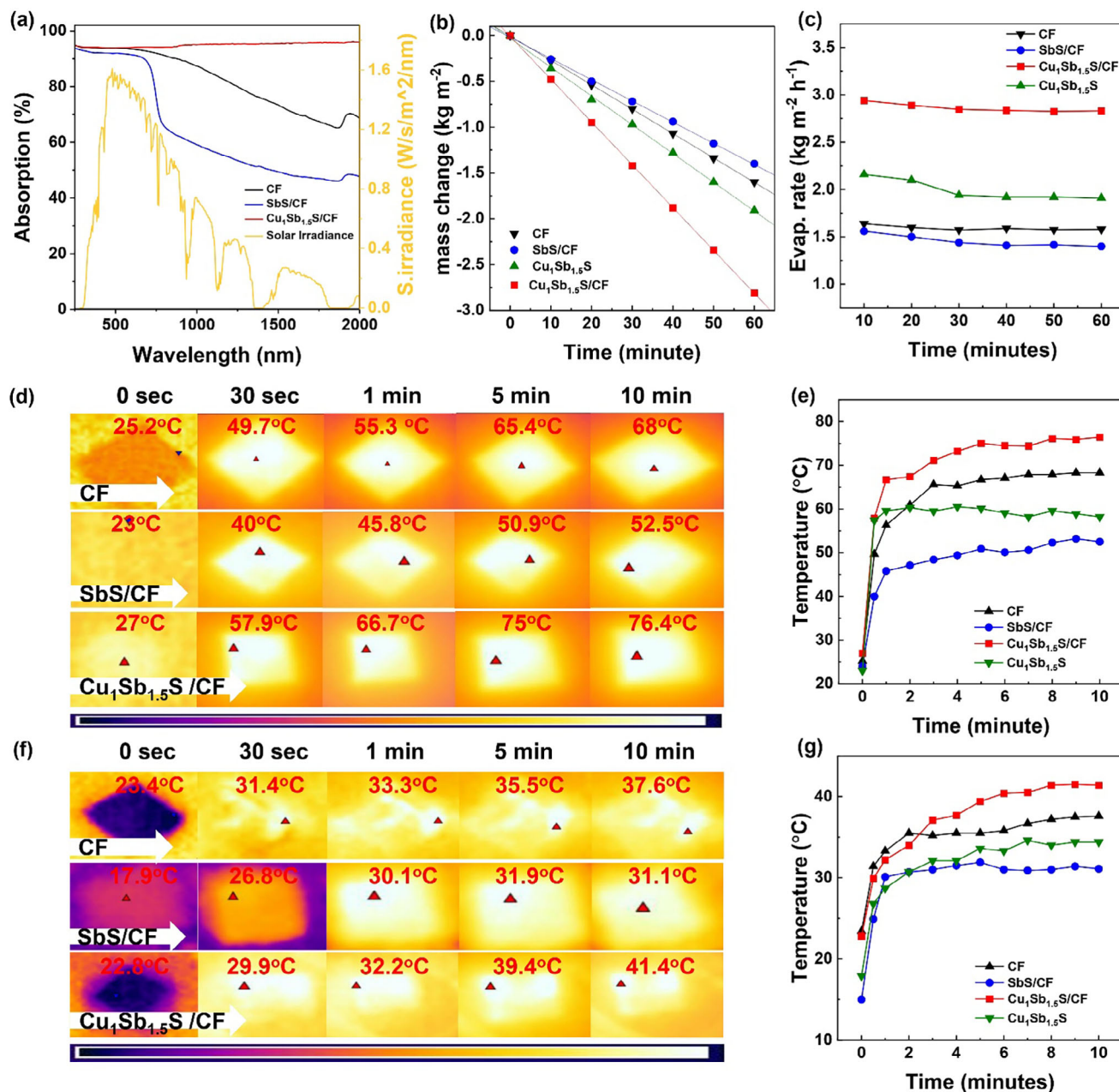


Figure 5. a) UV-vis absorption analyses, b,c) Change in mass and evaporation rate of solar desalination, d,e) thermal images and graph of dry surface temperature of CF, SbS/CF, Cu₁Sb_{1.5}S, and Cu₁Sb_{1.5}S/CF, f,g) thermal images and graph of wet surface temperature of CF, SbS/CF, Cu₁Sb_{1.5}S, and Cu₁Sb_{1.5}S/CF.

heterojunction of Cu₃SbS₄ with Sb₂S₃ extends the high absorption in the near-IR region. For instance, the study on optical activity for famatnite (Cu₃SbS₄) has been reported, illustrating the high optical absorption in near-IR due to its narrow bandgap of 0.9 eV.^[39] Another study reported the excellent optical absorption of Cu₃SbS₄ nanocrystals in the UV/Vis-NIR region,^[40] which demonstrates its potential as a photothermal material. Based on the comprehensive material structural characterization, especially optical absorption, the synthesized heterostructure could be an excellent material for the interfacial solar desalination process.

The interfacial solar evaporation experiment was performed under simulated solar light (AM 1.5G one sun irradiation 100 mW cm⁻²), the experimental detailed setup is illustrated in Figure S7a (Supporting Information). For a detailed comparison, the solar desalination test was conducted on different samples: CF, Cu₁Sb_{1.5}S/CF, SbS/CF, and Cu₁Sb_{1.5}S without CF. Figure 5b presents the mass change of the investigated samples, which elucidates the continuous reduction of water mass. The obtained results in Figure 5c reveal the excellent evaporation rate of 2.83 kg m⁻² h⁻¹ for Cu₁Sb_{1.5}S/CF compared to the bare CF (1.58 kg m⁻² h⁻¹) and SbS/CF (1.4 kg m⁻² h⁻¹).

h^{-1}). The outperforming evaporation rate of $\text{Cu}_1\text{Sb}_{1.5}\text{S}/\text{CF}$ is attributed to the synergistic photothermal effect of Cu_3SbS_4 and Sb_2S_3 . The improved results achieved due to the complementary absorption behavior of $\text{Cu}_1\text{Sb}_{1.5}\text{S}/\text{C}$ and the integration of Cu_3SbS_4 enable a broader spectral response compared to Sb_2S_3 functionalized CF, and their combined effect facilitates interfacial charge separation under solar irradiation within a heterostructure that boosts the energy to be dissipated non-radiatively as heat. The alignment of absorption activity (UV/Vis-NIR) with surface temperature ($\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3/\text{CF} > \text{CF} > \text{Sb}_2\text{S}_3/\text{CF}$) indicates the heterostructure facilitates more effective solar-to-thermal energy conversion. Figure 5d,e presents the thermal images and graphs of the investigated samples that were captured at the dry state (before desalination), Figure 5f,g presents the wet condition (during desalination). At the dry state Figure 5d,e, the $\text{Cu}_1\text{Sb}_{1.5}\text{S}/\text{CF}$ composite exhibits the highest surface temperature, reaching 76.4°C , significantly surpassing that of pristine CF (68.3°C) and SbS/CF (52.4°C). Figure 5f,g shows the operational photothermal performance of the materials under wet conditions, which presents the relative trend consistent with the dry state of high photo-to-thermal conversion. Accordingly, the $\text{Cu}_1\text{Sb}_{1.5}\text{S}/\text{CF}$ composite shows the highest wet surface temperature of 41.4°C followed by CF (37.6°C) and SbS/CF (31.1°C). During operational conditions at the wet surface, the lowering of temperature is obvious due to the cooling effect of saline water. The superior photo-to-thermal conversion indicates the effective radiation absorption (according to the optical absorption results) that maintained the heat localization at the wet-air interface. This thermal behavior under working conditions relates well to its highest evaporation rate. As revealed by scanning electron microscopy (SEM) of the investigated samples, it provides further insights to understand the crucial role of the surface morphology of solar evaporators. The vertically stacked nanosheets (nanochannels) increase internal multiple light reflections that help to trap solar photons. In results, it concentrates the photothermal energy at the interface that retains the produced heat locally, decreasing the thermal distribution into the bulk or surrounding water. The effect is proven with infrared imaging demonstrating explaining higher surface temperatures for the heterostructure. In comparison SbS/CF rod-like morphology presents less surface interface for light interaction, fewer scattering due to fewer trapped photons, resulting in poorer photothermal and evaporation performance. The formation of the composite not only provides high absorption from UV/Vis-NIR but also facilitates the water transport due to nanochannels formation. The surface morphology plays a pivotal role in enhancing the performance of photothermal evaporators. Another interesting point is the comparison we made between $\text{Cu}_1\text{Sb}_{1.5}\text{S}$ ($1.9\text{ kg m}^{-2}\text{ h}^{-1}$) vs $\text{Cu}_1\text{Sb}_{1.5}\text{S}/\text{CF}$ ($2.83\text{ kg m}^{-2}\text{ h}^{-1}$). These findings indicate the significant contribution of the CF in addition to the optimum heterojunction between Cu_3SbS_4 and Sb_2S_3 . In fact, the unique hydrophilic pores in the CF architecture provide high water transport toward the photothermal layer. In recent findings, Bai et al demonstrate similar outcomes for carbon foam/PVDF that show the evaporation rate of $1.27\text{ kg m}^{-2}\text{ h}^{-1}$ due to its hydrophilicity.^[15] Furthermore, the present study shows much improved results in comparison to our recently reported work on CuS functionalized CF showing an evaporation rate of $1.92\text{ kg m}^{-2}\text{ h}^{-1}$.^[41]

To provide experimental evidence on the hydrophilicity, the surface wettability using contact angle analysis was performed for the pristine CF and $\text{Cu}_1\text{Sb}_{1.5}\text{S}/\text{CF}$. Figure 6a shows the instantaneous water droplet absorption in less than a second for both samples. This evidence highlights the hydrophilic character of CF, which is attributed to the presence of oxygen and nitrogen in the graphitic skeleton of CF.^[15,41] Hydrophilicity is a crucial factor in solar desalination to achieve a high evaporation rate, in the waste PET-derived carbon foam, the oxygen and nitrogen containing surface functional groups introduced during the carbonization of PET impart high wettability and surface energy to the CF, which allows water to be rapidly drawn into and foster the capillary action of vapor evaporation. As seen in the surface morphology of carbon foam in Figure S4a (Supporting Information) it presents tens of open-cell pores architecture formed due to the physical template effect of molten salts and foamy effect of in situ formed tiny molecular compounds such as CO_2 and H_2O in the degradation and crosslinking process in the CF; these structural features act as continuous capillary channels for ensuring consistent water availability at the evaporation interface. The contact angle observation further solidifies these results, with rapid absorption of water droplets confirming the high wettability that drives the capillary movement of water from the bulk reservoir upward to the photothermal surface. Hu et al have demonstrated in a study on waste-derived carbon foam that wettability is a function of oxygen-containing groups and a proportional relation of the number of pores on the surface, which results in capillary movement of water molecules.^[13] The $\text{Cu}_1\text{Sb}_{1.5}\text{S}/\text{CF}$ nanocrystal decoration does not alter CF hydrophilic characters, is a requisite for efficient water transport and high evaporation at the interface due to constant water supply. The interfacial desalination process for the bare sample CF and the outperforming solar evaporator $\text{Cu}_1\text{Sb}_{1.5}\text{S}/\text{CF}$ was conducted thrice, the evaporation rate was measured every 10 min, and the mean evaporation rate is presented with the error bar in Figure 6b. The evaporation efficiency of $\text{Cu}_1\text{Sb}_{1.5}\text{S}/\text{CF}$ is calculated from the value obtained for water vaporization enthalpy from DSC (Differential Scanning Calorimetry) analysis. The $\text{Cu}_1\text{Sb}_{1.5}\text{S}/\text{CF}$ sample presents an excellent evaporation efficiency of 94.4%, supporting the performance of the synthesized solar evaporator. The evaporation efficiency is a key parameter (as well as the evaporation rate) to evaluate the potential of solar evaporators for desalination.^[42] The present results outperform to recently reported carbon-derived solar evaporators, such as: MOF-porous carbon 64.41%, Co-N-C/CF 87%, and Carbon nanoparticle fabric 76%.^[43–45]

The evaporation rate is a key parameter when evaluating the potential of solar evaporators. The stability test in this context ensures that this rate remains consistent, predictable over time, and reliable. Due to a high saline aqueous environment, reporting of the evaporation rate over a longer experimental time demonstrates how gradually salt accumulation affects the evaporation rate. The stability test was performed under one sun irradiation using a glass microfiber filter (Whatman GF/F, CAT No. 1825-047). The stability test presents a decline in evaporation from 2.86 to $2.51\text{ kg m}^{-2}\text{ h}^{-1}$ in five hours Figure 6c. To confirm the salt crystallization on the surface of the solar evaporator, the real photographs were recorded before and after

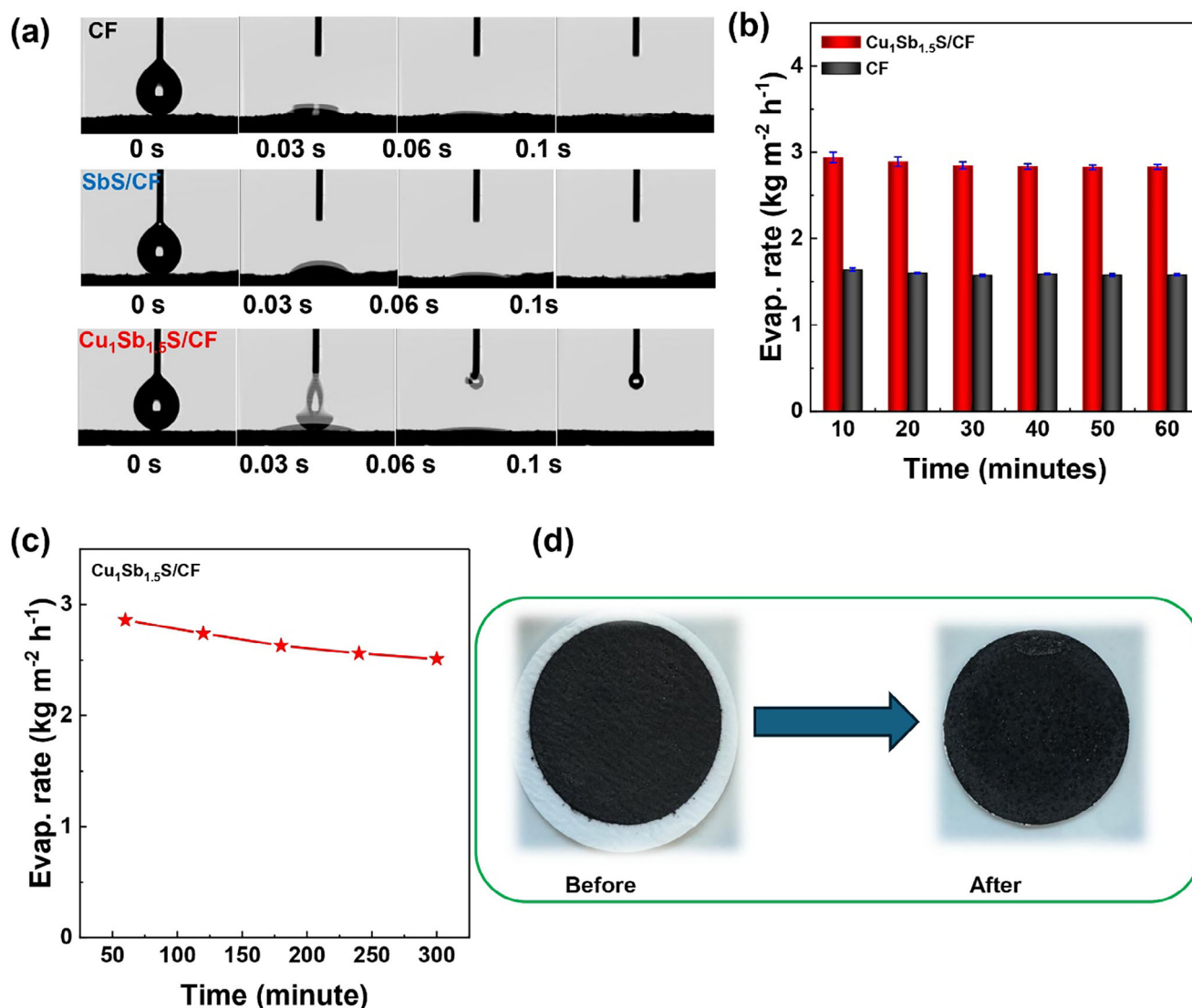


Figure 6. a) contact angle analysis, b) evaporation rate with error bar c) stability graph of Cu₁Sb_{1.5}S/CF on 3.5% NaCl saline water under one sun irradiation, and d) Real photographs of Cu₁Sb_{1.5}S/CF before and after stability test.

desalination. Figure 6d illustrates that there is no significant visual appearance of salt crystals on the surface, and the observed minor decline ($\sim 12.24\%$) in evaporation rate might have occurred due to saturation of salt concentration in the remaining water or in the cotton sponge that works as a water transport toward photothermal evaporators. The minor decline over the test interval signifies good operational stability of the photothermal system. Post-stability characterization was performed to assess the structural integrity and operational durability of the Cu₁Sb_{1.5}S/CF solar evaporator after five hours of prolonged use. As shown in Figure S8 (Supporting Information), the XRD patterns remain essentially unchanged, with no detectable shifts in peak positions or emergence of new phases. This clearly confirms that the crystalline structure of Cu₁Sb_{1.5}S/CF remains stable under illumination and extended solar exposure. The Cu₁Sb_{1.5}S/CF heterostructure

exhibits exceptional desalination performance. For instance, the sodium concentration before the desalination experiment (the saline feed water) was 1.2838×10^4 mg/L⁻¹. Following the solar-driven evaporation experiment, we have condensed back the evaporated water and analyzed the sodium content by inductively coupled plasma optical emission spectroscopy (ICP-OES), which shows a significantly reduced sodium concentration of only 1.5×10^1 mg/L⁻¹. This corresponds to a remarkable salt removal efficiency of $\sim 99\%$ (Figure S7c, Supporting Information). To further solidify this finding, the ohmic resistance of condensed water and the feed saline water (before and after desalination) was also recorded. For both sample analyses, an equal amount of sample volume (5 mL) was taken in a beaker with an internal diameter of 3 cm, the ohmic value was recorded using a Digital Multimeter (DM01M), and the distance between the meter electrode was ~ 1.5 cm. Figure S7c (Supporting Information) shows that the ohmic resistance

Table 1. Comparison of $\text{Cu}_1\text{Sb}_{1.5}\text{S}/\text{CF}$ with recently reported carbon-based nano solar steam generators under one sun irradiation.

Solar Evaporators	Evap. Rate [$\text{kg m}^{-2} \text{h}^{-1}$]	Refs.
N-doped carbon foam	1.39	[46]
MoS_2 -loaded carbon foam	1.48	[47]
3D Janus foam	1.78	[48]
Wood slice loaded Pd, Au, Ag nanoparticles	1.15	[49]
carbon-coated Fe_3O_4 NPs	1.07	[50]
CuS /polyethylene membrane	1.02	[51]
$\text{GO}/\text{Ti}_3\text{C}_2\text{T}_x$ MXene	2.09	[52]
Co-N-C/CF	1.88	[44]
CuS -carbon foam	1.92	[41]
NiSe-hyd	1.85	[53]
CoSb_x	1.40	[54]
HEAO/PDMS-coated wood	1.90	[55]
$\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3/\text{CF}$	2.82	Present study

of the condensed purified sample (5.02 M Ω) is significantly higher compared to saline water (0.327 M Ω). These observations indicated the dramatic decrease in salt concentration in purified water that ultimately reduced the conductivity of the water sample.

Table 1 presents a detailed comparison of the evaporation rate of the recently reported solar steam generators with the present finding. Our work confirms the critical role of composite engineering for photothermal-derived desalination, the enhanced performance of $\text{Cu}_1\text{Sb}_{1.5}\text{S}/\text{CF}$ achieved due to the combined effect of CF presenting high hydrophilicity with low thermal conductivity (0.113 $\text{W m}^{-1} \text{K}^{-1}$)^[37] and photothermal effect of Cu_3SbS_4 and Sb_2S_3 in enhancing both photothermal conversion and water evaporation performance, emphasizing the potential of composite microstructures for efficient solar desalination applications.

3. Conclusion

Interfacial solar desalination is an emerging technology for the production of fresh water utilizing renewable solar energy. The present study illustrates the upcycling of waste PET plastic into CF and further hydrothermal decoration of CF through $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3$ to prepare a solar steam generator. XRD and XPS analysis confirm the crystal structure and chemical state of the synthesized materials, and SEM-EDS present the nanochannels morphology. Optical analysis (UV/Vis-NIR) indicates excellent optical absorption (96%) that provokes the high photothermal output. Bridging the advantage of morphological transformation and the synergistic effect of heterostructuring, an enhanced evaporation rate of 2.82 $\text{kg m}^{-2} \text{h}^{-1}$ was obtained, with 99% removal of salt concentration. These findings suggested the sustainable development of engineered nano-evaporators from chalcogenide-functionalized waste plastic-derived carbon material, which represents the rational design of a solar steam generator to enable circular economy practices.

4. Experimental Section

All the chemicals and reagents used in the present research work were purchased from Sigma Aldrich: $\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$, $\text{SbCl}_3 \cdot 5\text{H}_2\text{O}$, NaCl, ZnCl_2 , Melamine, HCl, and thiourea.

Synthesis of $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3/\text{CF}$ material: Initially, the carbon foam was synthesized by using the procedure reported in,^[15] In detail, 1.5g of waste PET bottle sheet was mixed with 0.75g of melamine and 3g of eutactic salt ($\text{ZnCl}_2/\text{NaCl}$ (58/42)) and carbonized at 340 °C for 30 min with a heating rate of 10 °C/min. After cooling to room temperature, the obtained product was washed with 0.5M HCl and distilled water repeatedly until neutral pH, and then dried at 60 °C (labelled as CF). The functionalization of CF with $\text{Cu}_3\text{SbS}_4\text{-Sb}_2\text{S}_3$ was carried out using a hydrothermal synthesis approach. 1mM $\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$ and 1.5mM $\text{SbCl}_3 \cdot 5\text{H}_2\text{O}$ were mixed in 100 mL of distilled water and sonicated for 20 min, the mixture was placed on a magnetic stirrer with the addition of 0.15g of CF and 2mm of thiourea and further stirred for 30 min. After stirring, the precursor mixture was transferred into a Teflon-lined stainless autoclave and placed in an oven for 24 h at 180 °C. After cooling to room temperature, the black powder was centrifuged with several washes of distilled water and ethanol. Finally, the obtained materials were dried at 60 °C in a drying oven and placed in a desiccator. The same procedure was followed to synthesize material with different ratios of Cu and Sb (1:1, 1.5:1, 0.5:1, 1:1.5 and 1:0.5) in order to optimize the best combination and labeled as $\text{Cu}_1\text{Sb}_1\text{S}/\text{CF}$, $\text{Cu}_{1.5}\text{Sb}_1\text{S}/\text{CF}$, $\text{Cu}_{0.5}\text{Sb}_1\text{S}/\text{CF}$, $\text{Cu}_1\text{Sb}_{1.5}\text{S}/\text{CF}$, and $\text{Cu}_1\text{Sb}_{0.5}\text{S}/\text{CF}$. The same reaction time, temperature, and CF concentration were followed to synthesize Sb_2S_3 on CF with 1mM $\text{SbCl}_3 \cdot 5\text{H}_2\text{O}$ and 2mM thiourea, and the final product was labeled as SbS/CF .

Characterization: The UV/Vis absorption spectroscopy analysis (UV/Vis-NIR) was performed using an ultraviolet-visible spectrophotometer LAMBDA 1050⁺, Perkin Elmer with an integrating sphere. A Philips PW1050/37 diffractometer was used to carry out the X-ray diffraction (XRD) analysis. X-ray photoelectron spectroscopy (XPS) was performed using an ESCALAB 250 (Thermo Fisher Scientific USA) spectrometer with an x-ray source monochromated Al K α 150W and energy pass 200 eV for the survey and 30 eV for high-resolution scans. The surface morphology and elemental mapping (SEM-EDS) analysis were carried out using an FEI Magellan 400 FEG-SEM with EDS detector, X-Max 80 mm² SDD (Oxford Instrument). The HR-TEM (High-resolution Transmission Electron Microscopy) micrographs were obtained via the JEOL ARM 200F microscope with 2 CS correctors of CC3M competence center of Institut Jean Lamour. The microscope was equipped with an MSC794 camera Gatan one view, JEOL HAADF detector, and a double-tilt sample holder. Hydrophilicity analysis was performed using the FTA 1000 Analyzer System for the contact angle measurements. Differential Scanning Calorimetry (DSC) analysis was carried out using a 1020 Series DSC 7 thermal analysis system, with the following temperature range 20 °C to 150 °C at 5 °C/min. The Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) was performed with a Perkin Elmer Optima 5300SV spectrometer.

Solar Desalination: The interfacial solar desalination experiments were conducted by preparing photothermal evaporators through vacuum filtration. Specifically, 0.1 g of the material was first dispersed in 20 mL of distilled water and sonicated to ensure uniform suspension. The dispersion was then deposited onto a glass microfiber membrane (Whatman GF/F, CAT No. 1825-047) using vacuum filtration. After filtration, the membrane was dried at 60 °C to enhance film adhesion and mechanical stability. The resulting coated membrane served as the active photothermal layer in the solar evaporator. Then, 40 mL brine solution was taken in a glass beaker (0.6 M NaCl solution in the deionized water that was 3.5 wt.% average global seawater salinity) covered with polyethylene foam as a thermal insulator. A piece of membrane, 1x1 cm², cut, was placed on the cotton sponge that facilitates water transport to the membrane and passes through the thermal insulator. The solar desalination experiment was performed under one sun radiation (air mass 1.5 global, AM1.5G, 100 Wcm^{-2}), and the relative humidity was 35%. The surface temperature of the membrane was recorded in the dry state and during the desalination process using a thermal camera (FLIR C3-X).

The evaporation rate of the material was calculated using the following equation;

$$\text{Evaporation rate} = \frac{\Delta m}{S} \times \tau \quad (1)$$

where Δm is the mass loss of water (kg), S is the area of the evaporation (m^2), and τ is the evaporation time (h).

Evaporation efficiency (η) is calculated by using the following equation;

$$\eta = \frac{m h_{lv}}{C_{opt} q_i} \quad (2)$$

where m is the mass flux $\text{kg m}^{-2} \text{s}^{-1}$, h_{lv} is the enthalpy of liquid, C_{opt} is the optimal concentration, and q_i is solar radiation KW/m^2 .

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

chalcogenides, circular economy, photothermal evaporators, plastic upcycling, solar desalination

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Upcycled PET-Derived Carbon Foam Functionalized with $\text{Cu}_3\text{SbS}_4\text{--Sb}_2\text{S}_3$ Heterostructures for Efficient Interfacial Solar Desalination

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Supporting Information

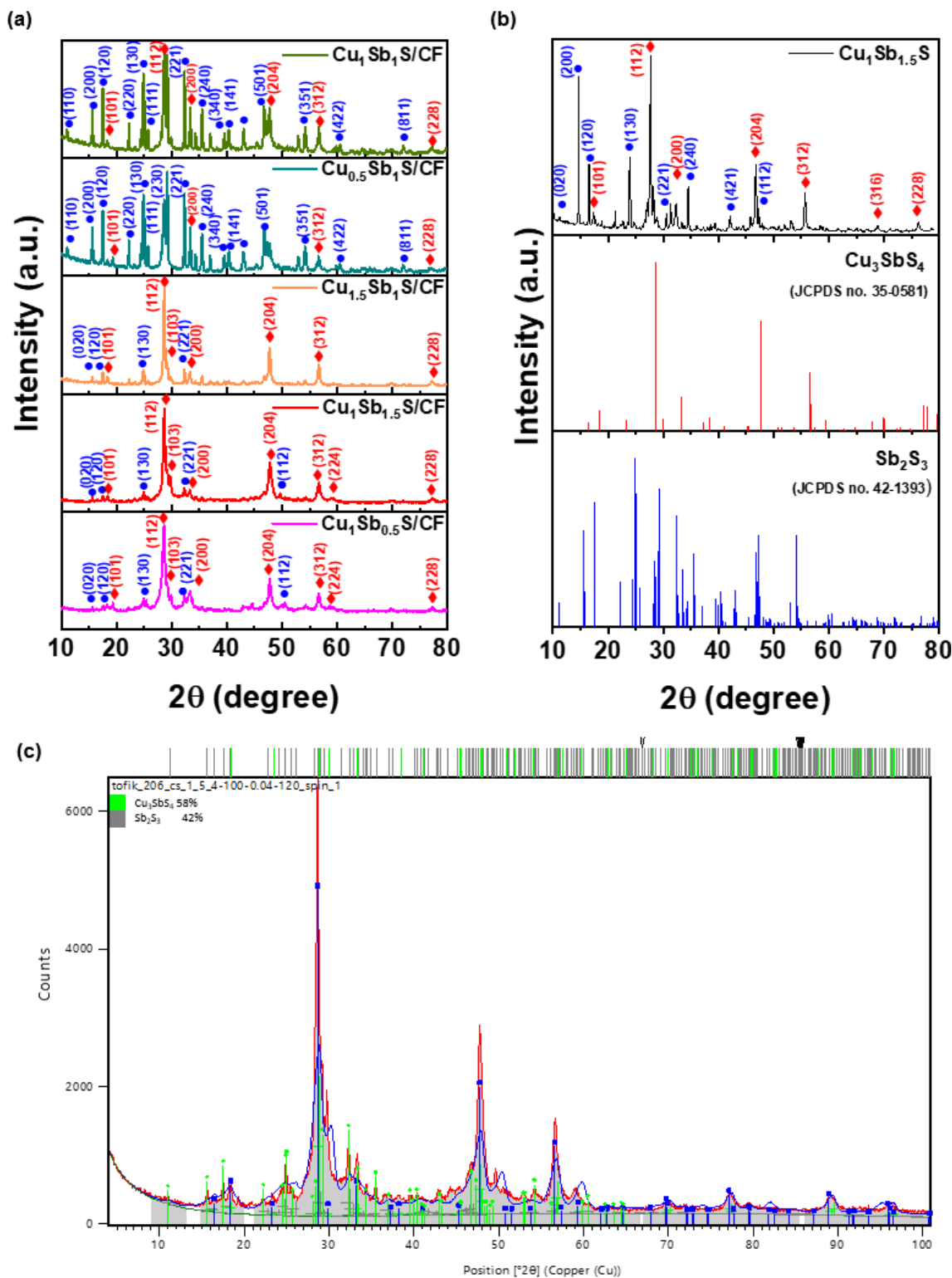


Figure S-1. (a) XRD pattern of the synthesized samples with varied concentration of Cu and Sb, (b) XRD pattern of $\text{Cu}_1\text{Sb}_{1.5}\text{S}$ without CF, (c) XRD Rietveld Refinement pattern of $\text{Cu}_1\text{Sb}_{1.5}\text{S}$.

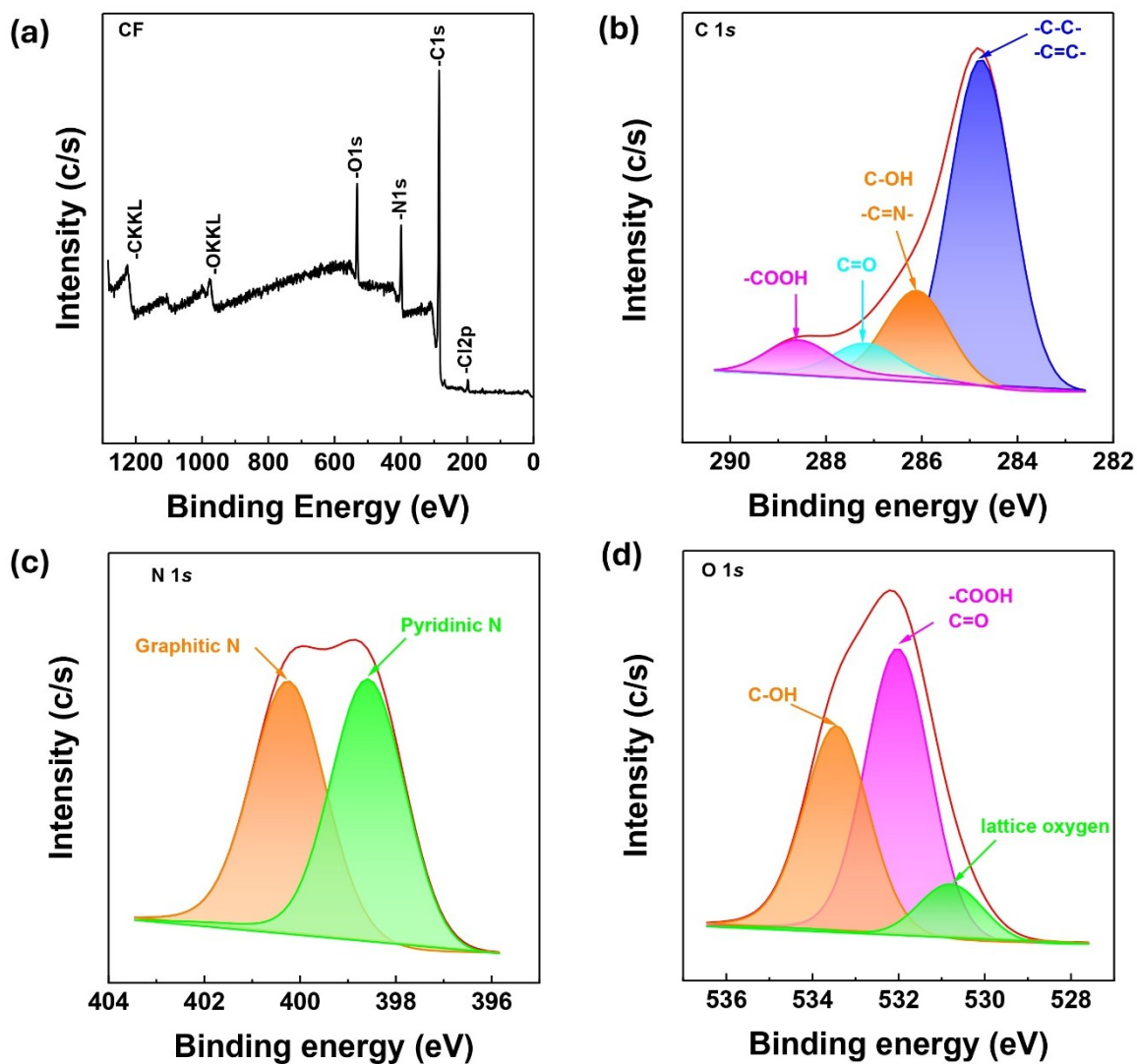


Figure S-2. (a) XPS survey spectrum of CF, high-resolution (b) C 1s, (c) N 1s, and (d) O 1s of CF.

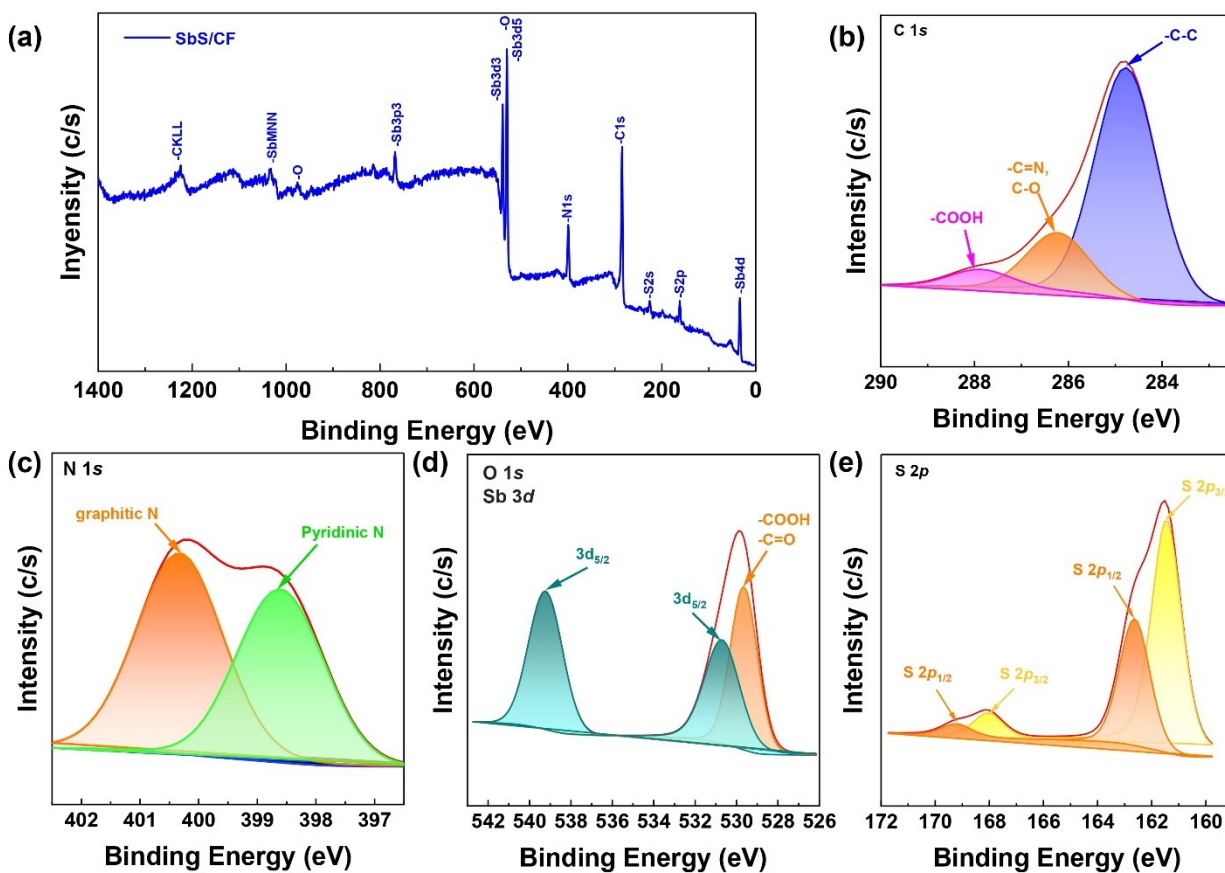


Figure S-3. (a) XPS survey spectrum of SbS/CF, high-resolution (b) C 1s, (c) N 1s, (d) O 1s and Sb 3d, and (e) S 2p of SbS/CF.

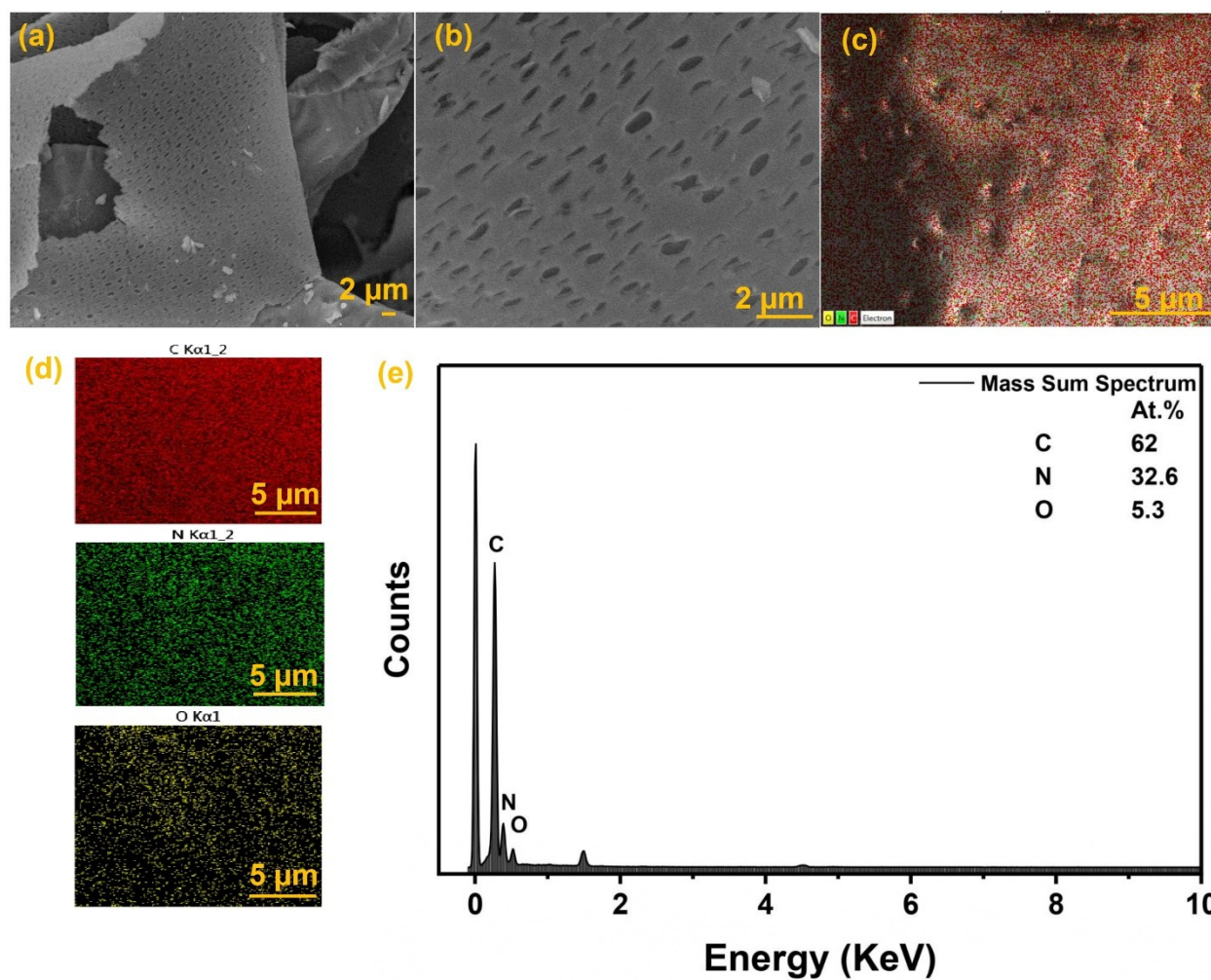


Figure S-4. (a-b) SEM images of CF, (c-e) elemental mapping and EDS spectra of CF.

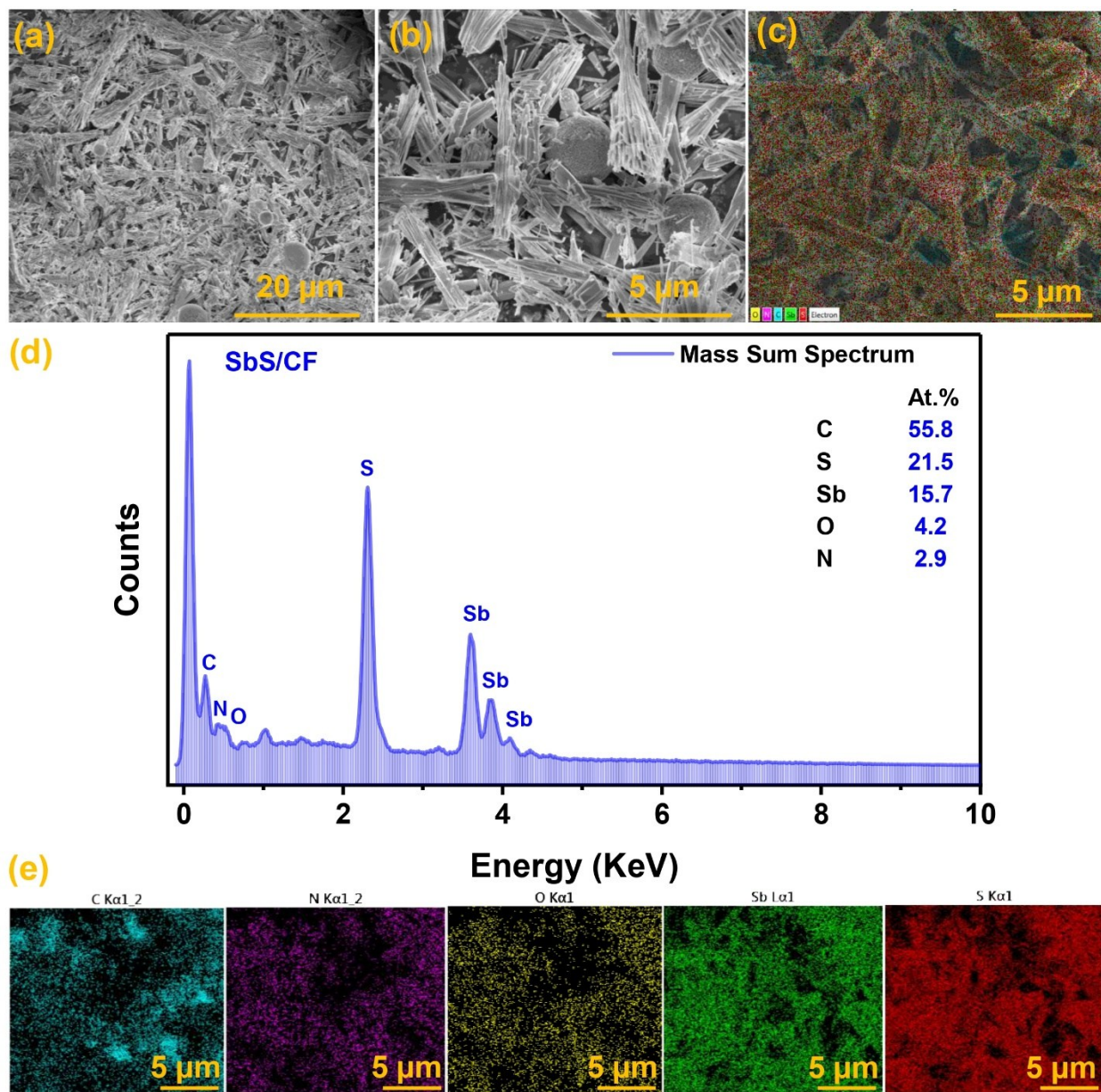


Figure S-5. (a-b) SEM images of SbS/CF, (c-e) EDS spectra, and elemental mapping of SbS/CF.

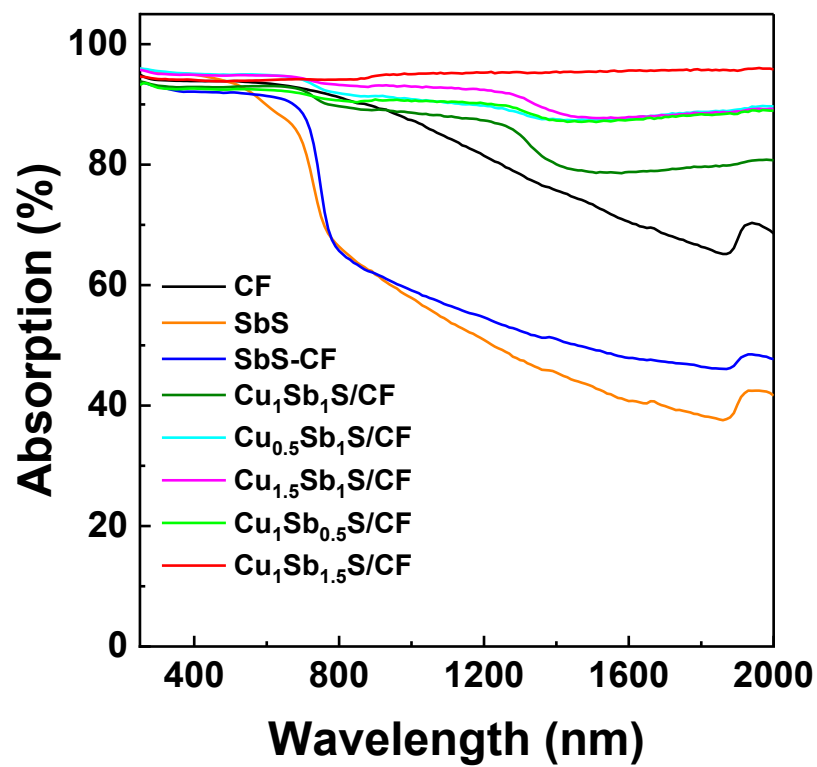


Figure S-6. UV/Vis-NIR spectra of all the synthesized samples.

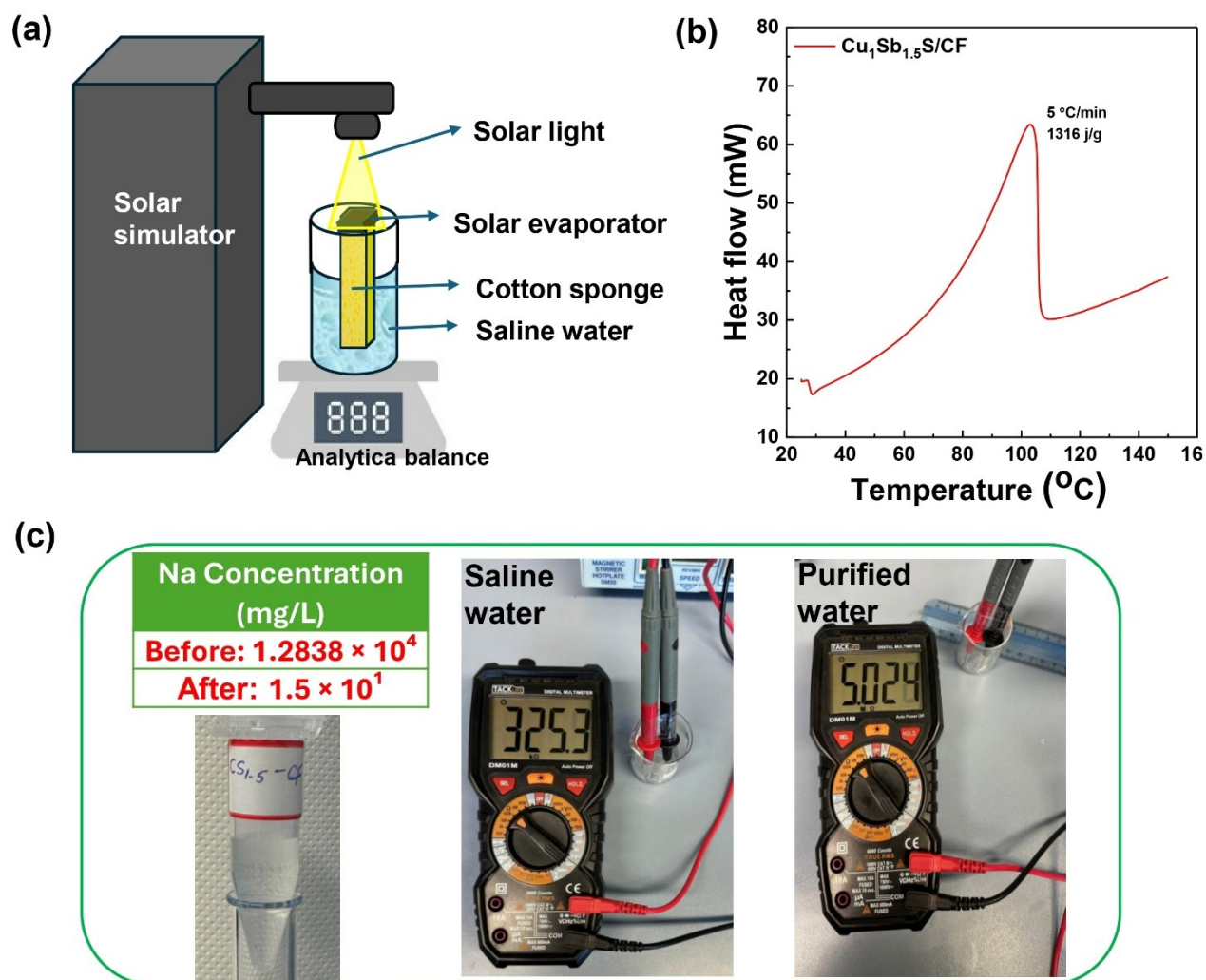


Figure S-7. (a) graphical illustration of solar desalination experiment, (b) DSC analysis, (c) Na concentration obtained from ICP-OES and resistivity measurement of saline and purified water.

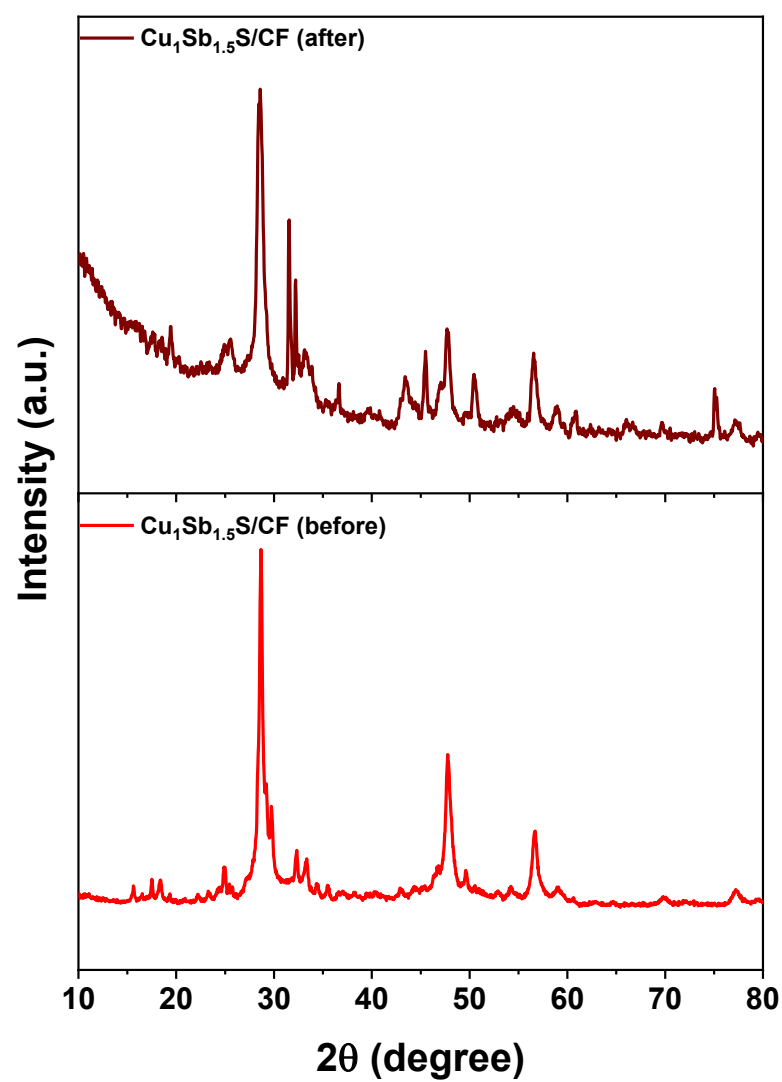


Figure S-8. XRD pattern of $\text{Cu}_1\text{Sb}_{1.5}\text{S/CF}$ before and after 300 minutes of solar desalination experiment.