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Energy Materials

Review

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Advances in photothermal water evaporation: synthesis, mechanisms, and coupled techniques

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Abstract

Recent advancements in light-driven interfacial water evaporation have underscored the potential of photothermal materials for producing clean water from various sources, including seawater, rivers, lakes, and wastewater. Despite these advancements, challenges in environmental management and energy conversion persist. The development of multifunctional photothermal materials and composites has addressed these challenges by integrating active species into water evaporation devices, thereby enhancing their performance and applicability. This review provides a thorough examination of recent progress in photothermal materials for water purification. It covers advances in material synthesis, optimization of evaporator configurations through various techniques, and their application in water treatment and clean water production. The discussion includes innovative heat management strategies designed to improve system efficiency. The review concludes by identifying current challenges and suggesting future research directions to advance the field of efficient water purification and clean water production.

Keywords: Photothermal materials, water purification, multifunctional composites, evaporator optimization, heat management strategies

INTRODUCTION

Water pollution and scarcity significantly affect global sustainability and public health, hindering human well-being and economic development. Population growth, urbanization, climate change, and environmental pollution worsen these challenges, particularly in developing nations[1,2]. Creating affordable freshwater remains a crucial socioeconomic issue, with current desalination methods consuming substantial energy[3]. Solar energy offers a promising solution to the water-energy nexus, providing limitless, eco-friendly power globally[4]. Conventional solar evaporation techniques generally heat the entire water volume in the reservoir, achieving a thermal efficiency of approximately 30%-45%[5,6]. In contrast, interfacial solar evaporation selectively heats only the air-liquid interface, yielding higher thermal efficiency at lower solar concentrations. Recent advances in photothermal materials and structural engineering have accelerated this progress[7]. Photothermal water evaporation employs the entire solar spectrum, converting it into heat for swift water evaporation and effective pollutant separation[8]. This method boasts high efficiency, scalability, and environmental compatibility, rendering it suitable for various water treatment purposes. Solar-powered interfacial photothermal conversion for water evaporation offers an eco-friendly and cost-efficient means of obtaining clean water from saltwater, lake water, or river water sources[9].

While photothermal materials and structures have made significant strides, their application in large-scale solar evaporation still faces considerable challenges. Issues such as salt crystal accumulation during desalination lead to material fouling, as it clogs the photothermal surfaces, necessitating frequent maintenance and reducing operational efficiency[10,11]. Another significant concern is heat losses from the photothermal layer to the surroundings, which limit the overall energy efficiency of solar-powered systems, especially during large-scale operations[12]. Furthermore, the intermittent nature of sunshine and microbiological contamination impeding light penetration represent a significant barrier to photothermal conversion, necessitating the development of energy storage or hybrid systems to provide continuous operation in wastewater treatment[13,14]. To overcome these challenges, integrating photothermal evaporation with catalytic degradation processes has shown promise in enhancing pollutant removal efficiency. This approach leverages the chemical reactions at the water-air interface, where materials such as metal nanoparticles, metal-organic frameworks (MOFs), and carbon-based compounds act as effective catalysts, speeding up degradation processes and improving water purity. These materials offer structural versatility and can be tailored for exceptional photothermal stability, strong sunlight absorption, and high conversion efficiency[15]. However, heat loss and inconsistent solar intensities continue to pose challenges, limiting continuous operation and overall efficiency. Integrating photothermal evaporation with energy conversion and storage technologies, such as tandem, hybrid, and self-powered generation, has the potential to improve electrical generation while also producing clean water and renewable energy[16]. This integrated approach not only manages the heat generated during evaporation to produce electricity but also stores excess energy, paving the way for more efficient, sustainable, and environmentally friendly long-term water treatment systems. Innovative strategies for water channel design, interface engineering, salt rejection during evaporation, and hybrid devices improve pollution removal and system efficiency[17]. Metal nanoparticles, MOFs, and carbon-based compounds serve as effective catalysts, expediting degradation processes. Integrating photothermal evaporation with energy conversion and storage technologies facilitates simultaneous clean water and renewable energy production.

This review presents a novel perspective by integrating and analyzing recent advancements in photothermal water evaporation and catalytic degradation. Unlike previous reviews that focus on isolated aspects, we offer a comprehensive examination of how these processes can be synergistically combined to enhance both energy conversion and water treatment efficiency. We provide an in-depth analysis of recent innovations, addressing current challenges and exploring the potential of integrating photothermal energy conversion with catalytic methods for improved water purification. This review not only highlights the advancements but also identifies gaps and suggests future research directions, aiming to drive the development of more effective and sustainable photothermal water purification technologies.

FUNDAMENTALS OF PHOTOTHERMAL WATER EVAPORATION

Principles and materials of photothermal conversion

Interfacial water evaporation driven by photothermal conversion relies on the transformation of solar or light energy into thermal energy, as depicted in Figure 1. The conversion mechanism for light-induced water evaporation involves the integration of light-absorbing materials within or on the surfaces of photothermal materials. These materials often include plasmonic nanoparticles or structures that exhibit localized surface plasmon resonances (LSPR), which enable the efficient absorption of solar energy with minimal reflectivity, thereby maximizing light absorption[18,19]. Upon light absorption, these nanostructures undergo non-radiative decay processes, known as plasmon decay, where the absorbed photon energy is rapidly converted into localized thermal energy due to the specific electronic and phononic properties of the materials[20]. This conversion leads to the formation of hot spots or localized heat sources within the photothermal material, particularly at the interface between the material and water. To maintain these heat sources localized and prevent their dissipation into the surrounding environment, porous materials and hierarchical structures are often employed[21]. These configurations effectively enhance the distribution of heat within the material, increasing the maximum surface area available for evaporation[22]. Moreover, the integration of hydrophilic materials and microarchitectures, such as micropillars and microchannels, is strategically designed to enhance capillary action. This ensures a continuous supply of water from the bulk reservoir to the heated regions and the material-water interface, thereby sustaining the evaporation process[23]. As the localized heat sources at the interface increase the temperature, water molecules gain sufficient kinetic energy to overcome intermolecular forces, allowing them to transition from the liquid phase to the vapor phase[24]. This phase transition is indicated by a rise in vapor pressure. The efficient design of the photothermal material ensures that this process occurs rapidly and continuously. The photothermal evaporation system includes components for gathering produced water vapor, preventing condensation, and promoting continuous evaporation[25]. Depending on the intended use of the photothermal water evaporation, the gathered water vapor is either condensed into liquid or released into the atmosphere.

Types of photothermal materials

The effectiveness of evaporation is greatly impacted by the choice of photothermal materials coating the device's surface. When choosing materials, it's crucial to assess their sunlight absorption and conversion efficiency. Metal nanoparticles, semiconductor materials, conjugated polymers [such as polypyrrole (PPy)], carbon-based materials, MOFs, covalent organic frameworks (COFs) and hydrogel materials are widely used due to their ability to efficiently capture solar energy [Figure 2]. These materials can provide significant activation energy, surpassing the energy input limit of up to 40 kJ/mol for water evaporation[26]. The photothermal effect of nanostructured materials enables the narrowing down of the heat modulation zone to the nanoscale[27].

Metal nanoparticles

Metal nanoparticles possess distinctive characteristics that render them well-suited for photocatalytic applications. Primarily, their small size results in a high surface-to-volume ratio, providing abundant active sites for catalytic reactions by exposing numerous kink and edge sites[28]. The augmented surface area fosters stronger interactions between nanoparticles and the targeted molecules, thereby leading to improved catalytic performance[29]. Moreover, the optical properties of metal nanoparticles, which are size-dependent, especially their ability to exhibit LSPR, enable efficient absorption and conversion of light[30,31]. Upon

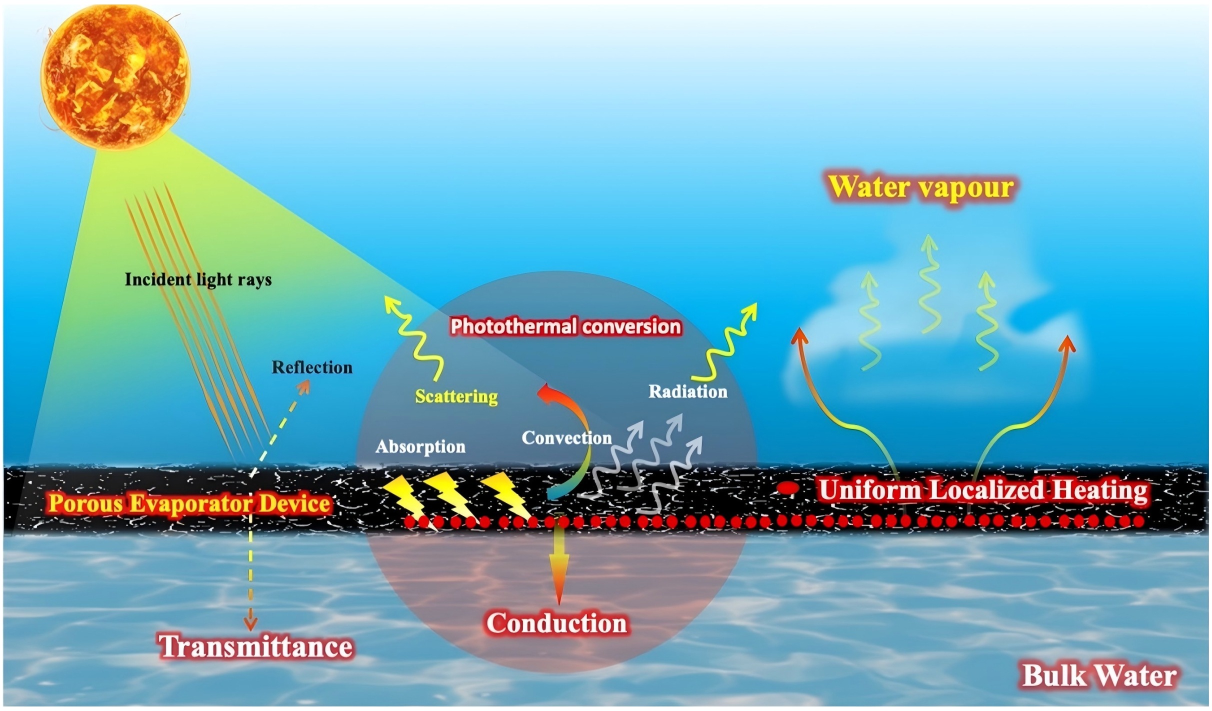

Figure 1. Schematic representation of the mechanism behind photothermal interfacial water evaporation.

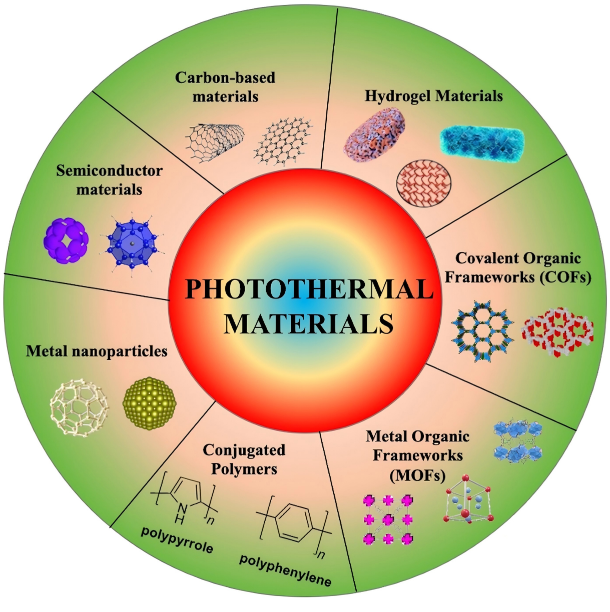

Figure 2. Types of overview of photothermal materials.

exposure to light of specific wavelengths, metal nanoparticles can produce highly energetic surface plasmons, thereby promoting photochemical reactions by facilitating charge transfer processes at the nanoparticle surface[32]. Moreover, the adjustable surface plasmon resonance (SPR) of metal nanoparticles allows for precise manipulation of their optical properties, such as absorption wavelength and intensity[33]. This adjustability facilitates the creation of photocatalytic devices that can efficiently utilize solar energy across various wavelengths. Additionally, metal nanoparticles possess excellent stability and recyclability, rendering them suitable for repeated utilization in photocatalytic applications[34]. Their resilience against photo corrosion and chemical degradation ensures reliability and durability in photocatalytic environments[35]. In summary, the exceptional amalgamation of expansive surface area, adaptable optical properties, and remarkable stability renders metal nanoparticles exceptionally enticing for photocatalytic endeavors, holding immense potential for addressing diverse environmental and energy challenges. Different types of metal nanoparticles have found applications in photocatalysis, leveraging their distinct attributes, particularly in photothermal applications such as interfacial water evaporation. Metals such as gold (Au) and silver (Ag) possess pronounced LSPR characteristics, enabling efficient light absorption across the visible spectrum. Moreover, they exhibit distinctive optical traits, including a customizable SPR within the visible to near-infrared (NIR) range[36]. They find extensive use in photocatalytic tasks such as breaking down organic pollutants, antimicrobial treatments, and generating hydrogen. Cui *et al.*, with deposition of gold nanoparticles (AuNPs) @c-silica hybrids onto filter fiber paper (FFP), achieved a superior solar thermal conversion efficiency of up to 94.6% under only one sun irradiation with this high conversion attributed to the synergistic photothermal effect between AuNPs and c-silica[37]. However, there are drawbacks to the widespread use of metal nanomaterials because of high costs typically involving noble metals. Synergistic composites, which combine metal nanoparticles with semiconductors, carbon-based materials, COFs, and MOFs, can significantly enhance photothermal and photocatalytic performance beyond that of the individual components[38]. For instance, the integration of bimetallic nanoparticle composites leverages the unique plasmonic properties of multiple metals, enabling more efficient light absorption across a broader spectrum. This results in enhanced overall photothermal conversion efficiency and increased photocatalytic activity[39]. These composite materials not only offer improved performance but also provide flexibility in tuning optical properties to match specific application requirements. Additionally, platinum (Pt), palladium (Pd), and copper (Cu) possess unique electrical and optical characteristics, rendering them suitable for applications such as CO_2 reduction, dye breakdown, and water refinement[40].

Semiconductor materials

Semiconductor materials, a promising avenue for photothermal conversion, exhibit distinctive traits that render them well-suited for photocatalysis due to their broad spectrum, ease of functionalization, and cost-effectiveness[41]. Their electrical band arrangement enables the capture of photons with energies matching or exceeding the bandgap threshold, leading to the generation of electron-hole pairs[42]. These carriers can participate in redox reactions, driving various catalytic processes. Moreover, semiconductor materials feature adjustable bandgaps, permitting customization of their absorption spectra to suit particular applications[43]. Their substantial surface area relative to volume and surface reactivity enhance their catalytic efficacy. Additionally, semiconductor photocatalysts exhibit durability, environmental friendliness, and suitability for operation under moderate reaction conditions, rendering them highly suitable for diverse photocatalytic tasks such as pollutant breakdown, water cleavage, and CO_2 reduction[44-46]. In the realm of photothermal conversion, semiconductors also operate through non-radiative relaxation. When exposed to light of energy equal to or greater than their bandgap, semiconductors become excited, generating electron-hole pairs. Subsequently, these photo-excited electrons and holes transition to lower energy states, emitting energy in the form of phonons. This phenomenon results in localized heating of the lattice, establishing a temperature gradient based on the material's optical attributes and characteristics of bulk/surface recombination[47]. Additionally, the semiconductor's narrow band gap significantly diminishes electron-hole pair recombination, thereby augmenting non-radiative relaxation light absorption. Moreover, the plentiful π orbitals facilitate electron excitation and thermal vibration within the lattices[48]. Various semiconductor materials, including metal oxides (such as TiO_2, Si, ZnO, Fe_3O_4, $BiVO_4$, WO_3, and Bi_2WO_6) and chalcogenides, have been investigated for their potential in photothermal conversion and interfacial water evaporation, owing to their distinctive characteristics[49-55]. Heterojunction composites formed by combining two different semiconductors offer significant advantages, particularly in enhancing charge separation and transfer, which leads to improved photocatalytic activity and photothermal performance[56]. Lv *et al.* employed a two-step hydrothermal process to synthesize a two-dimensional (2D) $MoS_2/ZnIn_2S_4$ composite[57]. This composite demonstrated excellent solar absorption capabilities, achieving a water evaporation rate of 1.54 $kg·m^{-2}·h^{-1}$. Moreover, the $ZnIn_2S_4$ deposition on MoS_2 facilitated a type □ heterojunction construction, resulting in a remarkable 98.7% photodegradation efficiency for dye wastewater while effectively eliminating secondary contamination. The advancement of such synergistic composites based on semiconductor materials not only boosts performance but also broadens the scope of their applications, paving the way for innovative solutions in various fields.

Conjugated polymers

Conjugated polymers consist of organic compounds featuring alternating single and double bonds along their backbone, facilitating the delocalization of π-electrons[58]. The distinctive π-conjugation of conjugated polymers imbues them with several desirable attributes, including superb electrical conductivity, optical transparency, adjustable bandgap, and mechanical flexibility[59]. Moreover, their chemical composition can be easily modified through functionalization or copolymerization, enabling precise manipulation of their electrical and optical characteristics[60]. With outstanding stability, low toxicity, and compatibility with various substrates, conjugated polymers hold promise for diverse applications in optoelectronics, sensing, energy conversion, and catalysis[61-63]. Their π-conjugated configuration facilitates exceptional light absorption spanning a broad spectrum, encompassing ultraviolet (UV), visible, and even NIR regions, thereby enhancing the generation of photoexcited charge carriers[64]. Moreover, the dispersed π-electrons function as efficient electron donors and acceptors, expediting the rapid separation and transfer of charges essential for photocatalytic reactions[65]. Furthermore, their bandgap can be adjusted through chemical design, allowing precise control over their photocatalytic activity and selectivity towards specific target reactions. In summary, the distinctive electronic structure, optical properties, and chemical flexibility render conjugated polymers highly suitable for photocatalysis[66-68]. Recent advancements have highlighted the potential of synergistic composites incorporating conjugated polymers. These innovative materials merge conjugated polymers with complementary components such as metal nanoparticles, carbon-based materials, and inorganic semiconductors, resulting in significantly enhanced photothermal and photocatalytic properties. Guo *et al.* synthesized a novel composite aerogel (CMC/SCMP) by physically doping and freeze-drying a combination of sulfonated conjugated microporous polymer (SCMP) and carboxymethyl cellulose (CMC)[69]. This CMC/SCMP aerogel exhibited outstanding adsorption capacities for Pb^{2+} and methylene blue (MB), with maximum values of 94.93 $mg·g^{-1}$ and 294.84 $mg·g^{-1}$, respectively. Furthermore, by applying PPy onto the CMC/SCMP aerogel surface, they developed a solar steam generator (CMC/SCMP-PPy) that achieved a remarkable photothermal conversion efficiency, with an evaporation rate of 85.57% under 1 $kW·m^{-2}$ irradiation. These synergistic composites capitalize on the unique attributes of each component, leading to superior functionality and presenting promising pathways for the development of efficient and sustainable photochemical processes.

Carbon-based materials

In addition to metal nanoparticles, semiconductor materials, and conjugated polymers, carbon-based materials have emerged as compelling options for photothermal conversion, owing to their distinctive properties and versatility[9,70]. Graphene, a 2D carbon allotrope, possesses robust thermal conductivity and optical absorption capabilities, rendering it well-suited for photothermal conversion[71]. Its expansive surface area[72] and adaptable electronic structure[73,74] facilitate precise management of light absorption and heat emission, rendering it suitable for photothermal therapy, water purification, and solar steam generation.

Additionally, carbon nanotubes (CNTs) boast exceptional mechanical resilience, thermal endurance, and electrical conductivity, making them well-suited for photothermal conversion endeavors. Their linear structure allows for efficient light absorption and swift heat dissipation[75], resulting in enhanced photothermal efficacy and functionality. CNT-based photothermal materials have showcased diverse applications, encompassing cancer treatment, desalination, and solar energy harvesting. Carbon-based nanomaterials, including carbon dots and nanohorns, offer distinct benefits in photothermal conversion. Carbon dots, leveraging quantum confinement effects and modifiable surface chemistry, demonstrate exceptional light absorption within the visible and NIR spectra. This attribute enables efficient photothermal conversion, particularly advantageous for applications in biological imaging and treatment[76,77]. In contrast, carbon nanohorns exhibit a distinctive horn-like morphology characterized by a vast specific surface area and outstanding light absorption capabilities[78]. These attributes render them exceptional for applications in photothermal therapy, drug delivery, and energy conversion. Jin *et al.* developed a cellulose-based composite film material by incorporating CNTs and reduced graphene oxide (CNT-rGO)[79]. This material featured a microporous structure, which enhanced its stability when floating on water and achieved an impressive photothermal evaporation rate of 1.85 $kg \cdot m^{-2} \cdot h^{-1}$ with a photothermal conversion efficiency of 90.2%[79]. Similarly, Wang *et al.* demonstrated a straightforward yet effective method to boost photothermal performance by integrating 2D rGO with 1D multi-walled CNTs (MWCNTs), achieving a solar thermal conversion efficiency of 80.9%[80]. These synergistic composites harness the unique properties of carbon-based materials, significantly improving photothermal efficiency and offering substantial potential for advanced solar-driven applications.

Metal-organic frameworks

Metal-organic frameworks (MOFs) have garnered attention as promising candidates for photothermal conversion in interfacial water evaporation owing to their unique structural and chemical characteristics[81]. They boast extensive surface areas, adjustable pore sizes, and customizable functionalities, rendering them well-suited for effective light absorption and heat generation[82,83]. The crystalline structure of MOFs offers precise manipulation over their composition and morphology[84] enabling the development of MOF-based devices with enhanced photothermal conversion efficiency[85]. Modification of the organic ligands within MOFs can enhance interfacial water evaporation by improving water adsorption, modifying surface wettability, and facilitating efficient heat transfer. Collectively, the exceptional properties of MOFs position them as ideal materials for advancing photothermal conversion in interfacial water evaporation, with promising applications in solar desalination, wastewater treatment, and sustainable energy production[86]. In recent years, synergistic composites incorporating MOFs have become a cutting-edge focus in the development of photothermal materials. These advanced composites combine the unique properties of MOFs, such as their high surface area and tunable pore structures, with the exceptional thermal conductivity and light absorption capabilities of graphene. The integration of MOFs with graphene leads to a significant enhancement in photothermal conversion efficiency and accelerates water evaporation rates. This synergy surpasses the performance of the individual components, highlighting the promising potential of MOF-graphene composites for advanced photothermal applications[87,88].

Covalent organic frameworks

These crystalline organic polymers, structured in two dimensions, boast robust covalent bonds, expansive surface areas, and adjustable pore architectures, facilitating efficient light absorption and conversion into heat[89]. Their π-conjugated framework fosters robust interactions with light, resulting in heightened photothermal conversion efficiency[90]. With chemical stability[91] and mechanical robustness[92], they ensure prolonged functionality even under demanding operational conditions. Their porous nature enables ample water adsorption and evaporation surfaces, facilitating swift water movement and elevated evaporation rate[93,94]. The modular synthesis approach of covalent organic frameworks (COFs) offers precise control over their structural and chemical characteristics, enabling customization of their photothermal performance to suit specific application requirements. The integration of COFs into synergistic composites marks a significant advancement in photothermal materials. By combining COFs with materials such as plasmonic nanoparticles or carbon-based elements, these composites achieve enhanced photothermal performance. For example, COF-metal nanoparticle composites leverage the strong light absorption properties of plasmonic nanoparticles alongside the high surface area and efficient thermal management capabilities of COFs, resulting in superior photothermal conversion and application potential[95]. This combination enhances photothermal conversion efficiency and accelerates water evaporation rates, surpassing the capabilities of the individual components. COFs stand out as a promising material group for photothermal conversion in interfacial water evaporation, poised to catalyze advancements in solar-powered water purification and energy harvesting technologies[96].

Hydrogel materials

Hydrogels are emerging as promising materials in the field of photothermal water evaporation due to their unique properties and versatility. These three-dimensional (3D), hydrophilic polymer networks are capable of retaining significant amounts of water, making them ideal candidates for solar-driven water evaporation applications[97]. Their high water retention and excellent light absorption capabilities are critical for efficient evaporation. Hydrogels facilitate continuous water transport due to their ability to absorb and retain water within their polymer matrix, thereby minimizing heat loss by localizing heat at the surface[98,99]. To enhance the solar absorption of hydrogels, various photothermal agents such as carbon-based materials and metal nanoparticles are incorporated. These agents improve the hydrogel's ability to convert light into heat, thereby increasing the temperature of both the hydrogel and the water contained within it[100]. Recent advancements include the development of composite hydrogels that integrate multiple photothermal agents and additional materials, enabling dual functionality for both photothermal water evaporation and electricity generation. This integration ensures a continuous supply of heat energy for extended applications[101]. For instance, Li *et al.* demonstrated a bifunctional solar evaporator utilizing a polyelectrolyte hydrogel-functionalized photothermal sponge[102]. This device achieved a water evaporation rate of 3.53 $kg \cdot m^{-2} \cdot h^{-1}$ and a solar energy conversion efficiency of 98.6%, along with a voltage output of 0.972 V and a current density of 172.38 $\mu A \cdot cm^{-2}$ under high-concentration brine conditions and one sun irradiation. Hydrogel-based systems can be synthesized using straightforward methods and biodegradable materials, which aligns with sustainability objectives. Their scalable production capabilities enhance their suitability for a range of applications, including desalination, water evaporation, and purification. The adaptability of hydrogels to diverse environmental conditions further supports their potential as effective and eco-friendly solutions in these areas.

COUPLED TECHNIQUES: DESIGN STRATEGIES

Evaporators [Figure 3A][103], essential in coupled techniques for achieving photothermal water evaporation, typically consist of membranes or hydrogels[104]. These components exhibit high water vapor permeability alongside low thermal conductivity, essential for effective water vapor generation[105]. For instance, the melamine sponge [Figure 3H][106], a commonly used porous substrate in solar steam generation, boasts exceptional hydrophilicity, a porous structure, affordability, and low thermal conductivity[107], all pivotal for efficient water vapor production. Incorporating photothermal materials onto the evaporator surface enhances light absorption, thereby converting it into heat for localized heating, expediting water evaporation. Strategies for heat management, such as thermal insulation layers or coatings, are deployed to minimize heat dissipation to the surroundings while maximizing energy efficiency[108]. Streamlining water transport, optimizing heat utilization, and enhancing cost-effectiveness of these evaporators are paramount

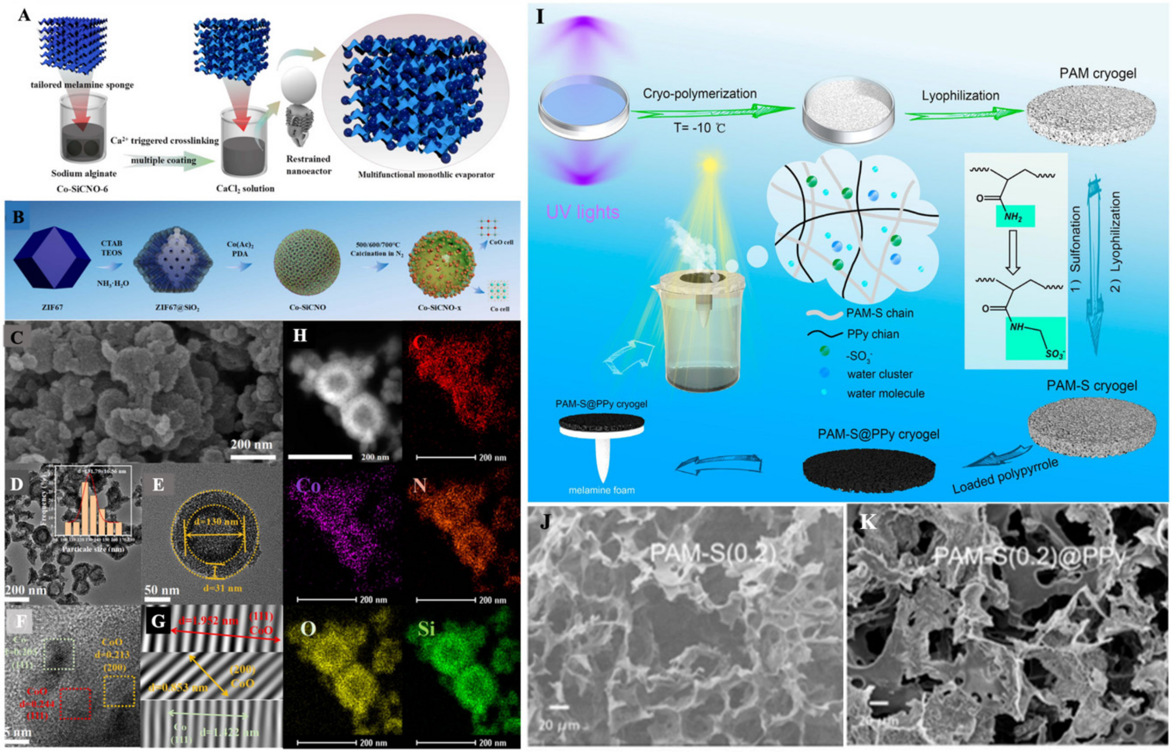

Figure 3. ((A) Fabrication of integrated Co-SiCNO-x evaporator for water purification and evaporation. (B) Schematic representation of the synthesis of Co-SiCNO-x. Representative SEM image (C), TEM image (D and E), HRTEM image (F), inverse FFT pattern of selected regions (G), HAADF-STEM image (H) and corresponding elemental mapping images of Co-SiCNO-6. These figures are quoted and reproduced with permission from Zhu *et al.*[103] Copyright 2024 Royal Society of Chemistry. (I)Sulfonated PAM/PPy Cryogels with Lowered Evaporation Enthalpy for Highly Efficient Photothermal Water Evaporation. (J, K) SEM images of PAM-S (0.2) cryogel before and after loading polypyrrole. These figures are quoted with permission from Hou *et al.*[106] Copyright 2023 Polymers-MDPI.

for their practical deployment across various applications, including water purification, desalination, and wastewater treatment.

Material synthesis

The efficiency of the photothermal water evaporation process heavily relies on the design of the catalytic material, necessitating meticulous selection and engineering of materials with specific properties to enhance their catalytic activity in chemical reactions such as pollutant degradation or energy conversion [Figure 3I-K][106]. Crucial considerations encompass the choice of catalytic active sites, surface area and porosity, along with stability and compatibility with the photothermal component. Commonly employed nanomaterials such as metal nanoparticles, semiconductor materials, and carbon-based materials are favored due to their high surface area, tunable pore structures, and unique optical and electrical properties. Utilizing natural plant materials via carbonization and graphitization presents an economically viable and established method for solar evaporator production, yielding remarkable performance. Surface functionalization and doping with heteroatoms such as nitrogen and sulfur are frequently utilized to augment catalytic activity and selectivity. In our research, we employed polyhedral ZIF67 as the initial template, subsequently modifying it with mesoporous silica and coating it with cobalt-incorporating polydopamine (PDA), followed by graphitization, resulting in the creation of the Co-Si/C hybrid hollow nanoreactor [Figure 3B][103]. This complex boasts a hollow configuration comprising abundant mesoporous channels, ensuring high dispersity and fine size of the metal species within the mesochannel, thereby facilitating efficient diffusion and contact of molecules during the reaction process. This configuration provides ample catalytic and polar adsorptive sites. Additionally, the silica network contributes to the stability of the carbon framework and active metal species, ensuring structural integrity and minimizing metal leaching during catalytic reactions [Figure 3C-H][103]. Employing the integrated photothermal monolith evaporator, featuring Co-SiCNO-6, demonstrates remarkable water purification and evaporation rates of 2.0 kg·m^{-2}·h^{-1} and a photothermal conversion efficiency of 93.14%. Du *et al.* employed the polyhedral ZIF67 nano template, followed by modification with mesoporous silica and the incorporation of Cu via PDA coating[109]. Subsequent thermal treatment was conducted to deposit Cu metal onto the silica layer, resulting in a hollow porous nanoreactor comprising Cu and Co_2SiO_4 confined within a SiC hybrid shell. The uniform dispersion of ultrafine bimetallic species across the mesoporous hollow shell ensures optimal accessibility of catalytic active sites. The resulting nanoreactor exhibits exceptional catalytic degradation performance for norfloxacin (NFX), attributed to its large specific surface area, enhanced electrical conductivity, and synergistic effects of the bimetallic composition. Moreover, anchoring the nanoreactor onto a melamine sponge as a monolith evaporator significantly enhances both the evaporation rate and degradation efficiency of contaminants, underscoring its promising practical application potential. Moreover, Li *et al.* employed electrospinning and carbonization techniques to fabricate FeNi alloy nanostructures embedded in a graphitic CNF matrix using Prussian blue analogs (PBAs) as precursors[110]. The optimized $FeNi_3$/CNF-3 sample exhibits a high specific surface area, broad light absorption, abundant micro/mesopores, and well-organized interlayer channels. These characteristics contribute to an efficient water evaporation rate of 1.51 kg·m^{-2}·h^{-1} and a solar evaporation efficiency of 93.3% under one sun irradiation. The results highlight the adaptability and efficiency of employing polyhedral ZIF67 as a template for crafting intricate nanoreactors and evaporators. These engineered constructs showcase remarkable solar evaporation efficiencies, significant water evaporation rates, and outstanding catalytic performance, suggesting potential uses in energy conversion and water purification. The addition of additional modifications, such as metal integration, carbonization methods, and mesoporous silica, enhances the overall structural stability and dispersion of active species in the final composites.

Hierarchical design of structures

The concept of hierarchical morphology in structure design has recently garnered attention as a crucial strategy[111]. It typically integrates porous materials, nanostructured surfaces, and interconnected networks, synergistically enhancing photothermal conversion efficiency for interfacial water evaporation. These structures exhibit multiscale features ranging from the nanoscale to the microscale, offering significant advantages tailored to maximize light absorption, localize heat, and improve evaporation kinetics [Figure 4A and B][112]. On the nanoscale, photothermal materials incorporate plasmonic nanostructures such as metallic nanoparticles or nanopatterns, which generate LSPR upon illumination. This effect efficiently converts incident light into heat, creating localized hot spots[20,113]. The hierarchical organization of plasmonic nanostructures within a porous or structured matrix enhances light trapping, ensuring uniform heat distribution across the material [Figure 4C][114]. For example, Wang *et al.* contrasted flat surfaces with porous nanostructures in their review due to the high refractive index of photothermal materials, which results in significant light reflection [Figure 4F and G][8]. The highly porous nature of hierarchical structure induces multiple reflections within the pores, thereby amplifying light absorption. This effect is strongly dependent on the angle of incident light, as demonstrated in hierarchical graphene foam [Figure 4D and E][115] and cauliflower-shaped hierarchical copper nanostructures [Figure 4A and B][116], both of which exhibit significantly lower reflectivity compared to non-hierarchical, flat-surface materials. This underscores the significance of hierarchical structures in enhancing solar conversion efficiency. This implies that incorporating plasmonic nanoparticles onto a porous substrate could enhance localized heating through plasmonic resonance while ensuring adequate thermal dispersion. Moreover, integrating hydrophilic materials into hierarchical microarchitectures, such as micropillars, microchannels, or microstructured surfaces, at the nano and microscales[117-119] facilitates water uptake and transfer to the evaporation surface.

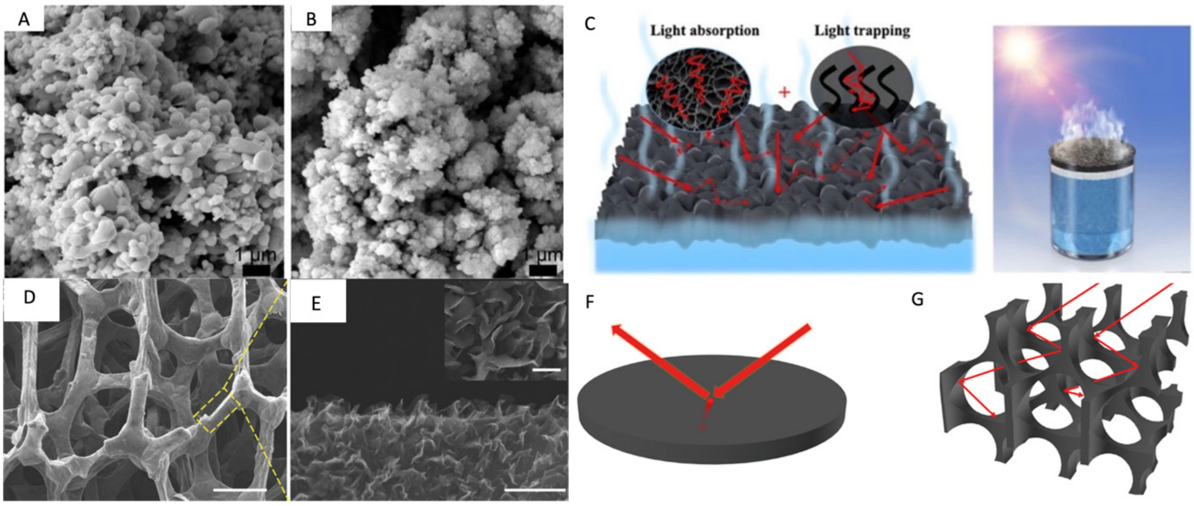

Figure 4. (A, B) Magnified SEM images of micro-nano structures fabricated by fs laser on Cu surfaces. This figure is quoted with permission from Fan *et al*.[116] Copyright 2016 Royal Society of Chemistry. (C) A schematic drawing of hierarchical structured evaporators providing a synergistic performance in light absorption and trapping. This figure is quoted with permission from Lei *et al*.[114] Copyright 2021 Springer Nature (D, E) SEM images of the hierarchical-Graphene foam. This figure is quoted with permission from Ren *et al*.[115] Copyright 2017 Wiley-VCH (F, G) Comparison of a flat surface to a hierarchical structure in terms of their light reflection and dependence on the incident light angle. This figure is quoted with permission from Wang Peng[8]. Copyright 2018 Royal Society of Chemistry.

This ensures a continuous water supply to the heated interface for sustained evaporation[120,121]. This hierarchical arrangement of microstructures enhances heat dissipation and evaporation, thereby increasing the overall evaporation rate[21]. The synergistic interplay of these hierarchical morphologies across different length scales enables photothermal water evaporation systems to achieve high evaporation rates, energy efficiency, and versatility. Inspired by natural systems[122], this hierarchical design approach utilizes recent manufacturing methods to fully realize the potential of solar-powered water purification and desalination technology. Recent advances in biomimetic engineering have led to the development of natural cellulose sponges with unique hierarchical structures, making them exceptional candidates for photothermal applications. These biodegradable materials align perfectly with the growing demand for sustainable solutions in environmental remediation. Saleque *et al.* engineered a chemically modified luffa sponge (LS) derived from the mature fruit of Luffa cylindrica (LC)[123]. This innovative approach transformed the LS into a highly effective solar photothermal material for water purification. By employing dopamine treatment and candle soot surface coating, the researchers significantly enhanced the hydrophilicity and solar absorbance of the LS, achieving a solar evaporation rate of up to 1.30 $kg \cdot m^{-2} \cdot h^{-1}$, five times higher than that of freshwater under one sun illumination.

Configuration of evaporator

Evaporator membrane structures are engineered to effectively separate water vapor from liquid by leveraging their porous nature[124]. This assists in filtering out pollutants as water vapor easily permeates through. The size and placement of these pores also impact their separation capabilities[125]. Consistent performance is ensured through uniform pore diameters, which are typically preferred for greater selectivity at lower flux rates. Surface modification techniques such as hydrophilization and hydrophobization can enhance water wettability or repellency on membrane surfaces[126,127]. The structure is configured in various geometries[128] based on specific application requirements, each offering advantages in terms of surface area, packing density, and ease of assembly. The integration of photothermal materials into membranous evaporators relies heavily on the substrate materials, which play crucial roles in light absorption, heat generation, and water transport, while also providing structural support [Figure 3J and K][106]. The choice of substrate material critically affects the system's overall performance, efficiency, and durability. Optimal substrates exhibit high absorptivity and low reflectivity, good thermal conductivity, high porosity, and hydrophilicity, and resistance to harsh environmental conditions, such as seawater. Recent advancements have focused on developing sustainable, strategically engineered substrates, with significant attention given to natural materials such as wood and sponges. For example, Xie *et al.* demonstrated an eco-friendly method for constructing a conical 3D wooden evaporator using flexible wood as the substrate and a tannic acid (TA) complex as the light-absorbing material, achieving a water evaporation rate of 1.79 $kg{\cdot}m^{-2}{\cdot}h^{-1}$ approximately 1.6 times higher than conventional 2D evaporators[129]. A carefully selected substrate enhances photothermal conversion, ensures continuous water supply, and withstands environmental challenges, thereby facilitating effective and sustained water evaporation.

Furthermore, photothermal materials with suitable properties, such as excellent light absorption and thermal conversion efficiency, are carefully selected[130]. These may encompass plasmonic nanoparticles, renowned for their unique optical characteristics arising from their interaction with electromagnetic radiation, leading to phenomena such as SPR. This results in heightened light absorption, scattering, and confinement at the nanoparticle surface[131]. Integrating these photothermal materials involves techniques aimed at maximizing solar radiation absorption and converting it into thermal energy for water evaporation. These techniques are categorized into two main groups: direct incorporation and modification of the evaporator surface.

Direct incorporation

Techniques for the direct incorporation of photothermal materials, such as plasmonic nanoparticles[132] or carbon-based materials, include *in-situ* growth[133], deposition[134], and coating[135]. These methods immobilize the materials onto the surface or embed them within the membrane of the evaporator [Figure 5A][136]. For example, Wang *et al.* discovered that using PPy doped with phytic acid (PA) as a mediating layer significantly promoted the growth of Prussian blue (PB) on cotton fibers (CFs)[136]. The PB deposition ratio increased from 12.29% (PB@CFs) to 32.4% (PB/PPy@CFs). The PA-doped PPy also influenced the PB growth time [Figure 5B and C][136], likely due to the chelation effect between the phosphate group in PA and the Fe_3^+ in PPy, resulting in better *in-situ* PB growth. However, beyond certain conditions, the deposition ratio of PB decreased, possibly because excessive PA molecules occupied the active sites of PPy [Figure 5C][136]. The growth of PB on PPy@CFs was completed in four hours, resulting in excellent light absorption, hydrophilicity, wettability, and photothermal properties. The surface could heat up to 81.5 °C under one sun illumination, with a water evaporation rate of 1.36 $kg{\cdot}m^{-2}{\cdot}h^{-1}$ and a photothermal conversion efficiency of 90.96% (PB/PPy@CFs), along with good stability. This suggests that these techniques require careful design and characterization to be effective. Similarly, Du *et al.* created homodispersed SiO_2 nanospheres (SiO_2 NS), which were subsequently coated with a liquid-phase Co/PDA and carbonized, resulting in unique SiO_2@Co/C bifunctional nanospheres [Figure 5D][137]. The catalyst, consisting of ultrathin carbon, ultrafine plasmonic Co_3O_4, highly exposed active sites on the surface of nanospheres [Figure 5E-G][137], and a well-developed interconnecting N-containing network structure, achieved excellent performance in contaminant degradation and showed potential to enhance photothermal conversion efficiency for solar-driven interfacial water evaporation. Our group also constructed a carbon layer-confined bimetal FeCo-modified silica nanosphere, which was employed for PMS activation and interfacial solar-driven water evaporation under sunlight irradiation[138]. This system achieved an evaporation rate and efficiency of 1.26 $kg{\cdot}m^{-2}{\cdot}h^{-1}$ and 76.81%, respectively. These studies highlight the broad application potential of photothermal materials in pollution separation and freshwater restoration.

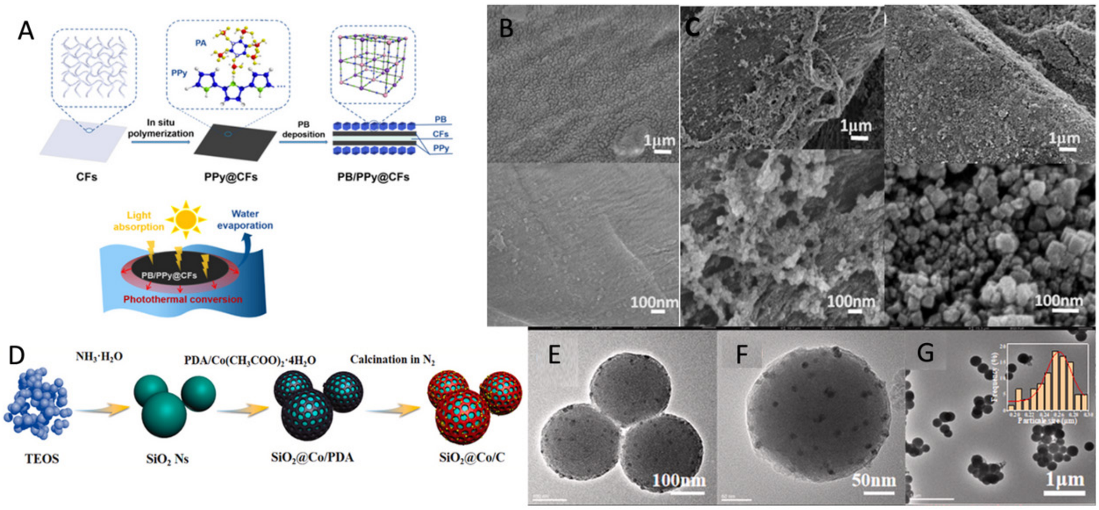

Figure 5. (A) Schematic illustration of preparation and photothermal interfacial water evaporation application and (B, C) SEM of in-situ growth of Prussian Blue on polymer [PB/PPy@CFs] composite. This figure is reproduced and quoted with permission from Wang *et al*.[136] Copyright 2022 Polymers-MDPI (D) Synthetic illustration for the targeted material of SiO_2@Co/C. (E-G) TEM images showing inert particle distribution of SiO_2@Co/C. These figures are quoted with permission from Du *et al*.[137] Copyright 2023 Elsevier.

Modification of evaporator surface

This can be achieved using methods such as dip coating[107], spin coating[139], and chemical vapor deposition[140], which enable precise control over the photothermal layer's thickness and coverage. Shao *et al.* utilized the interfacial gelation approach to selectively coat 3D porous substrates with various photothermal compounds[107]. In their study, they successfully coated rGO nanosheets, CuS cubic particles, CuO microparticles, and PDA nanoparticles onto 3D porous sponges [Figure 6G][107]. The rGO-coated sponge achieved a maximum evaporation rate of 1.69 $kg \cdot m^{-2} \cdot h^{-1}$ and an energy efficiency of 94.9%. The interfacial gelation coating method prevented material penetration, saving over 75% of the photothermal materials while maintaining a high evaporation rate. A 3 mm thick rGO-sponge (RS) prepared via interfacial dip-coating [Figure 6B and E][107] demonstrated exceptional light absorption (> 95%) across the UV-Vis-NIR spectrum, significantly outperforming a 3 mm thick sponge (75%) and a 10 mm thick sponge (85%) prepared by standard dip-coating [Figure 6A and D][107]. The standard dip-coating process involved immediate immersion of the sponge [Figure 6C and F][107] in rGO, whereas the interfacial gelation dip-coating required soaking the sponge in a 0.25 wt.% $CaCl_2$ solution for 30 s before dipping it in the rGO-SA solution. This study showcased the versatility of the interfacial gelation approach for selectively coating various photothermal materials, highlighting its potential for large-scale production of cost-effective 3D solar evaporators for efficient solar steam generation and broader practical applications.

Similarly, Wang *et al.* developed melamine sponges modified with metal-phenol networks (MPNs) to achieve photothermal properties and selective wettability, resulting in super hydrophilic and superhydrophobic characteristics [Figure 6H-J][141]. The sponge was treated with TA and (3-aminopropyl) triethoxysilane (APTES), followed by cross-linking with Fe^{3+} ions to form TA-APTES complexes via metal coordination. The partial cross-linking by APTES enhanced the coating's stability, and the sponge's superhydrophilicity was due to the hydrophilic groups from TA. The resulting super hydrophilic sponge (sponge@MPN) exhibited photothermal properties from the black Fe^{3+}-TA MPNs. Conjugation with octadecyltrimethoxysilane (OTS) produced a superhydrophobic sponge (sponge@MPN-OTS). The 3D evaporator maintained a high and consistent evaporation rate (approximately 2.3 $kg \cdot m^{-2} \cdot h^{-1}$) in 20 wt.% saltwater under 1 solar irradiation for 21 days. During outdoor tests, the device effectively directed salt

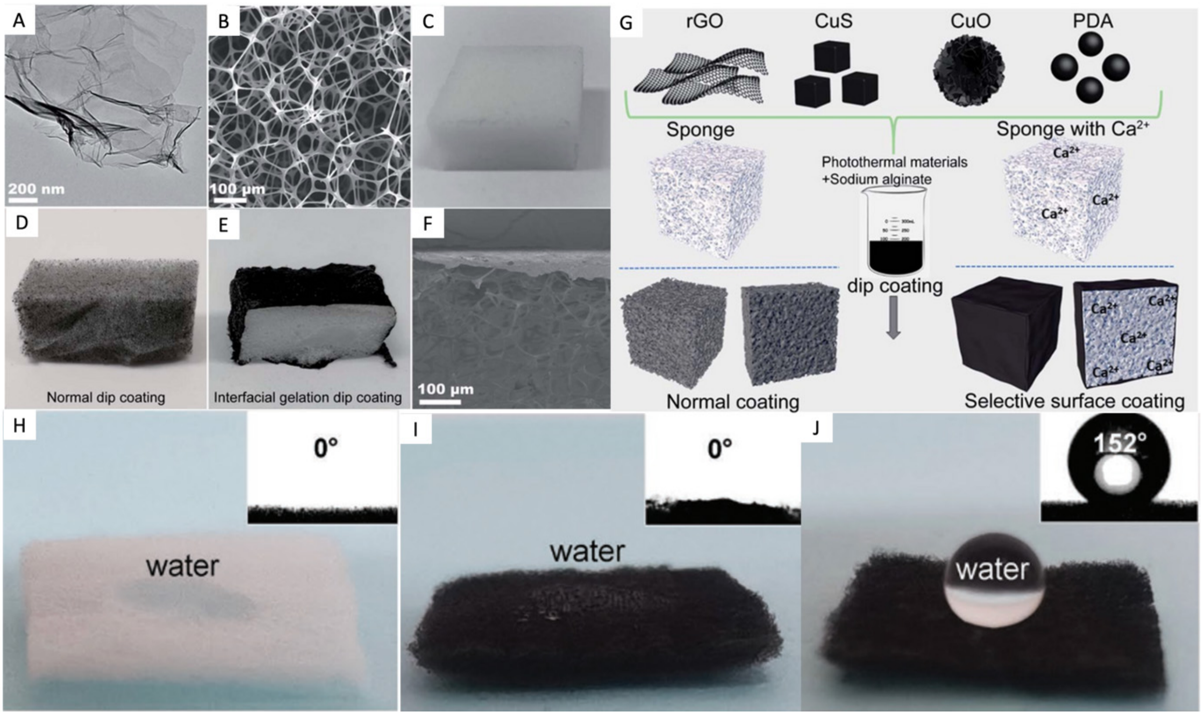

Figure 6. (A-F) SEM image and photograph of rGO in normal dip coating and interfacial gelation dip coating showing that the rGO was concentrated and localized on surface of sponge. (G) Schematic illustration of normal coating and selective surface coating leading to a higher concentration of photothermal materials (right bottom), which enhances the light absorption and solar evaporation on the surface. These figures are quoted with permission from Shao *et al*.[107] Copyright 2020 Royal Society of Chemistry. (H-J) Photographs of original sponge, sponge@MPN, and sponge@MPN-OTS with increased contact angle due to selective coating of MPN on sponge for photothermal evaporation. This figure is reproduced and quoted with permission from Wang *et al*.[141] Copyright 2023 Wiley-VCH.

crystallization and achieved clean water production rates of 1.65-1.82 kg·m^{-2}·h^{-1} while processing concentrated brines (10, 15, and 20 wt.%). Salt crystallization occurred preferentially on the side-twining threads in contact with the superhydrophobic photothermal sponges, preventing salt build-up on the evaporator's top surface and achieving zero liquid discharge. These advancements in modifying 3D evaporators provide a robust platform for photothermal water evaporation research. The spin-coating process begins with the material being coated and diluted in a solvent, which is then applied to the substrate surface. The substrate is spun at high speeds, and the film thickness is determined by the spinning speed, surface tension, and viscosity of the solution. This process forms a gelatinous network on the substrate, which hardens into a solid film once the solvent is removed[139].

Moreover, Yu *et al*. introduced a novel and straightforward method for solar interfacial desalination using MoS_2 double-layer evaporators[142]. This method involved mixing the entire solution and spinning it for 18 h to create functionalized MoS_2 coatings. Functional groups were added to the MoS_2 surface by introducing sulfhydryl groups to S vacancies. This functionalization allowed MoS_2 to bond stably to a polyurethane sponge, enhancing evaporation. The binder securely attached the MoS_2, with the accumulated MoS_2 on the surface increasing the light absorption area and rate. However, the MoS_2 solution without a binder showed weaker adhesion compared to the coating. After applying the functionalized MoS_2 coating, the color of the substrate changed from white to black, which improved light absorption. The hydroxyl-functionalized MoS_2 evaporator demonstrated excellent mechanical stability and flexibility, with an evaporation rate of 1.35 kg·m^{-2}·h^{-1} and 83% efficiency under one sun. This functionalized MoS_2-based coating, created through spin-coating, offers a scalable solution for solar interfacial desalination.

HEAT MANAGEMENT

Effective heat management is essential for enhancing the performance and stability of photothermal evaporation systems. Beyond selecting and designing photothermal materials with tailored optical and thermal properties, strategies such as altering material composition, shape, and surface chemistry can optimize light absorption and heat generation while minimizing heat loss[143,144]. The advancement of cutting-edge materials has significantly enhanced heat retention capabilities, facilitating high-temperature solar steam generation. Van der Waals heterostructures, comprising 2D materials such as graphene and transition metal dichalcogenides (TMDs), demonstrate exceptional light absorption across a wide spectral range from UV to infrared wavelengths[145]. These materials possess superior in-plane thermal conductivity within individual layers, enabling precise control over thickness and composition to optimize heat distribution and retention. Their robust structural integrity ensures reliable performance even under prolonged exposure to elevated temperatures. A notable study by Wang *et al*. featured the preparation of WS_2-O-graphene/microfiber (MF) heterostructures, which maintained surface temperatures of 103 °C under light irradiation[146]. This remarkable thermal performance highlights the high light-to-heat conversion efficiency and effective heat management of the heterostructures. These advancements not only enhance solar steam generation but also offer promising applications in sterilization and water purification. The high-temperature steam produced by these materials is highly effective in microbial control, as it can sustain temperatures above 100 °C to eliminate bacteria, viruses, and other pathogens, thereby ensuring the sterility of medical instruments and surfaces. Additionally, this technology has significant potential for water disinfection, where the high-temperature steam can inactivate and remove waterborne microorganisms, providing a sustainable solution for clean water access in resource-limited areas. Integrating a thermal insulation layer helps trap heat at the interface, maintaining high temperatures at the liquid-solid interface and reducing heat loss to the surroundings using materials with low thermal conductivity[147,148]. Temperature sensors and feedback control systems can regulate heating components or adjust incident light intensity to maintain optimal operating conditions[149]. Additionally, cooling methods such as nano-cooling fluids can be employed[150]. Structured surfaces, such as micro/nanostructured coatings or porous membranes, enhance convective heat transfer and bubble nucleation, accelerating evaporation rates[151]. Heat sinks or thermal reservoirs effectively dissipate excess heat generated during evaporation[152], reducing thermal damage to evaporator components and maintaining system stability and longevity. Overall, implementing energy-efficiency measures such as thermal insulation, temperature control, improved heat transfer, thermal regulation of photothermal materials, and heat sink integration is crucial for boosting the performance and reliability of photothermal water evaporation systems. These approaches support efficient and sustainable water evaporation for various applications, including desalination, wastewater treatment, and thermal management.

APPLICATIONS OF ADVANCED COUPLED TECHNIQUES

Integrating coupled techniques into photothermal water evaporation systems significantly enhances efficiency through synergistic effects, improving photothermal conversion, water absorption, and evaporation rates [Figure 7B[153]. Several coupled techniques can be explored and applied to photothermal evaporation systems, aiding the process while addressing other critical environmental remediation needs. Combining photothermal materials with photocatalysts, typically semiconductor materials, can simultaneously achieve water evaporation and pollutant degradation [Figure 7A][154]. For instance, nanoparticles integrated into carbon-based photothermal materials can both evaporate water and degrade organic pollutants, making them effective for treating contaminated water sources. Photocatalysts absorb light and convert it to heat via the photothermal effect, raising the surface temperature and accelerating evaporation. When photocatalysts absorb light, electrons are excited from the valence band to the conduction band, generating electron-hole pairs that participate in redox reactions with oxygen and water

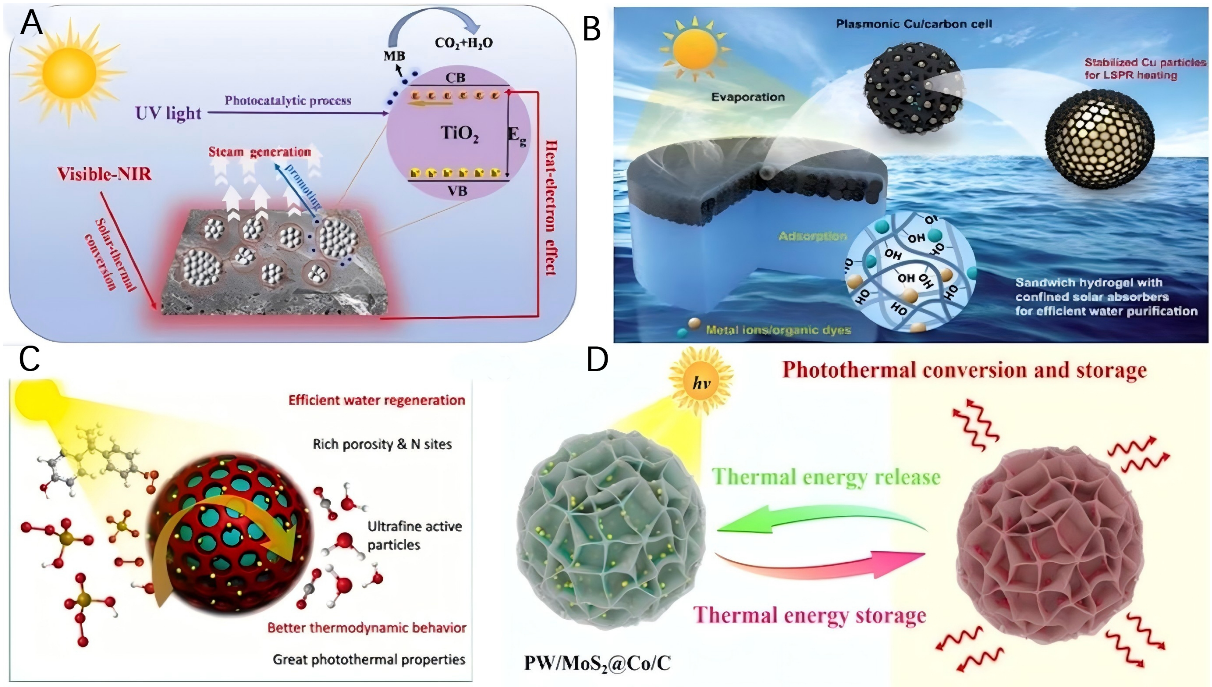

Figure 7. (A) Bi-functional carbon foam/TiO_2 composite absorber for photothermal water evaporation and photocatalytic degradation. This figure is reproduced and quoted with permission from Zeng *et al.*[154]. Copyright 2023 Elsevier; (B) Schematic illustration of sandwich hydrogel with confined solar absorbers. This figure is reproduced and quoted with permission from Tian *et al.*[153]. Copyright 2021 Wiley-VCH; (C) Schematic illustration of advantages for BPA degradation using SiO_2@Co/C catalyst with light irradiation. This figure is reproduced and quoted with permission from Du *et al.*[137]. Copyright 2023 Elsevier; (D) Scattered Co-anchored MoS_2-based composite phase change materials fabricated through collaborative co-incorporation strategy. This figure is reproduced and quoted with permission from Li *et al.*[161]. Copyright 2024 Elsevier.

on the surface of the semiconductor material. These reactions produce reactive species that degrade pollutants. The structural design of the photocatalytic material enhances capillary movement and water transport, ensuring a steady supply of cleaner water that evaporates more readily than contaminated water. By combining photothermal and photocatalytic materials, a composite material harnesses the benefits of both properties, with the photothermal component providing heat and the photocatalytic component purifying the water and potentially contributing additional heat [Figure 7C][137]. For example, Xing *et al.* developed a high-efficiency solar evaporator using a composite of titanium dioxide nanoparticles (TiO_2 NP) and PPy nanoparticles[155]. TiO_2 NPs exhibit photoinduced hydrophilicity, and when combined with the photothermal effect of PPy nanoparticles, the solar evaporator achieved a water evaporation efficiency of up to 97.3% and a rate of 2.9 $kg \cdot m^{-2} \cdot h^{-1}$ under two sun irradiations. The system is responsive to ammonia, ceasing operation in its presence to prevent the pollutant from evaporating, and can degrade various organic contaminants due to the photocatalytic activity of TiO_2 NPs. Similarly, Wang *et al.* proposed the synthesis of $C_3N_4/NiIn_2S_4$ heterojunctions to achieve both efficient solar interface evaporation and photocatalytic production of H_2O_2[156]. This system reached an evaporation rate of 3.25 $kg \cdot m^{-2} \cdot h^{-1}$ and a solar evaporation efficiency of 215.06% under one sun (1 $kW \cdot m^{-2}$). The $C_3N_4/NiIn_2S_4$ heterojunction demonstrated excellent photocatalytic activity, generating 1080 $\mu mol^{-1} \cdot L^{-1} \cdot h^{-1}$ of H_2O_2, providing a compelling technique for designing photothermal materials and photocatalysts for effective interfacial evaporation and sewage purification. The stability of photothermal materials is crucial for their application in water evaporation. These materials need to maintain their heat-retaining capabilities, which drive the evaporation process, even after prolonged use. Developing photothermal composites or resultant materials using coupled techniques represents a significant advancement in the field.

Microbial contamination significantly threatens water safety and availability. Diverse water resources, including wastewater, rivers, and groundwater, are often polluted with pathogenic microorganisms due to domestic, industrial, and agricultural activities. For instance, wastewater discharge, agricultural runoff, and industrial pollutants commonly introduce bacteria and pathogens into rivers and surface waters, posing severe health risks and contributing to waterborne diseases[157,158]. Groundwater sources may also suffer contamination from septic tanks and agricultural runoff, exacerbating the problem. Addressing microbial contamination is crucial for ensuring clean water supply. Photothermal interfacial evaporation presents a promising approach, leveraging renewable solar energy to achieve high temperatures sufficient to inactivate pathogens. The process often incorporates UV irradiation and photocatalytic effects to enhance microbial disinfection. Advanced materials, engineered to maximize light absorption and heat retention, facilitate these high temperatures. These materials can also incorporate photocatalysts that generate reactive oxygen species (ROS) to further enhance microbial inactivation[159]. For example, Amarnath *et al.* developed a Cu-doped-NiO nanoparticle framework loaded onto rGO (rGO-Cu-NiO), which demonstrates effective interfacial water evaporation with an evaporation rate of 1.47 kg·m^{-2}·h^{-1} and a conversion efficiency of 92%[160]. Under 1 Sun and 2 Sun irradiation, the framework achieves a maximum surface temperature of 74 °C, making it highly effective for solar water purification. This approach not only addresses the challenge of microbial contamination but also aligns with sustainable solutions by utilizing solar energy to provide clean water while minimizing environmental impact.

Incorporating plasmonic nanoparticles and phase change materials (PCMs) into photothermal materials has been shown to enhance water absorption and retention while allowing thermal energy storage during weather changes [Figure 7D][161]. Plasmonic nanoparticles can be incorporated via coupled techniques into hydrogel networks to exhibit enhanced water absorption and retention while facilitating rapid heat transfer[162]. For instance, Tian *et al.* demonstrated high-efficiency solar water purification by trapping plasmonic Cu/carbon cell solar absorbers in the evaporation surface of a poly(vinyl alcohol) (PVA) hydrogel, achieving a conversion efficiency of 93.43% and a water evaporation rate of 2.08 kg m^{-2} h^{-1}, even with a 50% reduction in usage compared to conventional hydrogels[153]. Similarly, Chen *et al.* grew a copper sulfide (Cu_7S_4) shell on a gold nanorod (Au NR) core to create a plasmonic nanocomposite (Au NR@Cu_7S_4)[163]. This composite, incorporated into a hydrogel, offered an evaporation rate of 2.35 kg·m^{-2}·h^{-1} under 1 sun illumination due to the enhanced and broadened absorption from coupled plasmons. Combining PCMs with photothermal materials enables thermal energy storage during peak sunlight hours and release at night or during cloudy periods[164], ensuring a constant and stable water evaporation process, thus increasing freshwater production[165]. Recent advancements have demonstrated the successful integration of thermoelectric modules with PCMs to develop a multifunctional system capable of both thermal energy storage and electricity generation via the Seebeck effect[166]. This innovative approach provides a stable thermal environment for thermoelectric modules, ensuring the maintenance of a crucial temperature gradient across them, which is essential for efficient and consistent electricity production. The use of PCMs enhances heat retention, allowing for extended evaporation and condensation processes, even during periods of low solar intensity, thereby improving the overall system performance and reliability. The integration of thermoelectric modules also allows for the capture and conversion of waste heat into additional electricity, significantly improving the overall energy efficiency of the system. A notable example of this approach is demonstrated in the work of Saleque *et al.*, where their innovative system utilizes incident solar irradiance to produce interfacial steam[167]. At the same time, a rGO-coated cotton fabric (CF) effectively desalinates saltwater with an impressive evaporation efficiency of 86.98%[167]. By incorporating commercially available thermoelectric generator (TEG) modules, the system achieved simultaneous power generation of 339.26 mW, leading to a remarkable 7.3% increase in overall system efficiency. Moreover, Huo *et al.* developed a photosensitive interfacial material with excellent photothermal conversion properties by synthesizing CuS with a flower ball shape loaded onto cotton yarn and creating composite phase-change materials using constant pressure molding[168]. This material demonstrated good thermal storage performance and photothermal conversion efficiency, ensuring continuous operation in humid conditions. Li *et al*. also developed a nanoporous MOF (Ni-MOF) for the infiltration of paraffin wax (PW) in a vacuum, coated with solar-absorbing functional PDA for photothermal conversion and storage[169]. The resulting PW@MOF/PDA composite PCMs demonstrated outstanding thermal, shape, energy storage, and photothermal conversion stability, with a photothermal conversion and storage efficiency of 91.2%. These coupled techniques effectively address challenges related to water absorption, heat retention, and the limited duration of photothermal water evaporation. By maintaining efficient photothermal activity and water purification capabilities, these approaches ensure continuous freshwater production even during periods of reduced sunlight. These advancements highlight the potential for creating more efficient and durable photothermal materials, addressing water scarcity and pollution challenges effectively. The development of multifunctional photothermal composites represents a promising direction for future research and practical applications in sustainable water treatment technologies.

CHALLENGES AND FUTURE PROSPECTS

Recent years have seen notable advancements in the development of photothermal materials, hierarchical structures, and interconnected processes, enhancing their strategies for light absorption, photothermal conversion, and water evaporation. Despite the promising applications of these techniques and materials, significant challenges hinder the widespread adoption of this technology on a large scale and in everyday usage. These challenges can be grouped in environmental factors and material factor. Fundamental research and practical investigations are imperative to materialize this clean, green, and sustainable technology.

Environmental factors

The efficiency of solar-driven interfacial steam generation is significantly influenced by environmental factors such as humidity and wind speed. High humidity levels reduce the water vapor pressure gradient between the water surface and the surrounding air, leading to decreased evaporation rates. To mitigate this effect, innovations in materials with enhanced hydrophilic properties and increased surface area are crucial, as they improve water transport and minimize the impact of high humidity. Wind speed affects the process in two ways: moderate winds enhance evaporation by maintaining a high vapor pressure gradient by dispersing saturated air from the water surface, thereby increasing evaporation rates[170]. However, high wind speeds can accelerate heat loss and cool the evaporator surface, reducing efficiency. To address this challenge, integrating windshields or barriers around the evaporator can enhance convective heat transfer while minimizing heat loss. Additionally, developing materials that maintain high evaporation rates in humid conditions and adapt their thermal properties in response to varying wind speeds is essential for optimizing performance and addressing environmental challenges.

Material factors

Photocorrosion and material stability

The durability and stability of materials utilized in coupled photothermal systems pose significant challenges to the technology's viability. Materials such as plasmonic nanoparticles and hydrogels may degrade over time, especially when exposed to harsh environmental conditions such as saltwater and high temperatures, particularly prevalent in arid regions. Ensuring the longevity of synthesized or assembled materials is crucial for maintaining overall system efficiency. Enhancing corrosion resistance and implementing protective surface coatings can prolong the lifespan of photothermal materials. Incorporating self-regenerating materials can further enhance system durability. Exploring novel materials and drawing inspiration from natural structures and behaviors of plants, animals, and other organisms holds promise for future advancements in addressing material stability and durability concerns. For example, utilizing carbon-based materials such as graphene can give both structural stability and improved photothermal characteristics.

Pollutant degradation efficiency

While photothermal materials can effectively ensure water evaporation, they may not be efficient in degrading pollutants during water purification processes. Ensuring that the water is purified and free of contaminants requires integrating efficient pollutant degradation mechanisms within the photothermal system. Integrating photocatalytic materials with photothermal systems through coupled techniques can enhance pollutant degradation. Photocatalysts such as TiO_2 can generate ROS under light irradiation, which can degrade organic pollutants more effectively when combined with the heating effect of photothermal materials. Additionally, through material engineering, coupled systems can be designed to have specific active sites for pollutant adsorption and degradation, ensuring that the evaporated water is clean. To address these challenges, future research should focus on improving the stability and efficiency of these integrated systems. One approach is to develop novel composite materials that combine the strengths of both photothermal and photocatalytic components while mitigating their weaknesses. For instance, coating photothermal materials with a layer of stable photocatalysts can protect them from photocorrosion and enhance their pollutant degradation capabilities. Furthermore, exploring advanced material synthesis techniques, such as doping and surface modification, can create more robust and efficient systems. These innovations will be crucial for advancing the practical application of photothermal water evaporation technologies and achieving sustainable water purification solutions on a large scale.

Uniform heat distribution

Achieving uniform heat dispersion in large-scale photothermal evaporation devices presents several challenges. Variations in thermal conductivity among materials used in the photothermal layer and substrate can significantly affect heat distribution, with low thermal conductivity materials leading to uneven heating, localized hotspots, and diminished efficiency. Additionally, complex and uneven geometric designs of substrates can introduce regions with disparate thermal properties, further exacerbated by variations in solar irradiation due to shading or angle of incidence, resulting in non-uniform heat distribution. As the size of the evaporator increases, these issues become more pronounced, leading to greater susceptibility to temperature gradients and inconsistent water evaporation rates. To address these challenges, recent research has focused on several strategies. These include the development of modular systems with interconnected components to maintain consistent thermal properties over larger areas, the use of advanced material composites with enhanced thermal conductivity, and the application of thermal management techniques such as PCMs combined with thermoelectric modules. For example, Meng *et al.* employed a layer-by-layer assembly method to incorporate hydrogel, metal-oxide, and polymer into a multilayer film with individually controllable thickness, composition, and structure[171]. This device, characterized by its self-floating, deformable, and modular design, demonstrated a high solar thermal conversion efficiency of 91.4% and a maximum power output of 1.6 $mW·m^{-2}$, along with effective salt rejection, making it well-suited for seawater desalination applications.

Integration into existing structures

Integrating photothermal materials into existing water purification systems without extensive modifications can facilitate the technology's adoption for both everyday and industrial use. Collaboration between engineers and designers to develop compatible systems is essential for seamless integration into existing facilities, minimizing the need for constructing entirely new systems. Hybrid systems with easily installable modules offer a pragmatic approach to adapting existing infrastructure. Furthermore, adaptive systems equipped with sensors and controllers can be dynamically adjusted under varying conditions to optimize performance, ensuring efficient operation in real-time.

Economic viability

The economic feasibility of solar interfacial evaporation for real-world applications is a key consideration for its broader adoption. The cost-effectiveness of this technology is influenced by several factors, including the type and structure of photothermal materials used. Advanced high-performance materials, while offering superior efficiency, often entail higher initial costs. However, materials such as rGO, despite their initial expense, can provide long-term benefits and justify the investment due to their performance advantages. Modular and scalable system designs can help reduce overall costs by simplifying integration with existing infrastructure and lowering labor and installation expenses. The inclusion of auxiliary components such as pumps, sensors, and control systems can add to the initial costs, potentially hindering the full-scale deployment of this technology. Recent advancements aim to mitigate these concerns by developing all-in-one systems that minimize the need for additional controls and rely solely on solar energy. These innovations not only enhance sustainability but also offer economic benefits by reducing operational costs. Moreover, systems with high performance and low fouling or degradation rates require less frequent maintenance, leading to further cost savings over time. In contrast to conventional, energy-intensive methods, solar interfacial evaporation relies on renewable solar energy, leading to lower ongoing operational costs. While the initial capital investment may be significant, the long-term savings on energy costs can outweigh the upfront costs, making solar interfacial evaporation a cost-effective and sustainable solution in the long run.

Scalability and cost-effectiveness

Scalability and affordability are pivotal factors determining the practicality of this technology for widespread adoption in everyday applications. Large-scale production and cost-effectiveness are essential for promoting consumer acceptance, particularly considering the high cost associated with high-performance materials such as noble metals. Thus, research into alternative, cost-effective materials such as earth-abundant metals is crucial, along with the development of low-cost synthesis methods to facilitate large-scale manufacturing and evaluate the technology's potential for practical applications. Reusing waste for photothermal materials makes this approach more accessible and economically viable for large-scale implementation. This also minimizes waste and helps curb the release of harmful emissions from waste in landfills and incinerations. Recent studies highlight the promising use of recycled materials in solar steam generation. For instance, Mehrkhah *et al*. developed a highly efficient and scalable photoabsorber device using recycled poplar wood as a substrate[172]. This substrate was coated with FeNi (Fe/Ni = 85%) and rGO. The resulting device achieved high photothermal conversion fluxes of 1.50 and 4.77 $kg{\cdot}m^{-2}{\cdot}h^{-1}$, and significantly reduced seawater salinity (by four orders of magnitude), the electrical conductivity (3,000 times) and the pH (by 1.35 times) after 40 min solar desalination. Additionally, Saleque *et al*. fabricated a solar evaporator by applying $TiTe_2$ quantum dots (QDs) decorated rGO onto a hydrophilic substrate made from a waste face mask[173]. This device demonstrated an evaporation rate of 2.09 $kg{\cdot}m^{-2}{\cdot}h^{-1}$ and efficiency of 87.79%, underscoring the viability of using recycled waste materials in sustainable solar steam generation. These examples illustrate the potential for repurposing waste materials to create effective and environmentally friendly photothermal water evaporation systems. For practical applications, a balance between cost, key properties and synthesis difficulty is very essential as illustrated in Table 1. Cost and scalability must be ensuring feasibility although high-efficiency materials are desirable. Emphasizing these aspects when presenting innovative research findings would enhance the discourse on the topic.

Role of artificial intelligence and machine learning

The integration of artificial intelligence (AI) and machine learning (ML) offers significant potential for optimizing the design and operation of photothermal water evaporation systems. AI and ML can greatly enhance efficiency, performance, and scalability. In the design phase, these technologies enable the analysis of extensive datasets to identify optimal materials, predict their properties under varying conditions, and

Table 1. Detailed comparison of photothermal materials, cost, difficulty in synthesizing and how it affects its scalability

Photothermal material	Cost	Synthesis difficulty	Material key properties	Scalability
Metal nanoparticles, e.g., AuNPs	High	High	High photothermal conversion, strong light absorption, excellent stability	Difficult
Carbon-based materials, e.g., rGO	Low	Moderate	High surface area, excellent light absorption, thermal stability	Feasible
MOFs	Moderate	High	High surface area, tunable properties	Moderate
COFs	Moderate to high	High	Expansive surface area, adjustable architecture	Moderate
Conjugated polymer, e.g., PPy	Low	Moderate	Chemical flexibility, distinctive electron structure	Feasible
Semiconductor materials, e.g., TiO_2	Low	Low	Distinctive electrical band arrangement, photocatalytic properties	Feasible
Hydrogel materials	Low	Low to moderate	Biocompatibility, hydrophilic, high light absorption	Feasible

MOFs: Metal-organic frameworks; COFs: covalent organic frameworks.

optimize system configurations. AI and ML facilitate the simulation of different design variations to enhance light absorption, heat management, and water transport. During operation, real-time monitoring through sensors combined with data analytics allows ML algorithms to forecast performance trends and dynamically adjust operational settings to maintain optimal efficiency. This adaptability accommodates fluctuations in external factors such as sunlight intensity, wind speed, and humidity. Additionally, AI and ML can detect potential failures or degradation in system components, allowing for proactive maintenance and minimizing downtime.

CONCLUSION

In essence, integrated techniques to photothermal water evaporation provide a holistic solution to the concerns of water scarcity and pollution, and have demonstrated significant potential for surpassing traditional solar stills. Unlike conventional solar stills, advanced solar evaporators integrate multiple functional components, such as photothermal materials, photocatalysts, hydrogels, solar concentrators, and thermal storage materials, into a single system. This integration enables the evaporators to achieve various desired functions, including enhanced photothermal conversion, energy storage, and catalytic degradation of pollutants, effectively addressing a broad spectrum of water scarcity challenges. These advanced systems demonstrate significant promise for real-world applications by providing sustainable and efficient solutions for clean water production globally. To further advance these technologies, establishing scientific standards for variables such as material properties, environmental conditions, and operational procedures is essential. This will ensure the accurate measurement of solar-to-vapor conversion efficiencies, a critical metric for evaluating the performance of various solar evaporation technologies. Additionally, the development of green solar evaporators that serve as carbon-sequestering agents offers a dual benefit: water remediation and climate change mitigation. By focusing on biodegradable materials capable of capturing and storing atmospheric carbon dioxide, these technologies could significantly contribute to reducing greenhouse gas emissions and paving the way for climate change solutions. With the increasing demand for clean water and renewable or green energy sources, research and innovation in this field will continue to progress, resulting in more sophisticated and optimized systems. Advancing these materials and associated systems will not only increase water production efficiency, but will also broaden the technology's uses, such as electricity generation, wastewater treatment, and thermal energy storage. In particular, photothermal water evaporation paired with heat-to-electricity conversion would enable sustainable solution to a realistic and widely applicable solution to the worldwide water crisis.

DECLARATIONS

Authors' contributions

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Availability of data and materials

The data supporting this study are available from the corresponding author upon reasonable request.

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Conflict of interest

All the authors declared that there are no conflicts of interest that could have appeared to influence the work reported in this paper.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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