



Review

Clean water and energy co-generation via alternative renewables

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ARTICLE INFO

Keywords:

Solar energy

Photothermal

Solar-driven evaporation

Desalination

Freshwater

Water-enabled electricity

ABSTRACT

Solar-driven interfacial evaporation (SDIE) is a promising approach for sustainable water-energy management, reducing reliance on fossil fuels and minimizing environmental impact. Integrated water-energy generation (WEG) systems harness SDIE to co-produce freshwater and renewable energy. Yet, prior reviews overlook critical gaps in energy extraction mechanisms, material-driven efficiency optimization, and scalable solutions. This review systematically analyzes WEG advancements, focusing on SDIE design principles, including advanced materials (e.g., photothermal nanostructures, hydrogel-based absorbers), optimized thermal management, and engineered water transport. We evaluate multi-source energy harvesting (solar-thermal, photovoltaic, salinity gradients) and their integration with SDIE to enhance co-generation efficiency. Key factors such as energy transfer dynamics, interfacial interactions, and environmental factors (salinity, irradiation) are linked to performance outcomes. To address challenges like material degradation, energy losses, and system complexity, solutions such as hybrid materials, modular designs, and adaptive thermal regulation are proposed. By bridging theoretical insights with techno-economic feasibility, this work establishes a roadmap for scalable WEG systems. It highlights innovations in multifunctional materials, energy recovery, and environmental adaptability while addressing practical barriers to real-world deployment. This review bridges materials science and engineering to guide next-generation SDIE technologies, emphasizing their role in addressing global water-energy demands through efficient, sustainable, and deployable solutions.

1. Introduction

Water and electricity serve as indispensable pillars of modern industry and daily living, powering manufacturing, transportation, communication networks, and domestic appliances. However, their production and accessibility face mounting challenges. Conventional electricity generation remains heavily reliant on finite resources like fossil fuels and nuclear energy, exacerbating environmental degradation through greenhouse gas emissions, air pollution, and resource depletion [1–7]. These practices not only accelerate climate instability but also strain water supplies, as thermoelectric power plants consume vast

quantities of freshwater, intensifying global water scarcity. Meanwhile, dwindling clean water reserves, driven by population growth and unsustainable consumption, compound the urgency for integrated solutions. To address these dual crises, transitioning to renewable energy systems such as solar, wind, and geothermal technologies is critical. These alternatives not only curb emissions but also reduce water dependency compared to traditional energy infrastructure [8–11]. Water shortages are being addressed by developing new photothermal-driven interfacial evaporation systems [12–16], which use localized heat to purify water [17–20]. These systems convert sunlight into vapor, offering a pathway to produce clean water in arid regions. However, their

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<https://doi.org/10.1016/j.cej.2025.167472>

Received 27 May 2025; Received in revised form 31 July 2025; Accepted 19 August 2025

Available online 24 August 2025

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energy potential remains underutilized: waste heat, mechanical vibrations, and chemical gradients generated during water purification are often discarded [21–23]. Capturing these low-grade energy streams could revolutionize decentralized power generation, particularly when integrated with solar-driven evaporation processes. By synergizing water production with energy recovery, such advancements promise to enhance resource efficiency, bridging the gap between sustainable water access and renewable energy generation in a climate-stressed world [24–26].

Harnessing solar energy through water-enabled electricity that employs photothermal evaporation at material interfaces represents a groundbreaking advancement in sustainable technology. This method plays a vital role in advancing eco-friendly energy solutions by optimizing sunlight capture while concurrently tackling two critical global challenges: limited freshwater access and the demand for carbon-neutral power [27–29]. By integrating water-cycle management with energy production via photothermal-driven processes, this strategy decreases reliance on fossil fuels and nuclear power, which currently dominate energy infrastructures. Such integration curbs emissions linked to climate change and accelerated progress toward environmentally conscious development. Furthermore, the system delivers a dual output—generating clean electricity and potable water—to underserved communities, directly improving societal well-being. Analysts suggest this approach could revolutionize resource sustainability, positioning it as a cornerstone for meeting evolving energy and water needs in the decades ahead.

Recent developments in SDIE systems, a technique that utilizes localized solar heating to purify water at the air–water interface, have shown significant promise in addressing clean water scarcity. In parallel, WEG strategies, which involve the simultaneous production of clean water and renewable energy, offer integrated solutions to tackle both water and energy challenges sustainably. SDIE has emerged as a promising method for leveraging solar thermal energy to simultaneously desalinate seawater and generate electricity in WEG systems [30,31]. Research in this field has expanded to explore complementary strategies for energy conversion, such as integrating wave energy converter technologies that harness kinetic energy from ocean movements to produce renewable electricity. Parallel advancements in material science have enabled the design of innovative materials and SDIE configurations capable of directly transforming solar and thermal inputs into electrical output, aiming to optimize the performance of integrated WEG systems [32]. These developments hold the potential not only to accelerate the practical applicability of WEG solutions but also to reconcile global energy demands with sustainable water resource management, fostering progress toward ecological and economic sustainability. While existing reviews detail the evolution of SDIE systems and analyze their material and structural components, critical gaps remain in understanding how operational variables such as fluid dynamics, solute concentration gradients, solar irradiance levels, and electrode positioning affect energy output efficiency, particularly via streaming potential mechanisms [30,31,33,34]. With the rapid expansion of renewable energy infrastructure and the pressing need for scalable, high-yield WEG technologies, a critical evaluation of recent breakthroughs, challenges, and emerging trends in this interdisciplinary domain is urgently required to guide future research and innovation.

This review examines cutting-edge water-enabled electricity generation technologies, emphasizing innovative strategies for sustainable energy harvesting within SDIE systems. It explores two primary approaches: direct solar energy conversion and water-energy synergies in desalination processes, which collectively enable carbon-neutral electricity generation. A detailed evaluation of multi-effect interactions within WEG systems is presented, alongside methodologies for optimizing hybrid WEG configurations through the integration of SDIE's photothermal, photovoltaic, and thermal energy applications. WEG systems are classified into five distinct categories according to their energy conversion mechanisms: hydrokinetic potential, solar

photovoltaic conversion, salinity gradient harvesting, piezoelectric transduction, and thermoelectric generation (Fig. 1). These technologies produce renewable electricity directly while maintaining freshwater output efficiency and eliminating greenhouse gas emissions. For each category, design optimizations, performance enhancements, and scalability prospects are critically assessed. Emerging applications such as energy diversification, fossil fuel displacement, and compact off-grid solutions are also highlighted. The analysis further identifies challenges and future opportunities for WEG systems, emphasizing their economic viability, enhanced energy yields, optimized water-energy synergies, and versatility relative to traditional power generation. By leveraging solar-rich, water-scarce environments, WEG technologies offer scalable solutions for sustainable electricity and freshwater access, supporting ecological resilience and stimulating regional socioeconomic progress.

As shown in Table 1, the most recent reviews on clean water production and energy generation have primarily focused on technical advancements in specific areas. For instance, some reviews highlight the design of concentrating solar power or hybrid systems, while others have concentrated on interface evaporation techniques and the development of innovative photothermal materials. Some recent studies have reported the development of hybrid energy generation systems based on potent photothermal materials for solar steam and electricity generation, as shown in Fig. 2 [35–44]. This review aims to offer a comprehensive theoretical framework for solar thermal water-electricity cogeneration, encompassing analytical assessments of liquid-to-vapor phase transitions and efficiencies. Additionally, it examines how these concepts apply across physical chemistry, material science, engineering, and thermodynamic physics to improve the efficiency of solar thermal evaporation and address challenges like physical factors, influencing condensation, and evolving condensing structures. By providing an in-depth overview, this review seeks to serve as a valuable resource for future research in solar water-electricity cogeneration and the integration of complementary energy conversion devices. In addressing these challenges, it emphasizes key strategies for achieving high condensate efficiency, operational methods, practicality, economic considerations, and other aspects of various techniques, while summarizing the design principles and development directions for these pathways.

2. Light harvesting and management for SDIE at hierarchical levels

Solar energy originates from electromagnetic waves composed of photons carrying distinct energy levels. Upon striking a substance, these photons engage with its atomic structure through absorption, reflection, transmission, or scattering, behaviors dictated by the material's optical and electronic characteristics [59]. Simultaneously, quantum mechanical interactions occur as photons collide with electrons, enabling energy exchange where electrons assimilate photon-derived energy. This stored energy is later emitted, triggering diverse transformation mechanisms such as photovoltaic (light-to-electricity), photothermal (light-to-heat), photoelectrochemical (light-to-chemical), fluorescence (light re-emission), and photoconductive (conductivity modulation) phenomena [60,61]. While these effects share foundational principles, their operational pathways and underlying physical interactions differ significantly [62]. Photoelectrochemical systems that split water to convert solar energy into chemical fuels often employ textured micro- and nanostructured surfaces rather than flat electrodes. Designs improve light capture through scattering and anti-reflective properties, while resonance effects further boost efficiency by enhancing charge separation [63]. In photovoltaic technology, optimizing the absorption and conversion of photons is critical for generating and transporting charge carriers efficiently, directly influencing the electrical output of solar cells. The limited light absorption of many materials stems from their intrinsic properties. To overcome this, the introduction of tailored nanostructures has proven effective in enhancing photonic interactions.

Solar Interfacial Evaporation & Water-Electricity Cogeneration

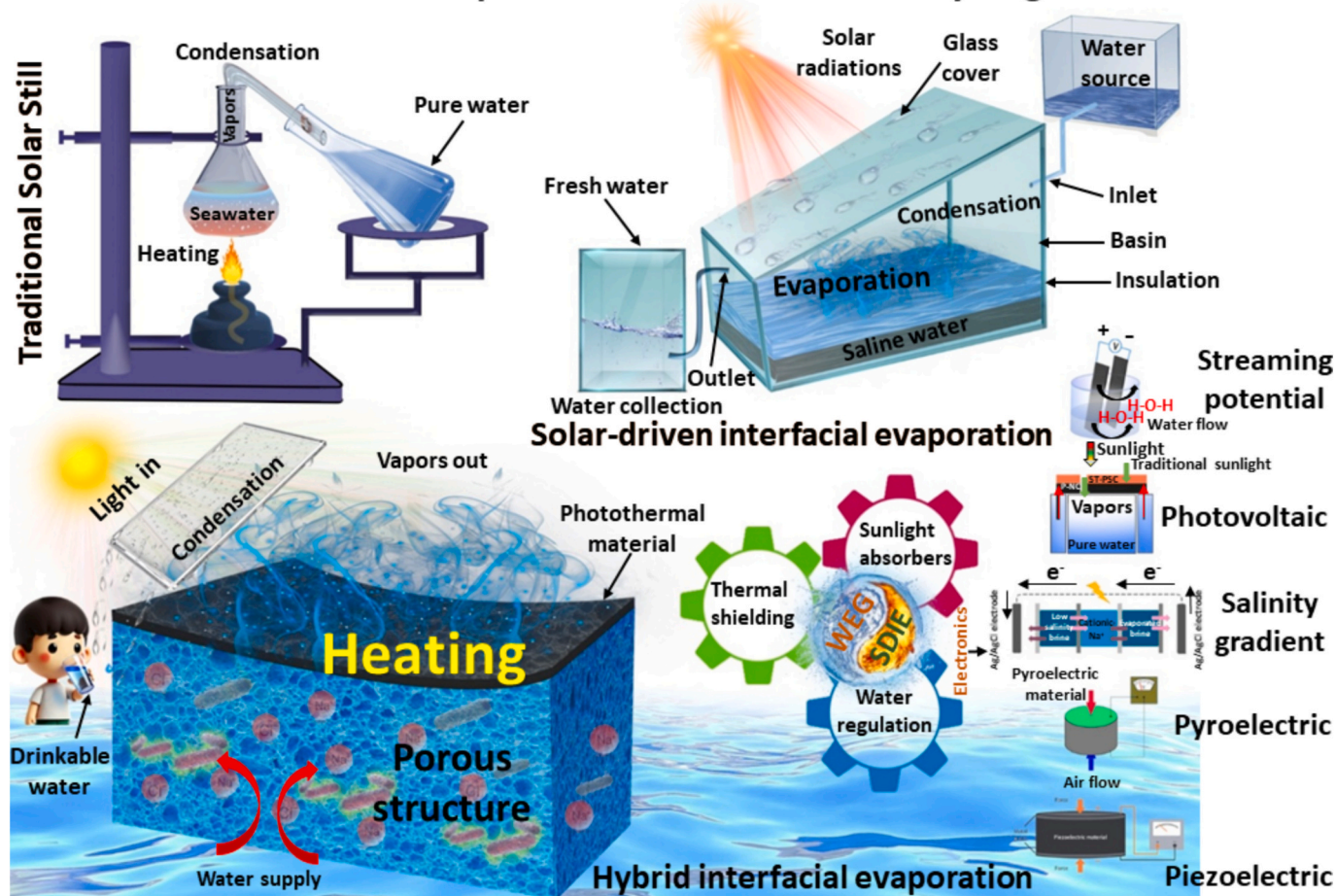


Fig. 1. Schematic diagram of the approach to harvest solar energy for solar-driven evaporation technology and water-enabled electricity generation.

A notable inspiration for structure-induced light absorption comes from the vibrant appearance of butterfly wings. While these vivid colors are commonly attributed to pigments, it is now well understood that structural coloration-caused by subwavelength-scale features-plays a significant role [64,65]. This biomimetic approach has led to the development of ultra-black materials that mimic nature's optical strategies. Examples include carbon nanotubes (CNTs) forest, moth-eye-inspired antireflection structures, and the inverse V-shaped architectures observed in butterfly wings [66–68]. These bioinspired designs achieve broadband light absorption by manipulating structure at various scales, as illustrated in Fig. 3 [61], where we categorize them based on geometry and light management mechanisms. Similarly, in SDIE systems, capillary forces driven by nanoscale porosity enable continuous water transport. Factors such as fluid properties, pore size and geometry, surface tension induced by evaporation, and material wettability collectively enhance capillary action, facilitating efficient water rise through the system. To address this, researchers have developed nanoscale architectures such as textured coatings, plasmonic enhancements, and light-trapping layers to maximize photon utilization. Similarly, optoelectronic devices like photodetectors rely on controlled light-matter interactions to convert incident light into electrical signals [69].

Effective light management strategies, such as extending interaction lengths and reducing interference, are essential for achieving high sensitivity and rapid response times. By engineering patterned arrays of micro- and nanostructures, devices can optimize light absorption and signal precision [63]. These engineered materials enable tunable optical functionalities across applications ranging from biomedical diagnostics to machine vision, driven by their hierarchical spatial organization and

aligned structural features, which collectively enhance light manipulation and energy efficiency. Considerable scientific and technological advancements focus on harnessing light and optical principles for diverse applications, including photocatalysis, solar energy systems, and optoelectronic innovations. These technologies rely on distinct processes triggered by light exposure, necessitating precise control over how photons interact with materials to enhance functionality and output [61]. To maximize energy conversion efficiency in such systems, strategic emphasis must be placed on two interconnected factors: (1) optimizing the absorption of photons across a wide range of wavelengths to fully exploit available light and (2) refining techniques to guide and modulate light within materials to strengthen interactions between light and matter [70]. Crucially, the success of these light-dependent technologies depends on both the engineered design of material structures at micro- and nanoscales and the intrinsic physical and chemical characteristics of the materials themselves, which collectively govern performance outcomes.

The SDIE, a key mechanism in solar-thermal desalination, relies on photothermal conversion—a process where photon energy is transferred to electrons without producing light, electron emission, or elevated energy states. Instead, the absorbed electromagnetic energy transforms directly into thermal or kinetic energy. This principle distinguishes SDIE from other solar-based technologies, as its light-harvesting efficiency depends on a multi-scale structural synergy. At the molecular or sub-nanoscale, the chemical properties of photothermal materials dominate. Moving to nano and microstructural levels, the arrangement of these materials and other system components becomes critical, while the overall geometry and configuration of the SDIE setup are optimized at

Table 1

Overview of recent review papers on clean water production and energy generation.

Sr. No.	Year	Key focus	References
1	2024	Discusses hybrid nanofluids in solar stills, their performance benefits, and guidelines for future development.	[45]
2	2024	Highlights the role of machine learning in designing membranes for energy, gas separation, and water treatment.	[46]
3	2023	Overviews of photocatalytic fuel cells for simultaneous water purification and green energy generation.	[47]
4	2023	Reviews water treatment methods with an emphasis on energy consumption for sustainable purification.	[48]
5	2022	Highlights electrochemical technologies for water purification, ion separation, and energy conversion.	[49]
6	2022	Discusses advancements in solar photothermal steam generation for water purification and energy applications.	[50]
7	2021	Reviews solar-assisted membrane systems for efficient and sustainable water purification.	[51]
8	2020	Summarizes carbon nanomaterial-based adsorbents for enhanced water purification applications.	[52]
9	2019	Overviews of reverse osmosis and nanofiltration membranes for advanced water purification.	[38]
10	2019	Explores graphene-based nanofluids for heat exchangers, solar thermal, and energy storage.	[53]
11	2019	Reviews sustainable methods for heavy metal removal from water using eco-friendly technologies.	[54]
12	2018	Discusses scalable and cost-effective absorbers for advanced solar steam generation.	[55]
13	2017	Examines plasma-based technologies for water purification and their emerging potential.	[56]
14	2016	Reviews advanced materials and technologies for next-generation desalination and water purification membranes.	[57]
15	2015	Explores integrated wastewater treatment and energy systems for sustainable resource management.	[58]
16	2025	Reviews renewable energy-driven decentralized systems for clean water and energy production, emphasizing off-grid and resource-scarce solutions.	This work

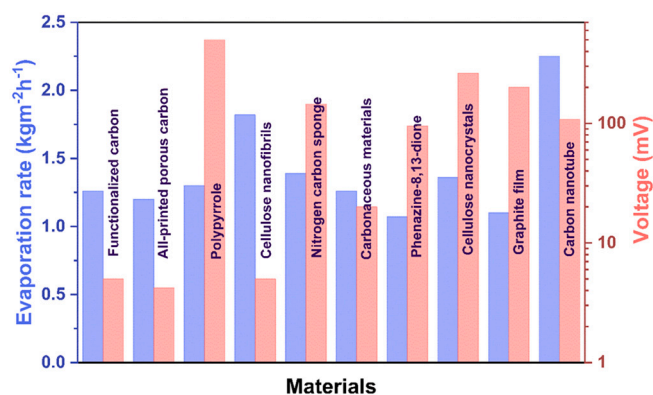


Fig. 2. Comparative analysis of recently reported hybrid systems for solar steam and electricity generation [35–44].

the macroscale. Research efforts have focused on refining light-to-heat conversion mechanisms to efficiently utilize the full solar spectrum (250–2500 nm wavelengths), minimizing energy loss through reflection or transmission to maximize absorption [63]. This layered approach—integrating molecular chemistry, material architecture, and system design—ensures effective solar energy utilization for sustainable desalination applications. Light energy capture and control at atomic and molecular scales rely on multiple synergistic processes [63]. These

include non-radiative energy dissipation in semiconducting substances, thermally activated oscillations arising from electronic state transitions between the highest occupied molecular orbitals (HOMO) and lowest unoccupied molecular orbitals (LUMO) in carbon-rich organic compounds and conjugated polymer systems, and—when scaling up to nanometer dimensions—plasmon-induced thermal effects in metallic nanostructures and composite materials [71]. When exposed to specific wavelengths of light, plasmonic nanoparticles (NPs) and composite materials demonstrate a phenomenon known as localized surface plasmon resonance (LSPR), observable across molecular, sub-nanoscale, and nanoscale dimensions [72,73]. This effect stems from the coordinated vibration of conductive electrons at the nanoparticle (NP) surfaces, amplifying the surrounding electric field. Following plasmon activation, excess energy dissipates via two primary pathways: radiative processes, where light is emitted as photons, and non-radiative mechanisms, which produce highly energetic charge carriers (electrons and holes). The non-radiative conversion of plasmon energy into these carriers involves Landau damping, a quantum process where plasmon quanta transition into intraband excitations within the conduction band or interband excitations between lower-energy d-bands and the conduction band [74,75]. The behavior of these carriers is shaped by the material's electronic structure and the geometric design of the nanostructures. Subsequent energy redistribution occurs through sequential relaxation processes. Electron-electron scattering rapidly disperses energy as high-energy electrons collide with lower-energy counterparts, equilibrating their energies. Concurrently, electron-phonon interactions transfer energy to the lattice, elevating its temperature and generating heat. This thermal energy propagates through phonon-phonon interactions, spreading vibrations that raise the material's local temperature [76]. Metals, with their high electron density and thermal conductivity, exhibit swift photothermal responses, outperforming semiconductors and organic materials. However, the reliance of LSPR on ultraviolet (UV) visible light limits its practical utility. To address this, the research emphasizes optimizing LSPR by tailoring NP morphology, size, geometry, dielectric surroundings, and interparticle electrostatic forces [77]. These adjustments aim to enhance light absorption and energy conversion efficiency for applications such as solar-driven thermal systems. By strategically engineering nanostructures, scientists seek to extend LSPR activity into broader spectral ranges while maximizing heat generation and charge carrier utilization [78].

At the molecular or sub-nanoscale, the ability of semiconductors to absorb light hinges on their bandgap, a critical property that shapes their efficiency in converting light to heat. When photons with energy matching or exceeding the bandgap strike the material, electrons transition from the valence band to the conduction band, leaving positively charged “holes” in the valence band [79]. The energy from these excited electrons can dissipate in two ways: through radiative processes, such as light emission, or non-radiative processes, where energy transfers to the material's atomic lattice as heat. Non-radiative mechanisms dominate in many cases, primarily through two pathways: Auger recombination and Shockley-Read-Hall (SRH) recombination [80]. Auger recombination, more prevalent in materials with narrower band gaps, occurs when a recombining electron-hole pair transfers its energy to a third charge carrier (e.g., another electron in the conduction band or a hole in the valence band).

This energized carrier then releases excess energy as heat through interactions with the lattice. In contrast, SRH recombination depends on material defects, such as impurities or structural imperfections. These defects introduce midgap “trap states” that capture charge carriers in a two-step process: electrons first drop from the conduction band to the trap state, then recombine with valence band holes, releasing thermal energy. Both processes convert photon energy into localized heat by generating lattice vibrations (phonons), which propagate through the material and dissipate into the environment. Semiconductors typically absorb visible light via free carrier generation linked to their bandgap [81]. However, some transition metal-based materials extend

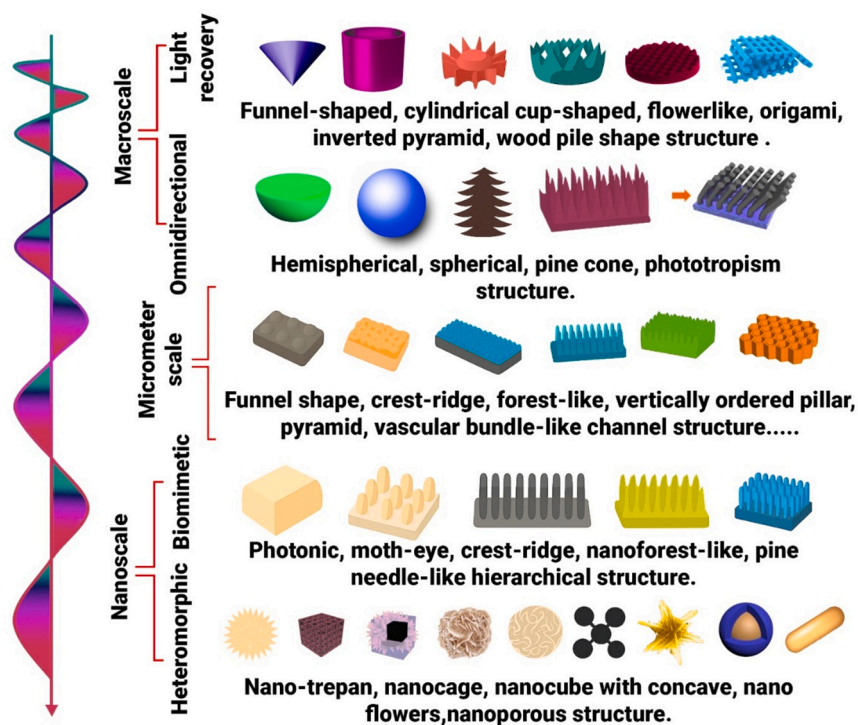


Fig. 3. Light absorption in advanced ultra-black photothermal materials enabled by hierarchically structured architectures across multiple scales [61].

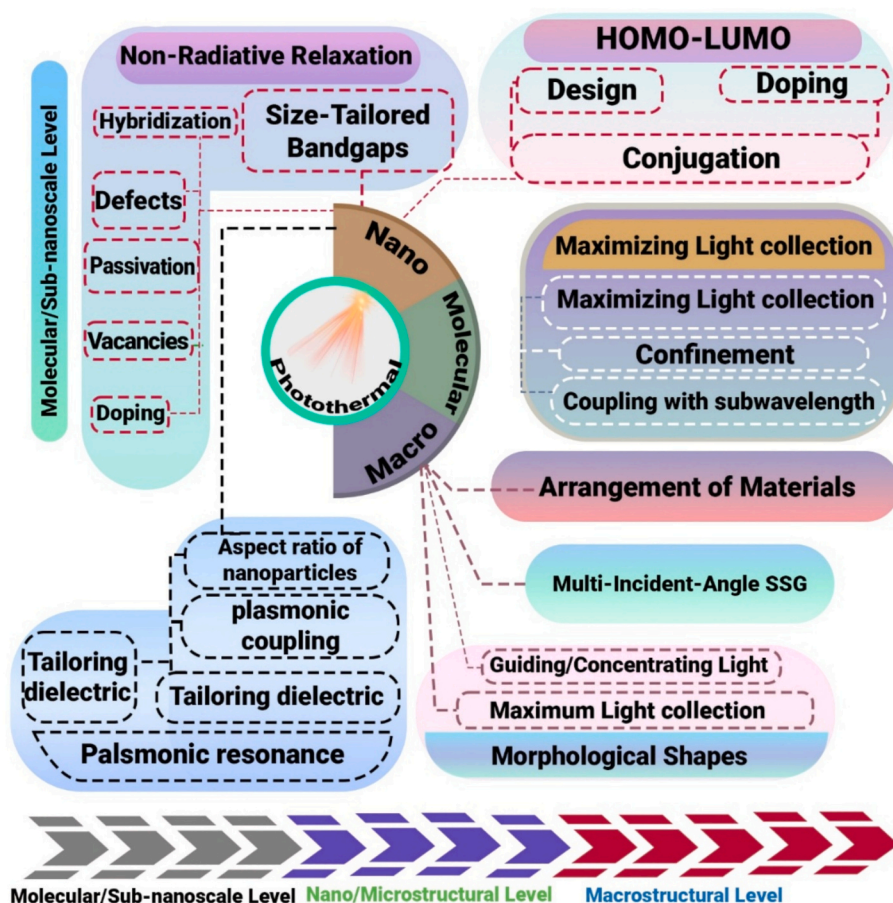


Fig. 4. Light-harvesting strategies at different scales for enhanced photothermal conversion efficiencies.

absorption into the near-infrared (NIR) region due to indirect band transitions or LSPR effects. Higher free carrier densities not only boost absorption but also amplify heat generation by favoring non-radiative pathways over light emission. To optimize photothermal performance in applications like SDIE, bandgap engineering is employed (Fig. 4). Reducing bandgap size or introducing midgap states broadens the absorption spectrum, enabling efficient capture of a wider range of photon energies for enhanced heat production [64–66,68]. Three primary approaches are frequently utilized at the macrostructural scale to enhance the efficiency of SDIE systems in capturing and utilizing light [82]. These include: 1) the careful selection and strategic integration of materials capable of absorbing a wide spectrum of solar radiation; 2) the development of structurally optimized frameworks designed to direct, concentrate, or trap incoming light effectively; and 3) the implementation of systems that maximize solar absorption across diverse angles of incidence. Unlike many solar-dependent technologies, SDIE demands focused research into scaling and refining its macroscopic architecture. This is due to the system's reliance on substantial spatial and volumetric capacity to accommodate energy conversion processes, particularly those involving sequential water phase transitions. Consequently, SDIE systems benefit from expansive physical layouts, which enable broader solar exposure and more efficient light utilization during evaporation [83].

The foundational concepts and methodologies for optimizing light usage in SDIE, as previously outlined, have seen broad adoption in recent studies. Despite this progress, much of the existing research prioritizes improving solar-thermal efficiency by targeting isolated structural elements or evaluating individual components separately when analyzing SDIE functionality [84]. However, progress in SDIE technology hinges on the interconnected relationships between diverse structural layers. To fully unlock its potential, it is vital to holistically evaluate how these layers interact and jointly influence system performance. Such integrated analysis reveals that cooperative interactions across structural tiers markedly strengthen the photothermal response, driving significant improvements in the practical efficacy of SDIE systems, as explored in subsequent sections: on a microscopic level, the approach prioritizes developing advanced substances capable of absorbing a wide range of sunlight and efficiently transforming it into thermal energy [85]. This requires substances with specialized light-to-heat conversion characteristics, such as graphene-based composites or metallic nanostructures engineered for optimal photon capture and minimal energy loss during thermal transfer. Researchers focus on adjusting the material's surface properties and microscopic architecture to improve the efficiency of sunlight-to-heat processes [86]. For example, surfaces modified at the nanoscale can incorporate light-trapping textures or specialized layers that reduce energy reflection, thereby increasing overall absorption capacity. These innovations target the precise alignment of atomic configurations and energy pathways to enhance performance in solar thermal systems [87,88]. The strategic organization of nanoscale-engineered components into specialized layers or surface treatments is critical for optimizing light absorption and controlling thermal distribution. These engineered systems are tailored to maximize light transmission efficiency and direct heat transfer to the water supply. For instance, integrating layers with microscopic pores can amplify interfacial contact with water, accelerating vaporization processes. Simultaneously, such porous architectures bolster material durability, ensuring stability under mechanical or thermal stresses during operation. At the macrostructural level, the system's framework is structured to complement and amplify the performance of its nano/micro-engineered counterparts. This involves shaping the SDIE system's geometry to maximize sunlight absorption across diverse daytime angles, sustain thermal retention, and efficiently regulate thermal release [89]. The broader architectural strategy further integrates features like thermal barriers to reduce energy leakage and strategically positioned reflective coatings to focus incoming sunlight onto absorption elements. By prioritizing these system-wide

adaptations, the design balances energy capture efficiency with controlled heat distribution [90].

2.1. Selection of materials for substrates and solar absorbers

The development of materials science for solar absorbers and supporting substrates has greatly enhanced the performance of solar evaporators during the past few decades. Many attempts have been made to engineer the current materials and prepare new ones. To get high absorption and thermal energy harvesting, a variety of solar absorbers are investigated. In order to provide effective water transportation and heat control at the same time, new substrates were researched. In the following, we concentrate on the fundamentals and methods of choosing solar absorbers and substrate materials to create interfacial evaporators with high evaporation efficiency.

2.1.1. Sunlight absorbers

A direct energy conversion process in which light incident on a substance is converted to thermal energy (heat) is known as the photothermal effect [55,91]. When exposed to sunlight, the light-induced electric field drives mobile charge carriers [92,93]. The carriers then transform the energy they have acquired into heat. Given that the solar spectrum at sea level spans from 280 nm to 2500 nm, one important characteristic of photothermal materials is their broadband light absorption [94,95]. To provide a high thermal energy output, the ideal photothermal material would absorb solar light across the whole spectrum. Numerous photothermal materials, such as plasmonic nanomaterials, semiconductors, carbon-based compounds, polymers, and biomass-based materials, show strong light absorption. These solar absorbers primarily use three types of photoexcitation: thermal vibration of organic molecules in polymers and carbon-based (nanocarbon) materials, non-radiative relaxation of semiconductor electron-holes, and plasmonic local heating of noble metal NPs. Here, we go over many kinds of photothermal materials and emphasize their economics, scalability, environmental effects, long-term stability, and photothermal efficiency.

2.1.1.1. Plasmonic nanostructures. The stimulation of localized surface plasmons under light irradiation is responsible for the noble metal NPs' photothermal action (Fig. 5a) [96,97]. Electrons show collective coherent oscillation when the incident light frequency is as the metal NPs' LSPR frequency [98,99]. LSPR decays either non-radiatively, producing hot electrons with very high kinetic energy that are ultimately transformed into heat, or radiatively, producing light scattering. Metal nanomaterials, including metal oxides and plasmonic metal NPs, have been widely used in interfacial photothermal evaporators [100]. Solar evaporators have made use of a variety of plasmonic NP types, including gold (Au) [101,102], silver (Ag) [103], copper sulfide (CuS) [104], copper (Cu) [105,106], aluminum (Al) [107], and palladium (Pd) [108] NPs. These NPs are very promising as photothermal materials for the effective conversion of solar energy into thermal energy for evaporation because they show localized surface plasmon exciton effects at particular wavelengths and broadband spectral absorption features. Because of their chemical stability, ease of production, and ease of tunability of size, shape, and optical properties, Au nanostructures have been extensively investigated for a variety of applications. In a thorough study of the formation of vapor on the surface of Au nanospheres under light illumination, Halas et al. [109] showed how solar evaporation using Au nanospheres allowed for volumetric heating [110]. Despite the low steam generation efficiency of 24 %, their discovery created opportunities for solar evaporators based on Au nanostructures. One concept used a self-floating Au NP coating at the air-water interface for localized heating to achieve high evaporation efficiency (Fig. 5b) [111]. Individual plasmonic NPs, like Au, have a narrow absorption bandwidth around their resonance peaks [111], which results in less-than-ideal

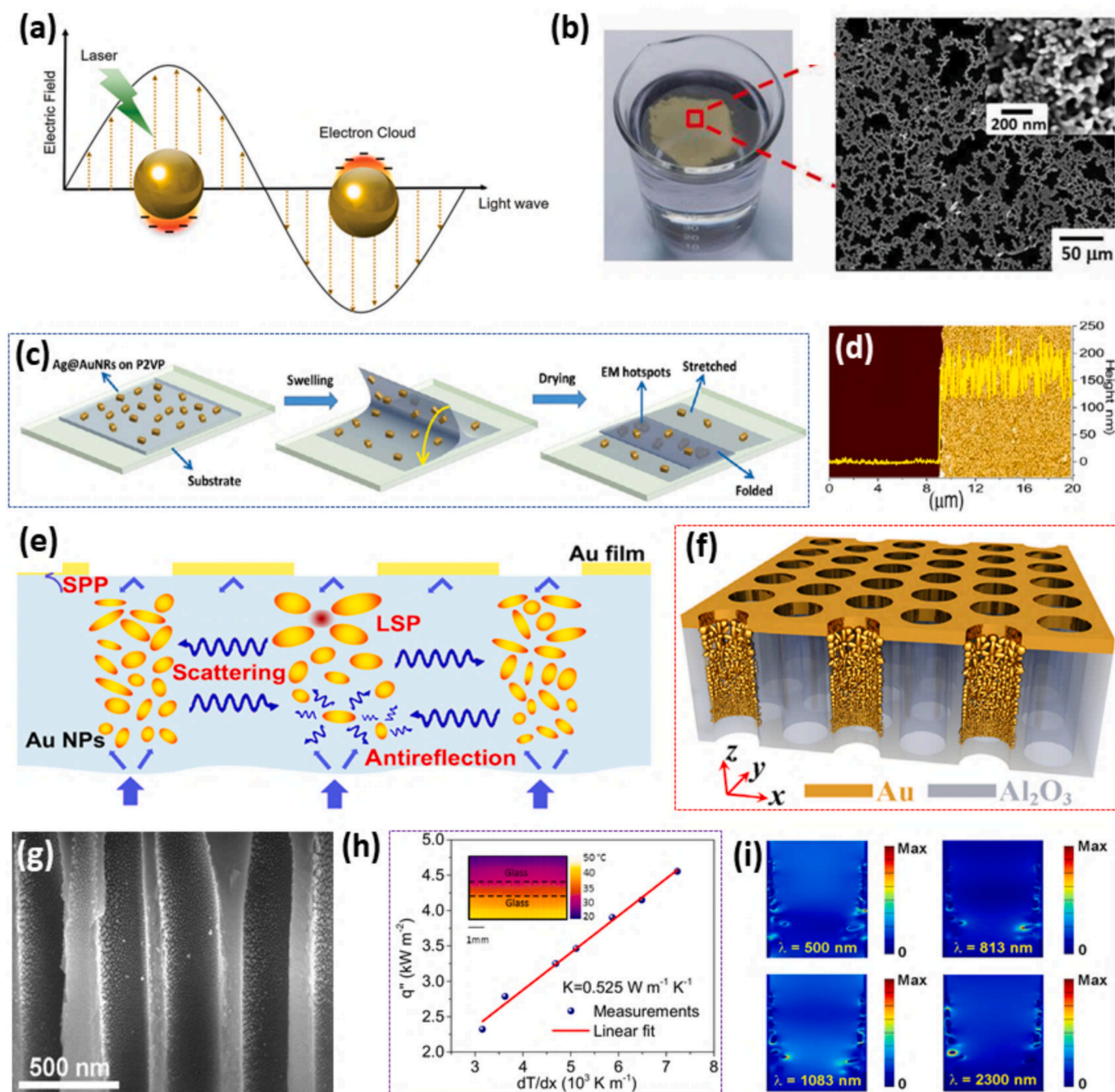


Fig. 5. (a) LSPR of Au NPs. Reprinted under license from [96]. Copyright 2022, Biocell. (b) An image of a floating film at the air-water interface that is more than 3 cm in diameter, as well as SEM images of a self-assembled Au NP film at both low and high magnifications. Reprinted under license from [111]. Copyright 2014, Europe PMC, Small. (c) A diagrammatic representation demonstrating how the swelling-mediated folding process reorganizes the nanostructures adsorbed on the plasmonic gel. (d) Ag@Au NRs are uniformly adsorbed on the P2VP film. The graphic displays the representative height profile perpendicular to the scratch edge. Reprinted under license from [115]. Copyright 2016, ACS Publications. (e) A perfect plasmonic absorber schematic. (f) Self-assembled plasmonic absorbers in 3D. (g) Cross-sectional SEM images of the Au/NPT sample. The Au/NPT sample's geometrical characteristics include its effective Au film thickness of around 60 nm and its average pore size D of about 300 nm. Reprinted under license from [118]. Copyright 2016, Science Advances, Applied Optics. (h) The observed values for plasmonic aerogel in the wet condition were 0.466 W m⁻¹ K⁻¹ and 0.525 W m⁻¹ K⁻¹, respectively. (The cross-section infrared images of the sandwich architecture used for the measurement are displayed in the inset). Reprinted under license from [112]. Copyright 2015, ACS Publications. (i) The distribution of cross-sectional electric fields at four arbitrary wavelengths was calculated. Reprinted under license from [118]. Copyright 2016, Science Advances.

photothermal conversion efficiencies. The interfacial heating evaporator's evaporation efficiency (44 %) under 532 nm laser irradiation at a power density of 10.18 W cm⁻² was noticeably better than that attained via volumetric heating. By immobilizing Au nanorods (Au NRs) on bacterial nanocellulose (BNC), a three-dimensional (3D) plasmonic biofoam was developed, surpassing the two-dimensional (2D) design.

When exposed to an 808 nm laser with a power density of 5.1 W cm⁻², the evaporation efficiency increased to 76.3 % [112]. The intrinsic narrow extinction bandwidth of Au NPs' LSPR is the primary barrier to their attaining broadband absorption. Au NRs typically have a full width at half maximum of 100–200 nm, while Au nanospheres typically have a full width at half maximum of 60–110 nm [112–114]. Tian et al.

demonstrated that the swelling-mediated folding process reorganizes the nanostructures adsorbed on the plasmonic gel (Fig. 5c) and also presented the Ag-coated Au NRs (Ag@Au NRs) uniformly adsorbed on the poly(2-vinylpyridine) (P2VP) film (Fig. 5d). When the plasmonic gel film is exposed to an acidic solution, it isotropically swells in the plane parallel to its surface, increasing the film's surface area. Electromagnetic hotspots are developed when two surfaces adsorbed with plasmonic nanostructures come into close contact due to lenticular fold patterns formed by the film's subsequent drying [115]. The LSPR wavelength of plasmonic nanostructures is influenced by their size, shape, composition, and coupling distance [113,115,116]. At a light intensity of 20 kW m⁻² [117], self-aggregated Au nanowire bundle array devices with a broad variety of nanoscale gaps demonstrated up to 57 % solar evaporation efficiency and 91 % ultra-broadband light absorption at 400–2500 nm. Using Au NPs with a broad range of sizes and shapes is an alternate method to increase absorption. Furthermore, the Al₂O₃ nanoporous substrate was coated with these Au NPs (Fig. 5e), having a 3D self-assembled plasmonic absorber (Fig. 5f). The cross-sectional scanning electron microscopy (SEM) image of the Au/nanoporous template (Au/NPT) sample is shown in Fig. 5g [118]. Plasmonic aerogel values observed in the wet condition were 0.466 W m⁻¹ K⁻¹ and 0.525 W m⁻¹ K⁻¹, respectively (Fig. 5h) [112]. Furthermore, the widely dispersed hot spots of our plasmonic structure are illustrated by the four computed cross-sectional electric field.

distributions at four arbitrary wavelengths, as shown in Fig. 5i [118]. In this investigation, 90 % evaporation efficiency was observed under solar irradiation at a power density of 4 kW m⁻², and light absorption was estimated to be around 99 % across the wavelength range of 400 nm to 10 μm. By joining a nanorod and a nanosphere on a filter paper, Fratalocchi et al. designed Au nanostructures that produced broadband absorption due to their coupled plasmon resonance [119]. At a light intensity of 2.3 kW m⁻², the solar evaporation efficiency consequently reached 87 % [120]. The long-term stability and recyclability of plasmonic nanostructures are further benefits. Wood combined with plasmonic Pd NPs shows exceptional stability after cycling for 144 h in solar steam generation, and Au NP-based solar evaporators have demonstrated outstanding recyclability of 98 % in saline settings [108,119]. Superior recyclability also lessens the environmental impact. Furthermore, the majority of plasmonic nanostructures can be manufactured on a large scale due to their wet chemical synthesis, which implies that interfacial evaporators can be produced on a large scale as well. However, the cost of the noble metals restricts their practical uses. By evaluating the performance of the same material on various spatial structures, the difference in evaporation efficiency between 2D and 3D spatial structures was investigated. Additionally, when using a conical 3D interfacial vapor generator, the related solar vapor generation efficiency surpasses an impressive 95 %. This emphasizes how crucial it is to design multifunctional materials by mixing elements with different functions in a synergistic way. During the investigation, materials with equipartition exciton effects, such as metal oxides and NPs, were created to have lower effects in the visible spectrum but strong absorption in the UV. Consequently, metal-based materials with the equipartition exciton effect have a low overall evaporation efficiency. Additionally, during evaporation, salt or other corrosive elements can harm metal materials, lowering the lifespan of the SDIE device. Moreover, a superior “thermal localization” effect over other absorbers is not possible due to metals' high heat conductivity. Lastly, some metallic materials may harm the environment during the manufacture of SDIE, and the expense of preparing them is not popular among ordinary ways. In conclusion, new photothermal materials with superior performance still need to be found, even though metallic materials have distinct light absorption bands.

2.1.1.2. Semiconductors. Compared to metal materials with an equipartition excitation effect, semiconductor materials have improved

optoelectronic characteristics and a wider range of real-world uses. First, semiconductors do exceptionally well at absorbing visible light, whereas metal-based materials have a considerable impact on absorption in the UV spectrum. Additionally, by producing photogenerated electron-hole pairs, semiconductors are very effective at accelerating the photoelectric conversion process. In order to generate energy, the efficiency of charge transfer to electron-hole pairs is essential. Because of their higher photovoltaic conversion capabilities, semiconductors are frequently chosen in renewable energy applications. The light-to-heat conversion of semiconductors is determined by their bandgap energy [121]. Light is absorbed and electron-hole pairs are created when the incident light's energy exceeds the semiconductor bandgap (Fig. 6a) [122]. The above-bandgap electron-hole pairs in a semiconductor with a narrow bandgap relax to the band edges, releasing the excess energy non-radiatively as phonons that are then transformed into heat. The electron-hole pairs, on the other hand, recombine close to the photothermal efficiency. In the solar spectrum, semiconductor materials exhibit strong absorbance (0.2–2.5 μm) and outstanding photothermal conversion performance when compared to metal-based materials with the equipartition excitation effect. For the production of solar steam, semiconductors with small band gaps have been thoroughly investigated. MoS₂ [123–126], Ti₃O₄ NPs [127], oxygen-deficient MoO₃ quantum dots [128], Fe₃O₄ [129], and black titania [127,130,131] are a few examples. Reducing bulk materials to the nanoscale, which promotes light scattering among NPs, is an attractive strategy to enhance optical qualities. Monolayer MoS₂, for instance, is a representative transition metal dichalcogenide that exists in polycrystalline form and displays different phases.

It has special electrical and optical properties. X-ray photoelectron spectroscopy (XPS) spectra of MoS₂ nanosheet showing the transition from the 1T phase to the 2H phase, as presented in Fig. 6b. A useful example of high-efficiency, sustainable saltwater desalination is the hydrophilic distillation membrane, broad-spectrum sun absorption synthesized (Fig. 6c) by Zhang et al. Further, they calculated the binding energy of the designed nanosheets (Fig. 6d) [132]. After being incorporated into a BNC aerogel, chemically exfoliated (ce) MoS₂ nanosheets absorbed 96 % of the incident light, while bulk MoS₂ absorbed 90 % of the light. The SEM images of MoS₂ in bulk (Fig. 6e), ce-MoS₂ (Fig. 6f), and bulk-MoS₂ nanosheets (Fig. 6g) have also been presented [124]. Bulk Ti₂O₃ showed 85.5 % light absorption over the whole solar spectrum, while 400 nm NPs showed 92.5 % total absorption [122]. One popular method for increasing light absorption in semiconductors with broad band gaps is to dope the semiconductors to lower the band gap [133,134]. Only at wavelengths less than 400 nm, which corresponds to the intrinsic high bandgap (~ 3 eV), does TiO₂ absorb UV light. On the other hand, black titania, which produced a narrow bandgap and achieved 96 % light absorption, partially reduced titanium oxide from Ti⁴⁺ into Ti³⁺ by adding oxygen vacancies [127]. These semiconductors are stable and non-toxic in watery conditions. However, doping necessitates treatment at high temperatures between 200 °C to 600 °C for the majority of semiconductors with large band gaps, which raises the cost of synthesis.

2.1.1.3. Carbon-based materials. Carbon-based materials or nanocarbons are excellent choices for photothermal applications because of their wide range of solar light absorption capabilities, especially in the visible and NIR spectrum [135,136]. When exposed to light, lattice vibration in carbonaceous materials produces the photothermal effect [137,138]. A tiny energy input excites the loosely held electrons in the π orbital of carbon materials, causing them to jump to the π* orbital [138]. When the excited electron returns to its ground state, heat is produced. Graphite [139], graphene, graphene oxide (GO) [140], GO/reduced GO (rGO) [141–145], CNTs [146,147], multiwalled CNTs [148], and carbon black (CB) [149] are among the various nanocarbon materials that have been investigated. The general method for enhancing optical absorption is to modify the structures of nanocarbon materials, which have a wide

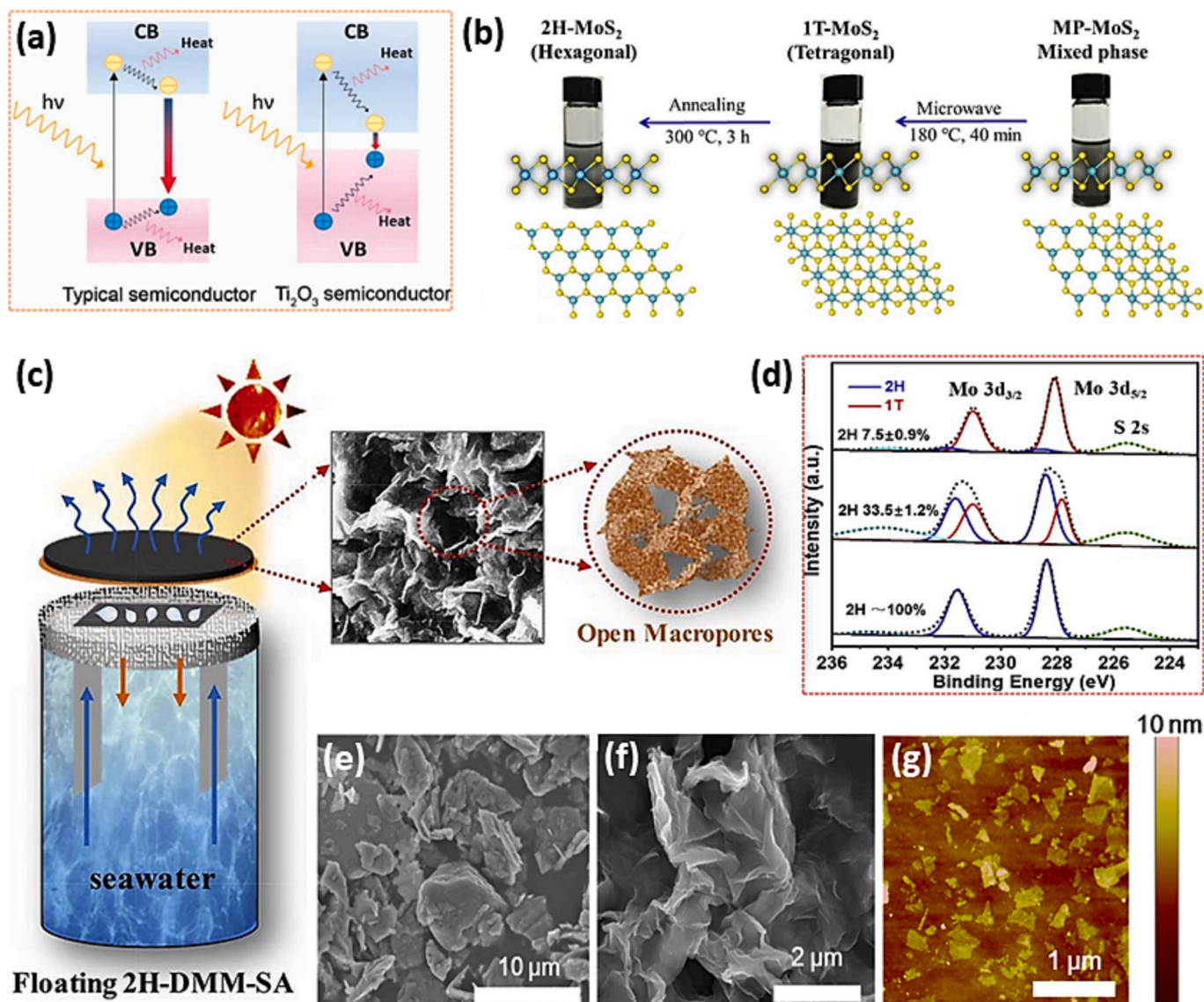


Fig. 6. (a) An example of electron-hole formation and relaxation in narrow-bandgap Ti₂O₃ (right) and a typical semiconductor (left). Reprinted under license from [122]. Copyright 2017, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. (b) 2H- and 1T-MoS₂ nanosheet synthesis and characterization. XPS spectra show the transition from the 1T phase to the 2H phase in Mo 3d and S 2s. (c) Schematic representation of the 3D dimpled MoS₂ membrane. (d) The binding energy difference between the 2S and 1T phases is roughly 0.8 eV. Reprinted under license from [132]. Copyright 2020, Elsevier. (e) SEM images of MoS₂ in bulk. (f) SEM images of ce-MoS₂. (g) SEM images of bulk-MoS₂ nanosheets deposited on a silicon substrate. Reprinted under license from [124]. Copyright 2018, Elsevier.

spectrum of solar absorption capabilities. Because of their high photo-thermal conversion efficiency, high specific surface area, and outstanding light absorption, carbon materials have been used as the preferred material for SDIE and WEG. Notably, the theoretical limit of solar interfacial evaporation ($1.47 \text{ kg m}^{-2} \text{ h}^{-1}$) can be readily exceeded by carbon-based materials with more than 90 % light absorbance and a sensible structural design. As a result, it is crucial to promptly analyze the most recent developments in carbon-based materials. Furthermore, the potential usefulness of these CNT@Si solar evaporators in desalination and water purification is highlighted by this study. A hierarchically structured graphene foam material with effective omnidirectional photothermal conversion was presented by Ren et al. [143]. For improved solar energy conversion efficiency, the material's organized pore layers with different densities and shapes allow for remarkable heat transmission and absorption of solar radiation. This graphene foam material's preparation process is thoroughly explained, including raw material selection, preparation, and post-preparation steps. According to the experimental results, the hierarchically

organized graphene foam is very well suited for effective solar thermal conversion because of its remarkably low thermal conductivity and outstanding solar energy absorption capabilities. Li et al. developed the vertically 3D-printed evaporator's structure (Fig. 7a). They placed the corresponding porous expanded polystyrene (PS) matrix inside the vertically 3D-printed backbone. The principle of the 3D printed evaporator has been presented in Fig. 7b [150]. In addition, carbonaceous materials' lattice vibration produces the photothermal effect (Fig. 7c) [138]. In another study, an advanced GO aerogel prepared by 3D printing had high porosity, up to 97.3 %, and a concentrated GO-based solution with a high enough shear elastic modulus and shear yield strength served as the perfect 3D printing ink. The SEM images of the GO/nanofibrillated cellulose (GO/NFC) layer junction (Fig. 7d) and GO/NFC wall showing adjacent GO/NFC composite sheets have also been displayed (Fig. 7e). Water absorption and dispersion inside the porous GO/NFC composite microchannels are facilitated by the hydrophilic NFC network deposited onto the GO substrate [151]. Cui et al. [152] used a monolithic graphene structure to demonstrate a photothermal

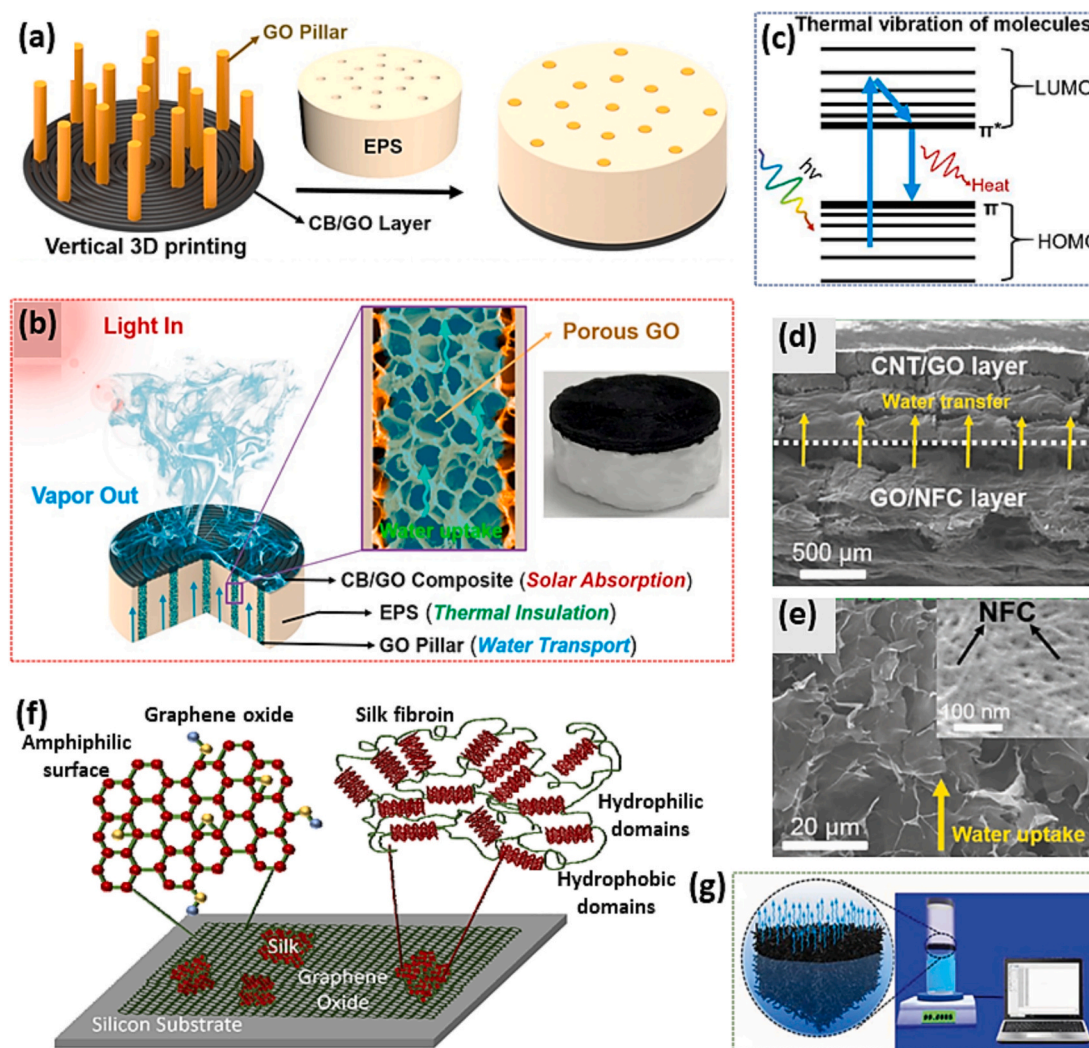


Fig. 7. (a) An example of the vertically 3D printed evaporator's structure. The corresponding porous expanded PS matrix is placed inside the vertically 3D-printed backbone. (b) An illustration of the principle of a 3D printed evaporator. Reprinted under license from [150]. Copyright 2017, Elsevier. (c) Thermal vibration of organic molecules. Reprinted under license from [138]. Copyright 2019, RSC Advances. (d) SEM image displaying the CNT/GO and GO/NFC layer junction. (e) GO/NFC wall SEM image showing adjacent GO/NFC composite sheets. Insets in (d) and (e) demonstrate the uniform distribution and lack of aggregation of the entangled NFC. Reprinted under license from [151]. Copyright 2017, Wiley. (f) Diagram illustrating silk's adsorption on GO. The GO diagram shows hydrogen (blue), oxygen (yellow), and carbon as atoms. In silk fibroin, hydrophilic groups (green) link the hydrophobic domains (red). Reprinted under license from [153]. Copyright 2016, ACS Publications. (g) Diagram for the production of solar steam. Reprinted under license from [147]. Copyright 2019, Wiley.

effect evaporator. The idea of photothermal modulation was put forth to maximize productivity by boosting the input power from solar cells and maximizing graphene's sponge-like shape. Additionally, adding solar cells to the system helps to heat the water in addition to facilitating photothermal heating. Even without system optimization, the special graphene evaporator produces water at an impressive rate of $2.01\text{--}2.61\text{ kg m}^{-2}\text{ h}^{-1}$ when exposed to 1 kW m^{-2} of solar light. This innovative study offers a fresh strategy for creating scalable and effective solar water-generating devices, which is a major step toward solving the world's clean water shortage problem.

Because of the enormous surface area of the 2D flake structure and strong hydrophilic surface, GO/rGO is a carbonaceous material that has been extensively researched for solar evaporation (Fig. 7f) [153]. To improve light capture, it is typically put together into a porous structure. For instance, the reflectance of rGO foam was just 2.5 %, but a compact rGO film made by vacuum filtration showed 13 % diffuse reflection [149,154]. For solar evaporation, several 2D and 3D combinations have been developed. Using the antifreeze-assisted freezing process, a membrane made of vertically aligned rGO nanosheets was prepared, and the run-through channels were advantageous for light absorption during

solar evaporation [155]. Fig. 7g shows the evaporator for the production of solar steam [147]. The broadband solar absorption was above 97 % because of this well-designed porous structure. The feasibility of producing a GO/rGO-based evaporator on a large scale is another benefit. A surfactant-foaming sol-gel technique that efficiently breaks up and reassembles the GO liquid crystals in dispersions using microbubble templates can be used to prepare a sizable region of rGO hydrogel [156]. A bulk aerogel with a structure-intact size of roughly 1 m^2 was developed following straightforward freezing and air drying. The large-scale open porous structure is a desirable option for large-scale solar evaporation because of its good mechanical qualities and strong solar-thermal conversion. Nanocarbon materials have broadband absorption and are far less expensive to synthesize than semiconductors and plasmonic NPs. They have become one of the most researched photothermal materials for solar evaporation because they combine the advantages of availability, chemical stability, non-toxicity, ease of synthesis, and scalability. However, to improve their spectrum range, supplementary light absorbers must be added because carbon-based materials' comparatively high radiation coefficient may limit their performance. Innovative research and development initiatives in this field have enormous

potential to propel advances in photothermal technology, which would have a significant impact on the generation of clean energy and the reduction of carbon emissions. Researchers can create photothermal materials with exceptional efficiency, stability, and affordability by utilizing composite structures that combine carbon-based materials with other light absorbers. This will help to accelerate the shift to a more ecologically friendly and sustainable future.

2.1.1.4. Polymeric materials. The energy conversion efficiency in full-spectrum sunlight is reduced by the unique energy band structure of commercial polymers, which restricts their absorption bandwidth [157,158]. As a result, researchers are concentrating on new polymeric materials as possible substitutes. To extend the absorption spectrum into the infrared, several modification techniques are being researched, including copolymerization, ion doping, and oxidative doping. These

efforts enable researchers to develop novel polymer materials that are more affordable and easier to manufacture, while also providing better performance. The creation of more effective and economical SDIE technologies will be greatly impacted by this research. The energy produced when the excited electrons in the LUMO relax to the HOMO is also responsible for the light-to-heat conversion of polymers. The most researched photothermal polymers for solar evaporation are polypyrrole (PPy) [159–164] and polydopamine (PDA) [165–169] because of their exceptional biocompatibility, low cost, ease of production, and broad-band absorption. One of the polymers' unique properties is its flexibility, which allows it to be deposited on a variety of curved substrates to help capture solar energy. Huang et al. presented the solar membrane interface for water evaporation. Solar radiation raises the local temperature of the mesh, which causes the water vapor to condense into freshwater clouds (Fig. 8a). The prepared polypropylene (PP) and PPy-

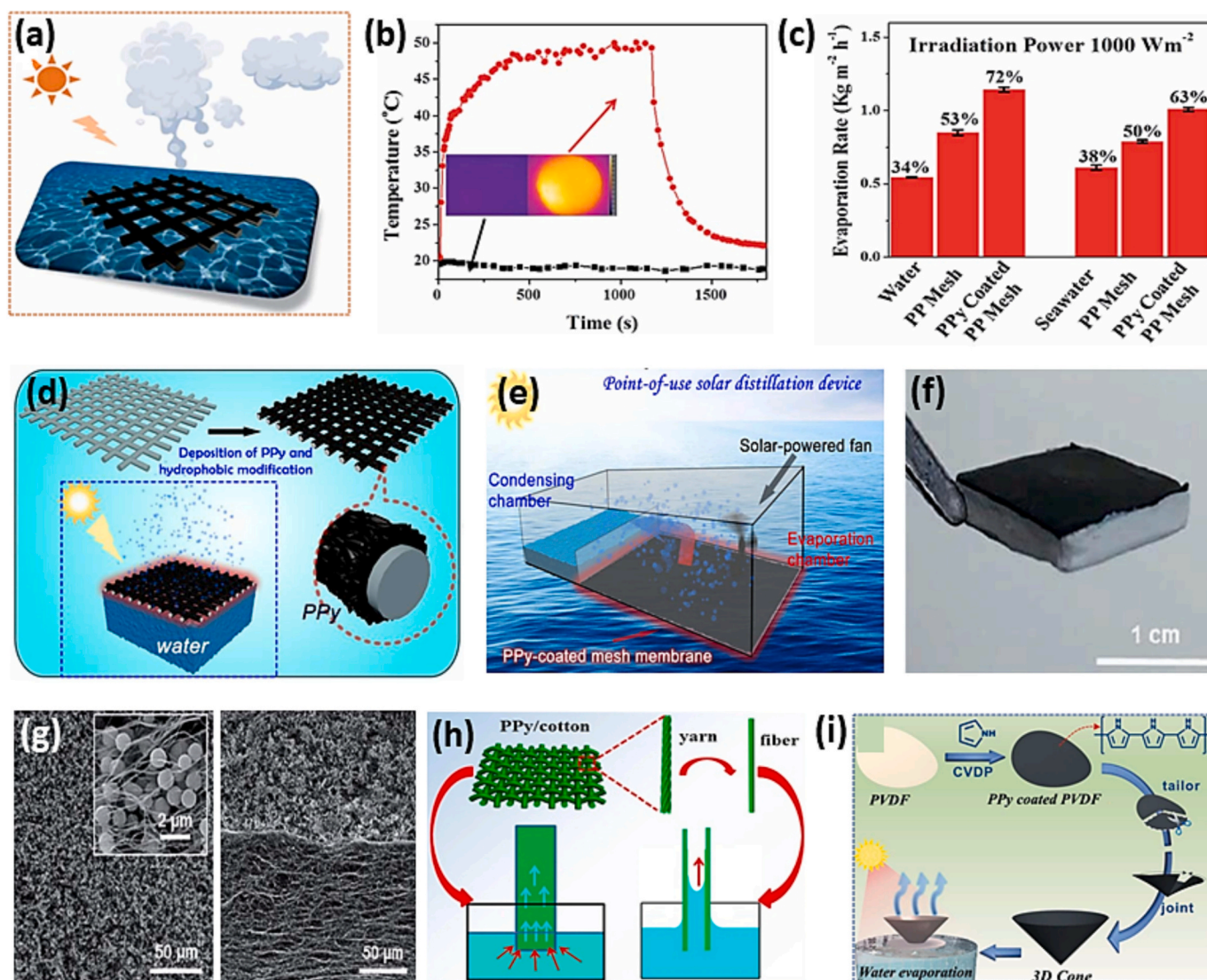


Fig. 8. (a) An example of a solar membrane interface for water evaporation. (b) PP and PPy-coated PP mesh are heated and cooled photothermally for 30 min of radiation. The temperature distribution of PP and PPy-coated mesh following 2 min of exposure is shown in the inset image. (c) Evaporation rate and efficiency of solar vapor generation in various settings (from left to right: pure water, floating PP mesh, and floating PPy-coated PP mesh on the saltwater). Reprinted under license from [161]. Copyright 2017, RSC Advances. (d) The PPy-coated stainless steel mesh's photothermal characteristics. Under solar radiation, the steady-state temperatures of the PPy-coated stainless steel meshes in air as a function of PPy coating thickness. (e) The point-of-use apparatus for direct and all-in-one solar distillation for the manufacture of freshwater is shown schematically. Reprinted under license from [162]. Copyright 2015, Wiley-VCH. (f) Optical image of the PDA/BNC foam's surface. (g) SEM image of PDA/BNC foam's surface (the higher magnification image is inset) along with its cross-section image. Reprinted under license from [169]. Copyright 2017, RSC Advances. (h) Diagram of the PPy/cotton capillary water absorption mechanism. Reprinted under license from [160]. Copyright 2018, Elsevier. (i) The photothermal cone's preparation. A diagram showing the fabrication of a PPy-coated photothermal cone through chemical vapor deposition polymerization and tailoring. Reprinted under license from [164]. Copyright 2018, RSC Advances.

coated PP mesh were heated and cooled photothermally for 30 min of radiation (Fig. 8b). After turning off the radiation, the temperature was allowed to drop gradually. The evaporation rate and efficiency of solar vapor generation in various compositions were measured (Fig. 8c). A fixed light intensity of 1000 W m^{-2} was used. There are 861 mm^2 of mesh [161]. Chemical vapor deposition polymerization on air-laid paper and *in-situ* solution-phase polymerization on cotton fabric are all simple methods for coating PPy (Fig. 8d). The PPy coating provided more than 90 % broad-spectrum solar light absorption and was stable. The apparatus used for direct and all-in-one solar distillation for the manufacture of freshwater is shown in Fig. 8e [162]. Motivated by the sticky protein found in mussels, PDA, which resembles eumelanin in structure, is well-known for its ability to adhere to nearly any surface by self-polymerizing dopamine in an alkaline solution [170]. Nearly all of the light in the UV–visible spectrum and most of the light in the NIR spectrum could be absorbed by a uniform PDA coating that was formed on a wood surface and carbonized onto cotton fabric [165,167]. The rough surface of the PDA layer also aids in light harvesting, and the hydrophilic characteristic of PDA guarantees that enough water will come into contact with the heated surface zone for evaporation. PDA microspheres were developed for solar evaporation as an alternative to applying a PDA layer to different surfaces. The size of these microspheres was adjusted to enhance light absorption. Moreover, Fig. 8f shows the optical images of the PDA/BNC foam's surface, while Fig. 8g presents the SEM image of the PDA/BNC foam's surface along its cross-section image [169]. The PDA/BNC bilayer structure that resulted from integration with BNC aerogel demonstrated up to 98 % light absorption in the 450–750 nm range. The biocompatibility, low toxicity, and biodegradable nature of PDA make it an environmentally benign material when compared to the majority of other photothermal materials covered above. Its versatile adhesion also makes it possible for PDA to be used on a large scale in aqueous environments with little impact on the ecosystem [169,171]. Though this assumption has not been well examined yet. Furthermore, Hao et al. designed an efficient PPy-based evaporator with an efficient absorption mechanism. They presented the absorption mechanism of PPy/cotton through capillary action (Fig. 8h) [160]. In another study, Wang et al. proposed the preparation of a photothermal cone. They demonstrated the fabrication of PPy-coated photothermal cones through chemical vapor deposition polymerization and tailoring (Fig. 8i) [164].

Through the use of suitable doping techniques and molecular structure design for effective photothermal conversion, NIR-absorbing conjugated polymers with low fluorescence have been effectively produced. In addition to significantly reducing Labor and material resource consumption, this method somewhat improves SDIE and WEG's cost-effectiveness. To create a 3D evaporator with a highly linked porous structure that could effectively transport water to the evaporation surface, Yu et al. [172] used polymer ingredients to create highly elastic porous self-assembled templating solar hydrogels. Additionally, these porous hydrogels demonstrated exceptional elasticity, which allowed them to rapidly regain their original shape even after being repeatedly folded, rolled, and twisted. The resultant system showed a remarkable 90 % steam conversion efficiency and $1.4 \text{ kg m}^{-2} \text{ h}^{-1}$ evaporation efficiency. Nevertheless, the system's heat loss could not be effectively controlled. Thus, by submerging carbon fibers in an acetone solution, Li et al. [173] created an evaporator with an effective water pathway, guaranteeing the preservation of the carbon fiber's microstructure and permitting steady water delivery to the evaporation surface throughout the evaporation process. The carbon fiber evaporation rate under 1 sun irradiation was $1.47 \text{ kg m}^{-2} \text{ h}^{-1}$ (92.5 %) in modeling trials. It is important to note that, whereas photothermal materials have advanced significantly, little has been done to improve their light absorption capabilities for use in SDIE devices. By simply carbonizing conjugated microporous polymer aerogels (CMPAs), Mu et al. [147] created an effective solar evaporator. Under 1 solar radiation, the evaporator achieves an ultrahigh conversion efficiency of 86.8 % and has a broad range of light absorption capacity (99 %). The CMPAs are characterized by low

heat conductivity ($0.192 \text{ W m}^{-2} \text{ K}^{-1}$), a wider absorption spectrum (99 %), low apparent density (57 mg cm^{-3}), and high porosity (92 %). Fast water transfer, self-floating ability, high photothermal conversion efficiency, and superior thermal insulation performance are all attributes of the CMPAs that are produced. Additionally, this material is appropriate for synergistic investigations in the field of WEG due to its programmable structure, adjustable porosity, straightforward production procedure, and high solar conversion efficiency.

2.1.1.5. Biomass-based materials. As green energy initiatives are put into practice, biomass-based WEG systems and SDIE devices are progressively taking the lead in the development of new energy technology. Some materials have a problem with leaks after usage, which can easily lead to secondary pollution in the environment. Biomass resources go through several innocuous processes that help prevent further environmental damage. Biomass materials may typically achieve high photothermal efficiency through straightforward physical synthesis. Following carbon-based materials, biomass materials are a new class of composite materials. As SDIE and WEG are developed, their structures, synthesis processes, and properties are becoming more generalized. By using light tracing simulation to create a vertical arrangement of bamboo leaves (BLs) modified with polyacrylamide (PAM), Wu et al. [174] developed a carbon-based evaporator made from BLs. To get vertical carbonized biomass layers (VCBLs) in the crucible, they heated the BLs. To accomplish PAM modification of the VCBLs and design the PAM-modified VCBLs (PVCBLs), the PAM precursor solution was then added to this crucible for *in-situ* polymerization. The preparation procedure of the PVCBLs evaporation apparatus is presented in Fig. 9a.

They also measured its temperature variation profile (Fig. 9b). Additionally, the constant dispersion of PAM hydrogels between these carbons that are vertically oriented carbons speeds up water transportation and shortens the evaporation distance. The evaporator showed outstanding photothermal efficiency (91.9 %) and improved durability for real-world uses. To prepare the hydrogel, Hao et al. [175] added sodium lignosulfonate (SLS) together with CNTs and polyvinyl alcohol (PVA). The hydrogel's ability to hold water was improved by the addition of PVA, while CNT was utilized as a photothermal material to prepare PVA/SLS CNTs. Under 1.0 solar irradiation, the PVA/SLS-CNT hydrogel showed an evaporation rate of $2.09 \text{ kg m}^{-2} \text{ h}^{-1}$. It also demonstrated outstanding salt resistance, antimicrobial, and self-cleaning qualities. Experiments with outdoor solar desalination showed that it could produce 13.0 kg of freshwater per square meter, which is enough to supply five adults' worth of water. Xu et al. [176] prepared the 2D and 3D photothermal evaporators (Fig. 9c). They demonstrated the procedure for the production of electricity in CNT-PPVA sponges (Fig. 9d) with an integrated system for producing power and desalinating saltwater (Fig. 9e). In contrast to traditional sun desalination systems, biomass-based solar seawater evaporation systems show great promise in terms of low operating costs, high efficiency in turning solar energy into vapor, and ease of use. The natural materials' original porous structure and water transport channels are preserved after carbonization, increasing their capacity to absorb light and expanding their water transportation capabilities. Additionally, a variety of evaporation systems, such as nanofluids [177], membranes [178], gels [179,180], Janus structures [181,182], and composite sponge structures [176], can be built using biomass materials. All of these systems have shown encouraging results in experimental investigations.

2.2. Substrate materials

Bilayer solar evaporators have been extensively investigated for the production of solar steam since the integration of supporting substrates for improved solar evaporation was validated. In general, the bottom layer transfers water to the upper solar absorber layer, manages heat, and offers mechanical stability. For solar steam generation to be very

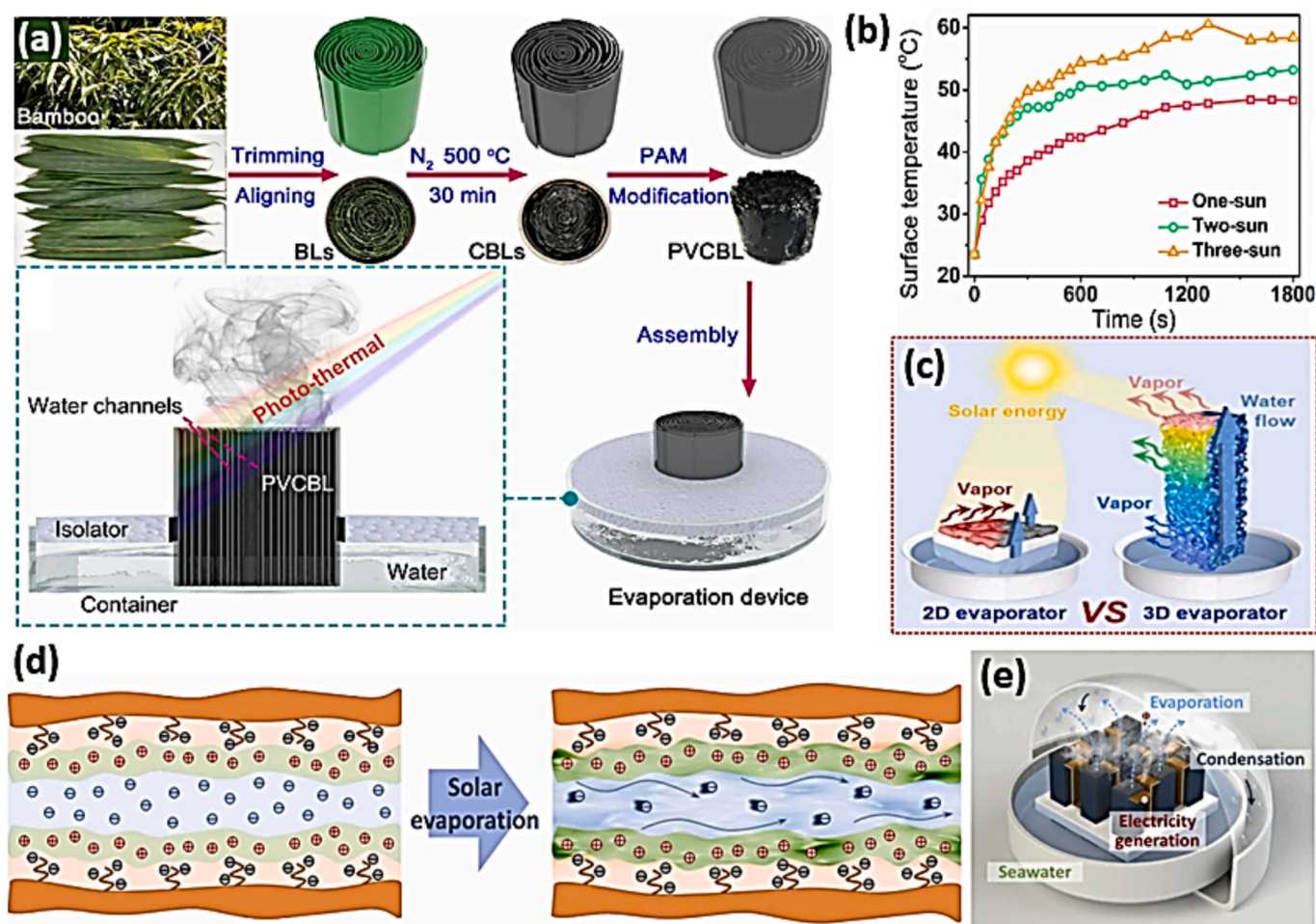


Fig. 9. (a) Diagrammatic representation of the PVCBL preparation procedure and the specially designed evaporation apparatus. An intricate schematic illustration of this device's cross-section. (b) Profile of the surface temperature variation that was measured. Reprinted under license from [174]. Copyright 2022, Wiley. (c) Diagram of solar-thermal evaporators in 2D and 3D. (d) Diagrammatic process for producing electricity in CNT-PP-PVA sponges. (e) Diagram of an integrated system for producing power and desalinating saltwater. Reprinted under license from [176]. Copyright 2022, Elsevier.

efficient, thermal control is necessary. The evaporation efficiency is greatly reduced when the temperature of the solar absorber layer rises in response to light irradiation. This is because heat is lost to the surrounding medium by convection, conduction, and thermal radiation. A floating solar absorber layer has been built for interfacial evaporation to prevent significant thermal loss in a traditional bulk heating device. Thin films made of self-assembling Au NPs, carbon NPs with iron oxide, or magnetic microspheres, for instance, floated over the water-air interface and produced evaporation rates significantly higher than those of bulk heating by distributing photothermal agents throughout the reservoir [111,129,183]. Heat conduction from the hot zone to the underlying bulk water reduces the efficacy of steam generation, even though interfacial heating in solar evaporation uses thermal energy more effectively. Substrates that function as heat barriers, which restrict thermal energy to the evaporative surface and increase the efficiency of steam generation, can be used to further reduce the heat loss from the photothermal layer to the underlying bulk water. A double-layer solar steam generator was created by Chen et al. using carbon foam as a thermally insulating substrate and graphite layers as sun absorbers. Because of its limited thermal conductivity, the carbon foam prevented heat from escaping from the heated surface area. Additionally, the carbon foam decreased the amount of contact between the hot zone and the water, further confining the heat to the evaporative surface. The efficiency of the solar evaporators rose from 65 % to 85 % during 10 sun irradiation (power density of 10 kW m^{-2}) with the addition of the

thermal insulator. The design of substrates with 280 excellent thermal insulation to enhance solar steam generation has received a lot of attention as a result of this ground-breaking study. Providing enough water to the solar absorber layers for evaporation is a crucial factor for substrates, in addition to heat control. Since capillary force is necessary for water transportation, the substrate is often built as an interconnected porous structure with enough channels for water pumping. The size and moisture characteristics of the pores determine the capillary force. Hydrophilic materials are typically used in the design of the water flow channel to further promote water movement. The best substrates can wick enough water to the photothermal layer to convert heat to vapor while also offering superior thermal insulation. Due to their low density, low thermal conductivity, and commercial availability, synthetic polymers such as PS [150,184], polyurethane (PU) [185–187], and polyvinylidene fluoride (PVDF) [188,189] are excellent options for supporting layers. To design a bilayer solar evaporator, photothermal materials can be easily placed on layers of synthetic polymers using straightforward physical or chemical techniques. The growing structural and material requirements for supporting layers at the nano- or micro-scale are hardly met by synthetic polymers, despite their ease of design and preparation. As supporting substrates for solar evaporators, inorganic materials with hierarchical porous architectures, low thermal conductivity, excellent aqueous stability, and low light absorption have been used. Because of its low heat conductivity and columnar pores that can optimize the interaction between light and photothermal materials,

nanoporous anodic aluminum oxide (AAO) is a desirable option for a supporting material when loading photothermal materials [107,117,118,190,191]. In the higher sections, the hierarchical pores act as templates for loading solar absorbers and as channels for the movement of water. On an NPT, for instance, Au and Al NPs were deposited. Under focused light, this porous plasmonic membrane allowed for over 96 % light absorption and over 90 % steam generation efficiency [107,118]. The AAO membrane's advantage is its ability to precisely regulate the pore sizes and periodicity using a variety of methods. By wet etching the ordered hexagonal nanopores of an AAO membrane, Bae et al. used a pore-widening approach to prepare a vertically aligned nanowire array (Fig. 10a). Following drying, self-aggregated nanowire bundles with microscale funnel shapes and different nanoscale gaps were produced. They found the SEM images of the black Au membrane using an organized hexagonal array of AAO templates and a 52-tilted bird's-eye view (Fig. 10b) [117]. Following the deposition of black Au film on the bundles, a multiscale porous plasmonic membrane demonstrated a 57 % evaporation efficiency at 20 kW m^{-2} of light intensity. There has also been an investigation into alternative substrate materials. This bilayered evaporator achieved an 82 % solar thermal efficiency. The bilayered material's cross-sectional SEM image with corresponding images for elemental mapping of carbon and silicon based on energy-dispersive X-ray spectroscopy (EDS) analyses, has been presented in Fig. 10c, followed by CNT-silica bilayer material

preparation (Fig. 10d) [192]. It has been observed that hydrophilic microporous silica substrates with low thermal conductivity can provide mechanical support, thermal insulation, and water pumping for a thin layer of CNT acting as a photothermal layer [192].

Recent literature has shown that hierarchical porous materials not only improve light absorption but also facilitate multi-directional water and vapor transport, which significantly enhances evaporation performance under diverse conditions. For instance, Xu et al. developed 3D porous aerogels, such as *N*-doped lignosulfonate/graphene oxide aerogels, that delivered evaporation rates around $1.57 \text{ kg m}^{-2} \text{ h}^{-1}$ with >95 % efficiency, and sustained performance without visible salt deposition [193]. A recent study by Xiang et al. [194] made a notable contribution by demonstrating a hierarchical porous evaporator that enables multiple routes of water migration, including capillary-driven transport, vapor diffusion, and salt ion regulation across interconnected channels. Their carbon-based solar evaporator exhibited efficient photothermal conversion, enhanced water delivery, and excellent anti-salt-clogging performance. Importantly, the authors emphasized how structural design at multiple length scales—from nano- to macro-pores—could optimize the synergy between water transport and evaporation kinetics. Such insights are invaluable for developing next-generation evaporators with robust, scalable, and high-performance architectures. Moreover, a notable demonstration by Eichhorn et al. reported 3D interconnected carbon foam structures achieving exceptionally high evaporation rates (~ 10.9

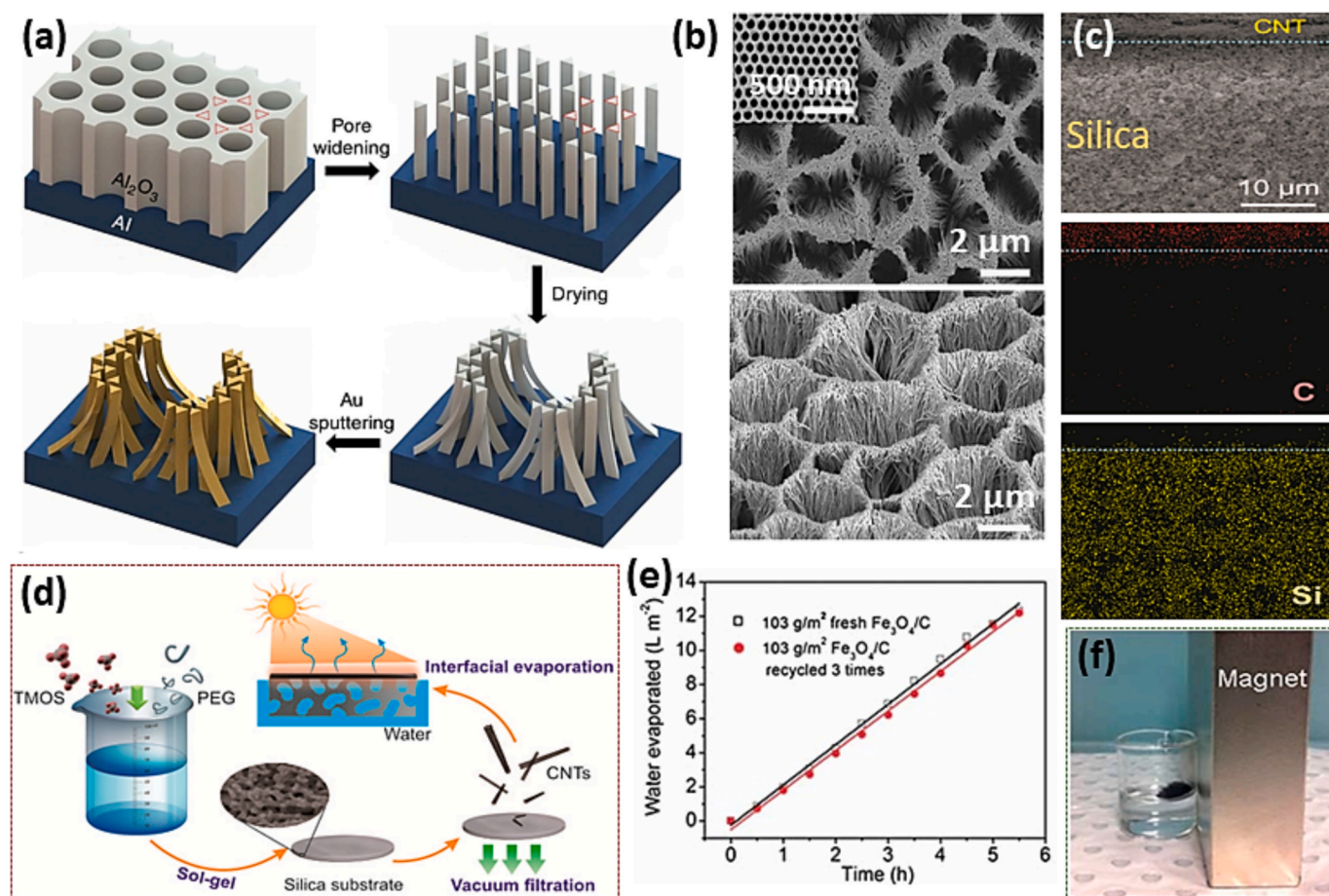


Fig. 10. (a) Diagrammatic representation of the procedure for preparing black Au membranes using the pore-widening technique on hexagonal AAO templates. (b) SEM images of the black Au membrane with a top view. Using an organized hexagonal array of AAO templates and a 52-tilted bird's-eye view (inset). Scale bars, 2 μm and 500 nm (inset). Reprinted under license from [117]. Copyright 2015, Nature Communications. (c) The bilayer material's cross-sectional SEM image shows a 5.6 μm-thick CNT layer above 0.3 mm-thick silica substrates and corresponding images for elemental mapping of carbon and silicon based on EDS analyses. (d) Diagrammatic representation of the CNT-silica bilayer material preparation. Reprinted under license from [192]. Copyright 2015, Wiley-VCH (e) The volume of water evaporation utilizing both new and three-time recycled Fe₃O₄/C particles. (f) Image of floating Fe₃O₄/C particles drawn to a recycling magnet. Reprinted under license from [183]. Copyright 2011, RSC Advances.

kg m⁻² h⁻¹) under one sun illumination, by facilitating rapid vapor diffusion through their open macropore network [195]. Sun et al. developed a bilayer cellulose-based aerogel with a purposefully designed salt-resistant topology. The hydrophilic bottom layer facilitates capillary water supply and salt backflow, while the photothermal top layer enhances light absorption and heat localization-resulting in sustained and efficient solar desalination and wastewater treatment under saline conditions. These recent advancements collectively highlight that rational engineering of porous frameworks is a fundamental strategy to maximize interfacial evaporation efficiency, stability, and applicability in real-world desalination or wastewater treatment systems [196].

Furthermore, Zeng et al. used floating light-absorbing magnetic particles to prepare a solar evaporator. They presented the volume of water evaporation utilizing both new and three-time recycled Fe₃O₄/C particles (Fig. 10e). Furthermore, they showed the image of floating Fe₃O₄/C particles drawn to a recycling magnet (Fig. 10f) [183]. A thermally robust substrate made with ultra-long hydroxyapatite nanowires was utilized to support CNT for solar steam generation in light of the high temperature produced by photothermal materials when exposed to light [197]. Heat loss from the solar absorbers to the bulk water was minimized by the inherent low thermal conductivity, and adequate water transportation was made possible by the interconnected porous network of the hydroxyapatite nanowire (HN) paper. The efficiency of this fire-resistant HN/CNT photothermal paper was 83.2 % when exposed to one sun. Aqueous environmental systems may be severely harmed by the use and disposal of supporting layers composed of dangerous or non-biodegradable materials. Therefore, future solar evaporation systems have a lot of potential thanks to cellulose-based supporting materials, which are biodegradable, renewable, and scalable. Commercially available air-laid paper with microscale pores, superior hydrophilicity, and low heat conductivity is a practical cellulose foam, developed via bottom-up bio-fabrication (BNC foam, realized by bacteria-assisted growth) or template fabrication, and has been proven to be a highly promising substrate for solar evaporation [112,124,154,169,198]. A novel, scalable method for creating BNC bilayered foams has been developed and demonstrated by Singamaneni et al. The bottom layer of the foam is composed of pristine BNC, while the top layer incorporates a variety of photothermal materials, including rGO, MoS₂, Au NPs, and even biodegradable PDA particles. Cellulose foam ensures great performance in solar evaporators by having low heat conductivity, nano- or micro-scale porosity, superior hydrophilicity, and water stability as a supporting layer.

Wood-based interfacial evaporators have been built using natural wood, which was inspired by the transpiration of trees, which uses a unique porous structure to transfer mass and heat [108,146,199–201]. Importantly, natural wood, which is primarily made of cellulose, has two important qualities: (i) a network of hydrophilic columnar micro-channels, which facilitates rapid water transfer; and (ii) superior thermal insulating qualities, which guarantee heat localization. Moreover, photothermal materials, including GO, Au nanostructures, and CNT, can be easily integrated to develop wood-based solar evaporators. As an alternative, photothermal characteristics can be produced by simply carbonizing the wood surface. Given all of these characteristics, wood seems like a highly appealing option for a solar evaporator's supporting substrate [202]. In general, the development of high-performance solar evaporation devices has been aided by the complex design and development of supporting layers with required characteristics, including water transportation, thermal management, and porous architectures. Future solar evaporation system design must take into account the use of renewable, eco-friendly, and scalable materials to facilitate the widespread use of interfacial solar evaporation technology.

2.3. Power generation mechanism

The exact mechanics underlying the evaporation-induced

hydrovoltaic effect are still up for debate, even though photovoltaic and thermoelectric generating principles have been widely accepted in the industry. Notably, when ions or protons migrate or collect at the water-material interface, the traditional stream potential theory is unable to explain how a steady electron current is produced within an inert metal or carbon electrode. Moreover, it seems that the evaporation-induced potential exceeds the boundaries set by the traditional streaming potential. Therefore, to resolve contradictions about evaporation-induced electric potential and provide insightful information, careful experimental design and molecular modeling approaches are essential. Although more research is necessary to fully understand the process underlying evaporation-induced electric power generation, it is crucial to recognize the tremendous advantages of combining this phenomenon with SDIE systems. Furthermore, achieving high-power WEG device production and effective deployment will depend critically on examining the power output of different stages within a multi-mechanism WEG system and understanding their synergistic integration.

2.4. Building the WEG advanced system

The WEG system is regarded as an intelligent solution for addressing the worldwide water crisis due to its abundant and renewable solar energy supplies. Practical solar vapor generators with high energy conversion efficiency must be developed. Power-generating efficiency is simultaneously impacted by SDIE efficiency. Several efficient techniques have been put forth in recent years to increase the rate of evaporation, such as 3D SDIE, multistage evaporation, water supply control, synergy with chemical phase change, electrochemical effect [203,204], and decrease of evaporation heat [205–207]. However, there is still room for improvement in the evaporation performance [208,209]. Conventional evaporator structures remain rigid and incapable of decomposition or deformation, despite attempts with various strategies like Janus structures [210], localized crystallization, noncontact evaporation [211], convective water flow [212], and core-less water layers [213]. This frequently results in salt deposition and a subsequent decrease in both evaporation efficiency and WEG efficiency. However, the concentration of water vapor close to the evaporation surface as a result of insufficient diffusion from the evaporator to its surroundings largely limits the evaporation rate in these static evaporation systems. This restriction reduces the effectiveness of the temperature gradient effect, piezoelectric power generation, and water-electricity cogeneration in SDIE devices. A water evaporation-induced electricity generator (WEIG) was constructed to examine the multiscale fibers network (MFN)'s power generation performance and enhancement mechanism, taking into account its advantageous hydrophilicity, high surface charge density, numerous mass-transfer channels, and efficient electron conduction network. Fig. 11a shows an MFN film (2.0 cm × 3.0 cm) laid over a polyethylene terephthalate sheet to represent the WEIG schematic based on the MFN. Following the determination of ohmic contact creation on the MFN film, the flexible MFN WEIG was submerged in a bath to guarantee that the working layer's bottom was in contact with deionized water. Water molecules are continuously moved forward along the bimodal pore channels by the natural evaporation from the MFN film's surface, which is fueled by capillary forces [214–216]. In this case, the ions in the water likewise keep moving higher while the unrestricted water flow continues. The hierarchical pore structure of the MFN, which ranges in size from large to small, was built using multiscale interfacial engineering. By using a "bottom-up" approach to embed the Ti₄O₇ nanofibers (T4NF) inside the assemblies of 2,2,6,6-Tetramethylpiperidine-1-oxyl (TEMPO)-oxidized cellulose nanofibrils (TOCNF), high-performance wood-based WEIGs based on MFN are disclosed. These include confined nanospace inherent in T4NF, interlayer slit-like channels produced by self-assembled TOCNF, in-plane nanogridded holes defined by the TOCNF matrix, and submicron junctions formed between size-differentiated building blocks. Crucially, the strong structure and mechanical stability of the MFN are supported by the interfibrillar

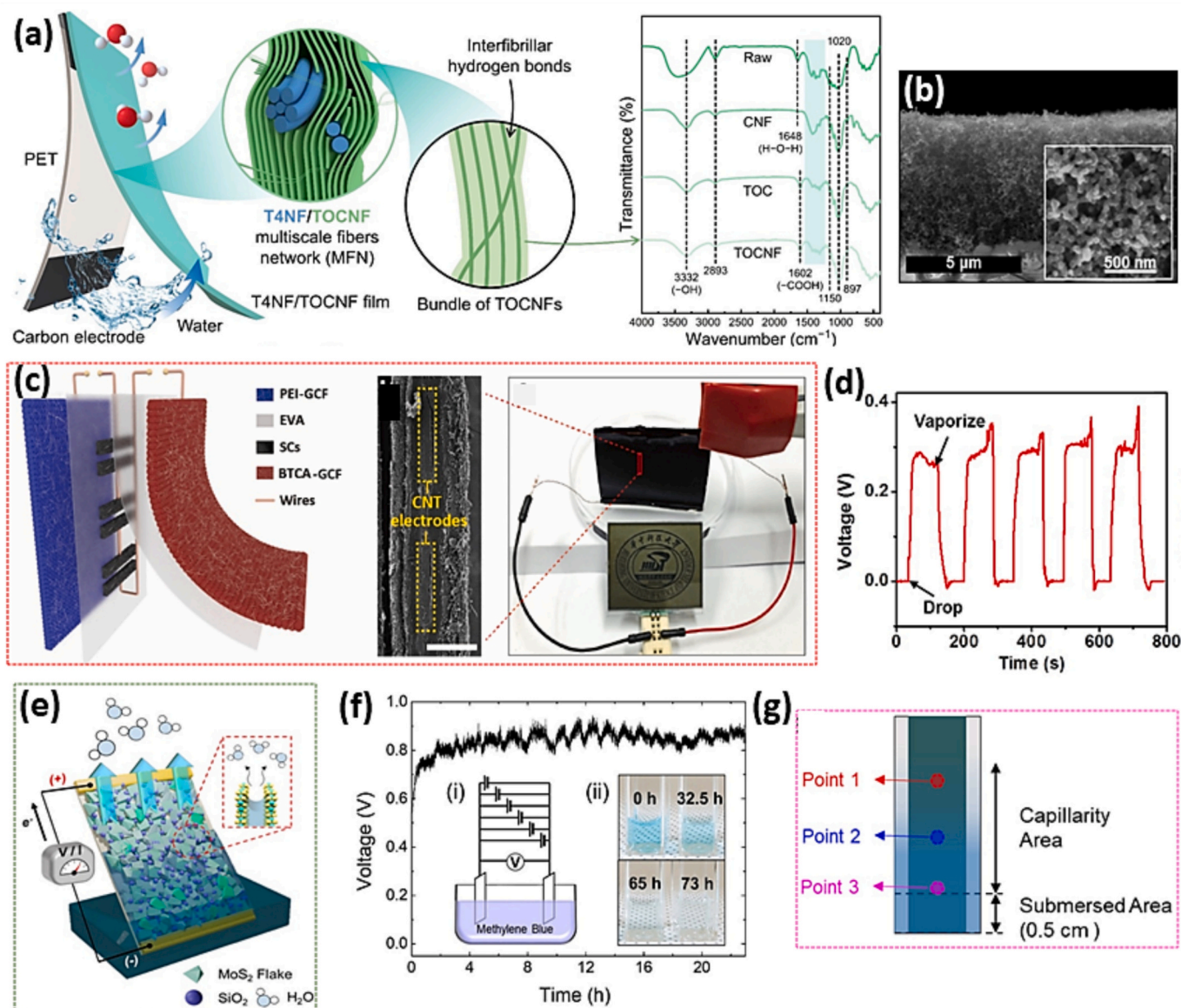


Fig. 11. (a) Fourier transform infrared spectra of raw cellulose, cellulose nanofibrils (CNF), TEMPO-oxidized cellulose (TOC), and TOCNF, respectively, are shown in the schematic diagram of a multiscale one-dimensional fiber-based network made from assemblies made of bundles of TOCNF and embedded T4NF building blocks. Reprinted under license from [219]. Copyright 2024, Elsevier. (b) Magnified SEM and cross-sectional images of the porous carbon film. Reprinted under license from [214]. Copyright 2018, Elsevier. (c) An integrated device's schematic with an SEM image displays the device's cross-section. Reprinted under license from [215]. Copyright 2019, Elsevier. (d) By regularly dropping 1 μL water droplets at the PFDTs@PCF/PCF interface, the open-circuit voltage was determined. Reprinted under license from [214]. Copyright 2018, Elsevier. (e) Diagram showing the $\text{MoS}_2/\text{SiO}_2$ composite film's evaporation-driven electrical energy generation. (f) Setup (i) for an experimental showing the voltage applied to an MB electrolysis bath with time and the related decolorization images (inset (ii)). (g) $\text{MoS}_2/\text{SiO}_2$ composite (7.7 wt %) film schematic image for XPS measurement. Reprinted under license from [215]. Copyright 2019, Elsevier.

hydrogen bonds that surround the polar groups-rich TOCNF building blocks [217–219].

According to Li et al., in ambient settings, a water droplet falling upon a piece of porous carbon film can be produced on its own. A liquid crystal display can be illuminated by twelve 5 μL water droplets that can produce a voltage of up to 5.2 V. By adjusting the ion concentration, the zeta potential of the porous carbon, and the direction of the droplet infiltration, the voltage may be adjusted. The findings show that a hydrophilic porous carbon film containing water droplets could serve as an affordable electricity generator for capturing natural resource energy. Furthermore, the cross-sectional and magnified SEM images of the porous carbon sheet are displayed in Fig. 11b [214]. Furthermore, the combined device with three CNT supercapacitors (SCs) and two pieces of porous carbon film (PCF) is displayed in Fig. 11c. The device's cross-

section is displayed in the SEM image. The CNT SCs are shown by the regions with yellow dashed squares. 200 μm is the scale bar [215]. Following the wiring and epoxy encapsulation of the exposed electrode regions, 1H,1H,2H,2H-perfluorodecyltriethoxysilane (PFDTs) was added to specific areas of the device to make them superhydrophobic. Furthermore, under ambient settings ($\sim 23.5^\circ\text{C}$ and relative humidity $\sim 71.7\%$), Li et al. repeatedly dropped 1 μL water droplets at the PFDTs@PCF/PCF interface to demonstrate the open-circuit voltage (Fig. 11d) [214]. As illustrated schematically in Fig. 11e, Li et al. used two pieces of modified carbon black-glass fiber hybrid film (GCF) and three CNT SCs to create the hybrid device. The SCs were made up of a PVA- H_2SO_4 gel electrolyte and symmetric CNT electrodes. Between the GCF were two pieces of interlayered ethylene-vinyl acetate (EVA) thin films. The EVA films contained encapsulated SCs. A flexible film with a

thickness of around 300 μm was created by hot pressing all the ingredients together. Furthermore, a methylene blue (MB) electrolysis bath voltage load (schematic experimental setup (i) as a function of time and associated decolorization images (inset image (ii)) was computed simultaneously. The 6-parallel linked devices were used to electrolyse the solution that included 100 μM KCl and 10 μM MB (Fig. 11f). Additionally, the schematic image of the $\text{MoS}_2/\text{SiO}_2$ composite (7.7 wt%) sheet for XPS measurement is displayed in Fig. 11g (size: $1 \times 2 \text{ cm}^2$). For water circulation (evaporation and capillary compensation), the samples were submerged in a NaCl solution for 0.5 cm for the duration of the night. Points 1, 2, and 3, which were 1.9, 1.2, and 0.5 cm from the bottom, respectively, were scanned using XPS [215]. Moreover, to increase their contribution to SDIE, magnetic materials have been further improved and used. Dynamically reconfigurable solar evaporators and static evaporative structures of magnetic materials were also constructed. To promote the development of water WEG technologies, this proof-of-concept work on dynamically tunable SDIE devices provides a fresh viewpoint for the formation of a sophisticated, dynamically tunable solar evaporation system. Table 2 lists the substrate material, synthesis route, sunlight intensity, evaporation rate, and conversion efficiency of several sun absorbers. Their structural optimization and inherent material qualities have a direct impact on their performance. Various features of some photothermal materials have been summarized

in the list below to assist researchers in choosing some that cannot be directly compared. It is also crucial to remember that for real-world applications to be economically viable, cost and performance must be matched.

3. Harvesting energy in WEG systems

For solar-driven interfacial photothermal evaporators to effectively convert solar energy into thermal energy, the light-absorbing substance is essential. Applications such as desalination and power generation depend on this conversion, underscoring the significance of energy and water resources for societal advancement. Salinity [244], pyroelectric/piezoelectric [245], thermoelectric [35,246–248], and thermo-electrochemical power devices are some of the more developed WEG systems available today [36,249]. These methods use solar energy, which is renewable, to generate power and steam. Furthermore, Table 3 displays the WEG systems, and it is evident that the structure's design and the photothermal material selection significantly affect the WEG's performance.

3.1. Effect of hydrovoltaics

The direct interaction of light absorbers with various water states

Table 2

Synthesis and sun-generating performance of 2D and 3D photothermal materials. The notation “—” indicates that the specific experimental data are not directly provided in this reference.

Material/composite	Structure type	Substrate	Synthesis method	Solar intensity	Evaporation rate [$\text{kg m}^{-2} \text{h}^{-1}$]	Conversion efficiency [%]	References
MoOx	2D	EPE foam	Calcination	1.0	1.26	85.60	[220]
$\text{WO}_{2.72}$ /polylactic acid	2D	—	Melt electrospinning	2.94	3.81	81.39	[221]
2D WOx nanosheets	2D	Polyethylene foam	Hydrothermal + Calcination + Exfoliation	1.0	1.10	78.60	[222]
Ti_2O_3 NPs	2D	—	Ball milling	1.0	1.32	<65	[122]
CuCr_2O_4	2D	—	Ball milling	1.0	1.18	—	[223]
CoFe_2O_4	Mixed	—	—	—	1.08 / 2.04	<100 / 140	[128]
CuS@PVDF	2D	PVDF	Hydrothermal + Phase inversion	1.0	1.43	91.50	[224]
Graphene foam	3D	—	Freeze-drying	1.0	2.10	95.00	[225]
MoS_2 @Graphene	3D	Cellulose membrane	Self-assembly	1.0	2.50	95.00	[141]
CNTs	3D	PVA sponge	Reflux + Drying	3.0	6.80	94.90	[226]
Porous CB	3D	—	3D printing	12.0	14.00	82.80	[199]
NiFe_2O_4	2D	—	—	—	1.01	—	[128]
Mn_2O_3	2D	—	—	—	1.17	—	[128]
MnCo_2O_4	2D	Quartz glass fibrous membrane	Hydrothermal + Calcination	1.0	1.22	—	[128]
Black titania nanocages	3D	—	Molten-salt-assisted + Calcination	1.0	—	70.90	[227]
$\text{CuCr}_2\text{O}_4/\text{SiO}_2$	2D	Expandable PS foam	Hydrothermal + Calcination	1.0	1.32	88	[228]
TiOx ($x < 2$) NPs	2D	Stainless steel mesh	Calcination	1.0	0.80	50	[229]
CuFeMnO_4	3D	Quartz membrane	Hydrothermal + Calcination	1.0	2.04	140.00	[230]
$\text{La}_{0.7}\text{Sr}_{0.3}\text{CoO}_3$	2D	EPE foam	EDTA Sol-gel + Calcination	1.0	1.67	92	[231]
3D $\text{WO}_{3-x}/\text{Ni}$ foam	3D	Cellulose acetate filter	—	—	—	—	[232]
MXene/PDA	3D	—	Cycle freeze-thaw	1.0	3.02	94.70	[233]
Poly(<i>N</i> -phenylglycine)	2D	Wood	Hydrothermal	1.0	1.64	90.40	[234]
CuO nanowire mesh	2D	Copper/EPE foam	Immersion + Alcohol + Calcination	1.0	1.42	84.40	[235]
Cu NPs/ C-TiO_2	2D	—	Microfluidic jet spray drying	1.0	1.50	92.20	[236]
Cu_2SnSe NS array	2D	Cellulose ester membrane/PS foam	Reflux	1.0	1.657	86.60	[237]
Cu_2ZnSnSe NS array	2D	—	—	1.0	1.643	85.70	[238]
$\text{Cu}_{1.5}\text{Sb}_4\text{S}_{13}$ NPs	2D	Cellulose acetate membrane	Reflux	1.0	6.60	—	[238]
$\text{CuCr}_2\text{O}_4/\text{SiO}_2$ composite	2D	Quartz glass fibers/Exp. PS	Impregnation + Calcination	1.0	1.32	—	[239]
C-TiO_2	2D	—	Coating	1.0	1.24	77.80	[240]
3D honeycomb CuFeMnO_4	3D	PS foam	Impregnation + Annealing	1.0	—	91	[241]
Co_3O_4 nanoforest	3D	Ni foam/EPE foam	Hydrothermal + Calcination	1.0	1.226	84.40	[242]
Ni-NiOx	2D	—	Hydrothermal + Calcination	1.0	1.45	94.0	[243]

Table 3

Recent studies on the WEG system.

Power generation model	Photothermal material	Substrate	Energy source	Solar absorption [%]	Evaporation efficiency [%]	Evaporation rate [$\text{kg m}^{-2} \text{h}^{-1}$]	Voltage [mV]	Power density [Wm^{-2}]	References
Water flow	Functionalized carbon materials	Graphite film	Flow and thermal	96	90	1.26	5	0.03	[38]
Two-shell system	All-printed porous carbon	Al_2O_3 plate	Water flow	> 90	86	1.2	4.2	8.1	[37]
Photovoltaic technology	PPy	Nonwoven fabrics	Photovoltaics and thermal	95	88.8	1.3	500	122	[39]
Pyroelectric	Nitrogen-enriched carbon sponge	Carbon sponge	Mechanical thermal	> 95	90	1.39	20	240×10^{-6}	[35]
Thermoelectric	Carbonaceous materials	Sponge	Thermal	95	81	1.26	95	0.4	[36]

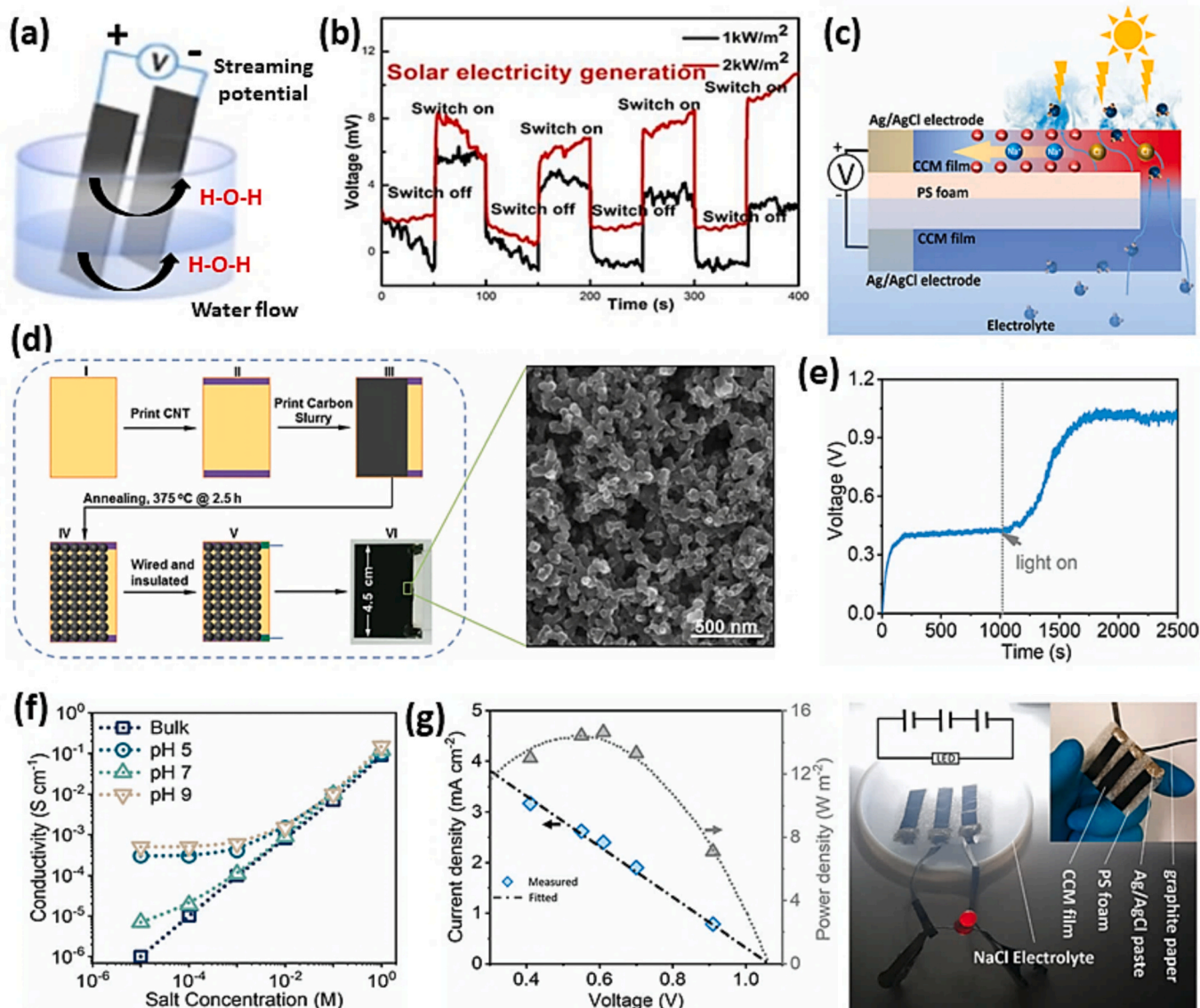


Fig. 12. (a) The water evaporation-induced electricity experimental setup. (b) The FCB generation voltage was measured under various light densities applied to the system. Electricity is generated by evaporation and water flow using a porous carbon sheet. Reprinted under license from [244]. Copyright Elsevier, 2019. (c) diagrammatic representation of ion transport and distribution in nanochannels in membranes made of CCM. Reprinted under license from [251]. Copyright 2021, RSC Advances. (d) Schematic diagram of the device fabrication process. Image VI shows the SEM image of the porous carbon layer and a picture of a wired and packaged device. Reprinted under license from [37]. Copyright 2017, Wiley. (e) The device's measurement of CCM transient open-circuit voltage. (f) The ionic conductivity of the CCM film at various pH levels (aqueous NaCl electrolyte) as a function of the salt concentration. (g) The device's computed power density and current density voltage curve under one sun illumination. An image of a red LED illuminated by several gadgets beneath a single sun. Reprinted under license from [251]. Copyright 2021, RSC Advances.

(flowing, fluctuating, dripping, or evaporating) to generate electricity is known as the hydrovoltaic effect. The most typical hydrovoltaic effect is the streaming potential. Among these, the streaming potential is the potential difference created at the liquid-solid interface that is defined by the difference in charge distribution. It suggests the creation of an electric field at the liquid-solid interface, which is crucial for the conversion and use of solar energy. By exposing the liquid in an isolated container to sunlight, SDIE devices use energy to facilitate gradual heating and eventual evaporation. The streaming potential produced at the liquid-solid interface during this process can promote electrochemical reactions, ease charge harvesting, and open up other energy conversion processes. The composition of the liquid, the solar energy intensity and frequency (the collision frequency of photons, atoms, and molecules on the surface of the materials) [250], and the geometric arrangement of the interface are some of the elements that affect the size and characterization of the streaming potential. Therefore, refining the design and improving the performance of SDIE systems requires a thorough understanding of the fundamental principles, and resilience is essential to guarantee the effective functioning of these evaporation systems. For instance, by employing polyethyleneimine to link functionalized CB (FCB) and mixed cellulose ester (MCE) membranes and PS foam as an insulating material, Hou et al. [244] created a unique FCB/MCE evaporator system. To encourage the continuous migration of free H^+ ions, the device water molecules and functional groups in the FCB/MCE were designed (Fig. 12a) to provide an induced voltage in mV (Fig. 12b). Similar to Zhou et al. [251], the size of the photothermal conversion material is altered to customize the charge motion in the channels of charged nanomaterials (Fig. 12c). To improve scalability and efficiency, Ding et al. [37] used the transpiration effect as inspiration to create porous carbon membranes that could provide a sustainable voltage of 1 V. These membranes can be used to store energy while still being able to be powered (Fig. 12d). Although power's cost-effectiveness generation potential has greatly improved with the advent of streaming potential, mechanical research still needs to advance. When charged ions are forced through the nanochannel by the temperature gradient and water flow on the material surface, the nanofluidic effect allows for increased electrical output. This results in a sustained voltage output of 1.1 V using both thermal and streaming potential (Fig. 12e). Further discussion and experimental observations have also been provided for better understanding (Supplementary information).

There is great potential for improving SDIE technology through a thorough examination of the features and regulatory approaches for streaming potential. Thus, making it possible to achieve sustainable energy use and increased energy conversion efficiencies. Therefore, a deep comprehension of streaming potential mechanisms will facilitate the development of effective and sustainable solar energy harvesting techniques. Furthermore, investigations were conducted into the cellulose nanofiber@conductive metal-organic framework (CCM) film's ionic conduction behavior in the in-plane direction. Fig. 12f displays the plots of the film's ionic conductivity against the electrolyte's NaCl concentration at various pH levels. The conductivity of bulk NaCl solution (pH = 7) at various concentrations was also tested for comparison. The bulk NaCl solution's conductivity was proportionate to its concentration, as anticipated. Conversely, the conductivity of the film in the electrolyte (pH = 7) at high concentrations of NaCl ($> 10^{-3}$ M) was comparable to that of the high concentrations of bulk NaCl solution. At low concentrations ($< 10^{-3}$ M), it did, however, marginally vary from the conductivity of the bulk NaCl solution. Furthermore, the plots progressively neared plateaus at low NaCl concentrations, and the departure became more noticeable as the electrolyte's acidity or basicity increased. These findings imply that, in either basic or acidic conditions, the surface-charged nanochannels in the CCM film controlled the ion transport. Two factors account for the high stability: (1) the fast water evaporation through the film and the continuous water supply created a constant wet-dry interface that generated the streaming potential; and (2) the film's low thermal conductivity allowed for the formation of a stable

thermal gradient across the film for the ionic thermoelectric voltage output. Based on the current density-voltage curve (Fig. 12g), the device's power density was estimated to be approximately 15 W m^{-2} [251]. Furthermore, under one sun illumination, three devices put together in series ($\sim 3 \text{ V}$) may power a red light-emitting diode (LED) (Fig. 12g) [251].

3.2. Effect of photovoltaics

With so many benefits, solar-driven interfacial evaporative photovoltaics (SDIEP) is a desirable renewable energy option. By using solar energy and renewable water sources as its main inputs, SDIEP demonstrates its dedication to environmental sustainability. In conclusion, SDIEP's key characteristics include cost-effectiveness, long-term viability, good water resource management, multiple energy conversion mechanisms, and efficient solar energy use, making it a promising technology in the field of renewable energy. Numerous benefits of the SDIEP technology increase its potential as a viable renewable energy source. First, it effectively uses solar radiation to create heat, which in turn causes interfacial evaporation and turns water into steam. By efficiently transforming solar energy into usable heat and light energy, this method allows for high utilization of solar energy and raises the overall energy conversion efficiency. Second, to transform solar energy into thermal and electrical forms, the SDIEP uses a complex energy conversion mechanism that integrates the photovoltaic and solar thermal effects. This combined strategy greatly raises the system's overall energy conversion efficiency. Third, SDIEP uses interfacial evaporation to produce power and electrical energy while using water as the working medium. Utilizing water resources is essential in areas where water is scarce, providing a beneficial and sustainable method of managing water resources. The integration of SDIE with photovoltaic power generation systems has grown in recent years. Cheng et al. [252] designed and constructed photovoltaic dual-responsive nanocapsules, using industrial paraffin wax (IPW) as the core phase transition material and cross-linked polystyrene (CLPS) and PPy as the shell materials, synthesized via rapid oxidative chemical polymerization. The resulting IPW@CLPS@PPy nanocapsules demonstrated outstanding shape stability and an ideal heat of phase transition of 114.2 J g^{-1} . Shape-stabilized phase change nanocapsules, characterized by their highly controlled photothermal response, were achieved. These capsules can absorb light energy and convert it into heat, which in turn induces a phase transition in the encapsulated material. Moreover, under the influence of an external electric field, the conductive PPy component facilitates additional energy conversion via electrochemical stimulation, contributing to a second trigger for the phase change. What distinguishes this system is its photo-thermo-electric triple response synergistic integration of photothermal conversion, electric-field-induced thermal response, and thermal energy storage in a single nanoscale system. The PPy layer not only acts as a structural shell and light absorber but also serves as an electrical conductor, enabling the nanocapsules to respond to multi-stimuli environments. This multifunctionality enhances their utility in dynamic energy storage and release applications, especially in wearable or smart devices where simultaneous exposure to light, heat, and electric fields is expected. This tri-stimuli responsiveness positions the IPW@CLPS@PPy nanocapsules as a novel and versatile platform for advanced photo-electro-thermal energy management systems. In addition, Zhang et al. [253] employed the novel idea of integrating intelligent buildings with semitransparent photovoltaic polymer solar cells (ST-PSCs) while guaranteeing their excellent performance and aesthetic appeal. Three sets of ST-PSCs (Fig. 13a) were designed by the cooperative efforts of the donor, acceptor, and polymer device. Three sets of high-performance ST-PSCs provide the best power generation and transparency balancing. The particular transmission window of ST-PSCs controlled the pace of water evaporation and the growth of algae. Since the creation of this work, SDIE and WEG have been doing more than just producing power and

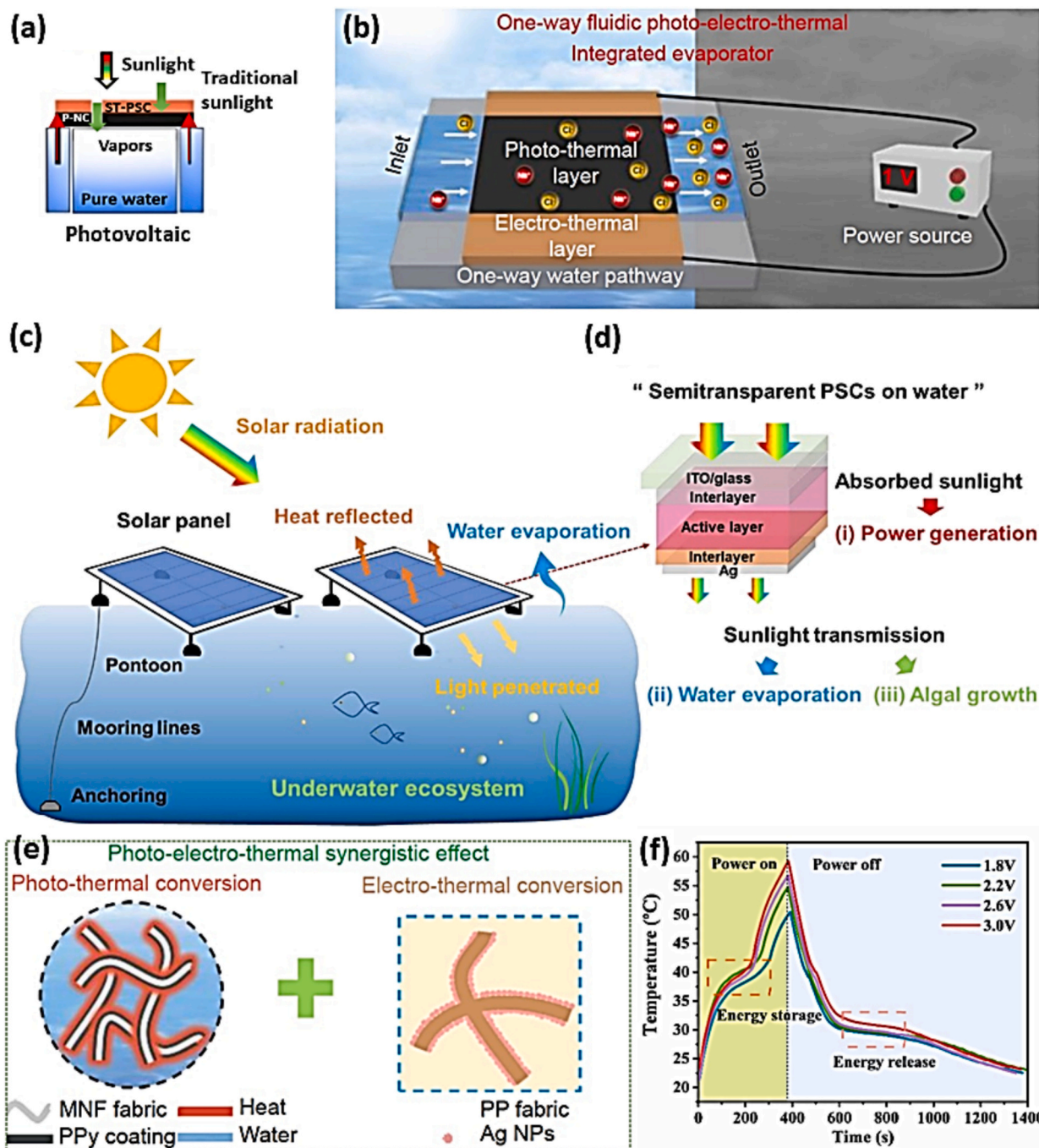


Fig. 13. (a) The ST-PSC/steam generation hybrid system's device structure is based on an inverted, monolithic design. (b) Diagrammatic representation of the one-way fluidic photo-electro-thermal evaporator that can desalinate in any weather. Reprinted under license from [254]. Copyright 2022, Springer Nature. (c-d) A comparison between the benefits of conventional photovoltaic cells and ST-PSCs. Reprinted under license from [253]. Copyright 2020, Elsevier. (e) Diagrammatic representation of the synergistic effects of photo-electro-thermal. Reprinted under license from [254]. Copyright 2022, Springer Nature. (f) The IPW@CLPS@PPy's temperature-time curves at various voltages. Reprinted under license from [252]. Copyright 2022, Elsevier.

absorbing radiation. The development of useful applications and interdisciplinary collaboration of ST-PSCs has been made appealing by their novel properties. To achieve all-weather, continuous water evaporation with superior salt resistance, Sun et al. combined photo-thermal and electro-thermal effects into a unique solar steam-generating technology. The design concept is depicted in Fig. 13b. To optimize the use of solar energy and increase the device's steam generation rate utilizing a low voltage supply, a thin photo-thermal layer with effective water supply pathways and an electro-thermal support layer with superior electrical conductivity were coupled. Nonetheless, further improvement is

required in the photovoltaic power generation system. Ji et al. [7] have developed a novel integration technique by naturally integrating a semitransparent photovoltaic (ST-PV) with an SDIE to create a solar-hydroelectric generator ensemble. This groundbreaking accomplishment makes use of the unique inverted device structure provided by the ST-PV/SDIE hybrid system performs exceptionally well, as shown in Fig. 13c-d, with a high-power output of 122 W m^{-2} and a steady moisture evaporation rate of $1.30 \text{ kg m}^{-2} \text{ h}^{-1}$. This groundbreaking study represents the first time SDIE and the emerging science of organic photovoltaic cells have been combined. It effectively up-scales solar

power generation to offer a dependable supply of electricity and drinking water, making it one of the few examples of extremely efficient WEG systems. However, the key to evaluating the device's sustainable use is how SDIEP affects aquatic species and the ecosystem. High thermal usage efficiency is anticipated from the combined impacts of photo-thermal and electro-thermal (Fig. 13e) [254]. Fig. 13f displays the IPW@CLPS@PPy's associated temperature evolution over an increasing period during electricity energy collecting and storage.

Furthermore, IPW@CLPS@PPy's temperature change curves at voltages between 1.2 and 1.6 V are examined. In the beginning, the temperature increases quickly with time, and the temperature curves show no temperature plateaus. This suggests that IPW in the IPW@CLPS@PPy does not undergo a phase transition at voltages between 1.2 and 1.6 V. The temperature rapidly declines to room temperature when the applied voltage is removed, and the discharge curves show no discernible temperature plateaus. The outcome demonstrates that the IPW@CLPS@PPy cannot be used to store and release energy at

lower electric voltages (1.2–1.6 V) [252].

3.3. Effect of salinity gradient

With its many benefits, salinity gradient power (SGP) generation is a viable and sustainable renewable energy source. Initially, SGP uses the salinity differential to produce electricity, demonstrating its renewable qualities that guarantee its continuous supply. Second, the SGP process is a clean and environmentally beneficial energy source because it does not include combustion, which removes carbon dioxide emissions and air pollutants. Additionally, SGP efficiently captures the energy from water bodies, especially in areas with significant salinity gradients like freshwater and marine interfaces, increasing the efficiency of energy use. The SGP's adaptability and wide range of applications enable its use in a variety of settings, including freshwater and marine environments, estuaries, salty lakes, and interfaces. Moreover, its potential is significantly enhanced when coupled with solar-driven evaporation, which

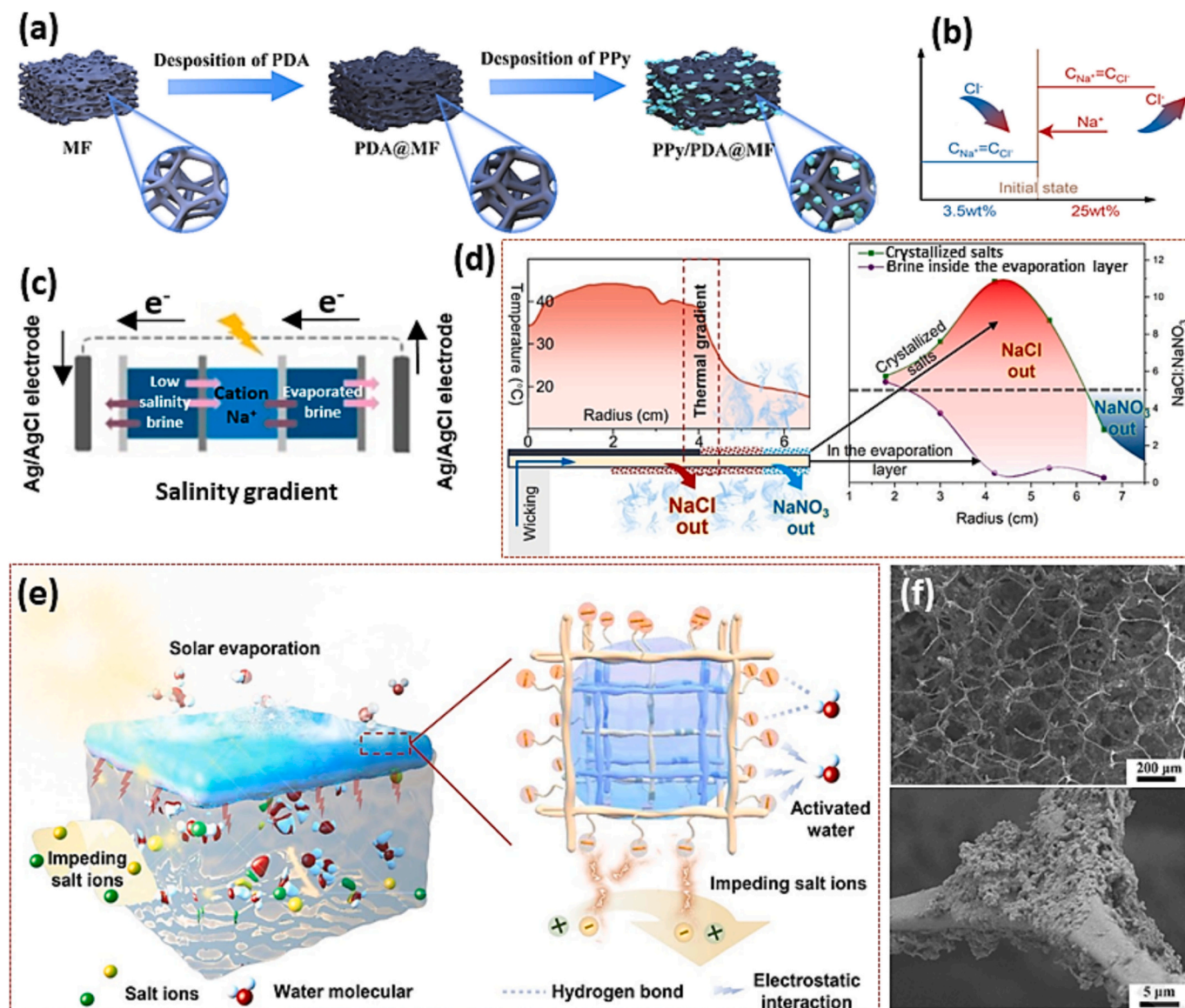


Fig. 14. (a) Schematic synthesis of PPy/PDA@MF. Reprinted under license from [256]. Copyright 2024, SSRN. (b) Performance of salinity-gradient power generation at night. Reprinted under license from [257]. Copyright 2024, Springer Nature. (c) Diagram of the setup for producing power using a salinity gradient. (d) The evaporation technique is driven by a solar-thermal gradient for fractional crystallization. Reprinted under license from [258]. Copyright 2025, Elsevier. (e) SDBS-C-loaded ionization electronegativity hydrogel suspends at the brine-air interface and produces vapor by converting solar energy to heat. Reprinted under license from [257]. Copyright 2024, Springer Nature. (f) PPy/PDA@MF substrate SEM photos at different magnifications. Reprinted under license from [256]. Copyright 2024, SSRN.

creates localized brine concentration gradients, serving as the driving force for SGP harvesting. Salinity gradients between river and seawater can be efficiently converted into energy using reverse electrodialysis (RED) (also known as SGP technology). However, the development of the RED process using natural wood is severely hampered by the high cost and complex production of the necessary ion-exchange membranes. An ionized wood membrane for this use was demonstrated by Wu et al. [255]. Cheng et al. loaded the PPy onto melamine foam (MF) by using PDA to prepare PPy/PDA@MF composites (Fig. 14a) [256]. A representative experimental setup and schematic layout are shown in Fig. 14b-c. Between low-salinity brine and high-salinity evaporated brine is ionization, and electronegativity in hydrogel. Here, the key interaction is that solar evaporation increases the brine's salt concentration during the day, thus forming a steep salinity gradient across the hydrogel. This gradient is then harnessed at night for continuous electricity generation, effectively integrating photothermal water evaporation with salinity-gradient-driven energy harvesting. Cations are preferentially moved toward the low-salinity side of the ionization electronegativity hydrogel under the salinity gradient. A charge separation process brought on by this cation-preferred ion transport causes an electrochemical potential difference between the two electrodes, which in turn causes the voltage to be generated. The electrochemical potential difference causes a redox reaction in the Ag/AgCl electrodes, which records current [257]. He et al. [257] drastically solved the issue of salt erosion of hydrogel and accelerated evaporation by modifying the hydrogel polymer chain with electronegative groups to prevent salt ion intrusion and activate water molecules. This not only improves the hydrogel's salt resistance during prolonged evaporation but also preserves the salinity gradient for consistent power output, demonstrating a direct synergy between evaporation control and electrochemical harvesting. Importantly, the system uses evaporated brine generated during daytime solar desalination for salinity gradient power generation during the night, achieving continuous water-energy co-generation through time-phased operation. Furthermore, He et al. [257] demonstrated an innovative hydrovoltaic strategy to address the challenges of salt accumulation and limited nighttime energy harvesting. By electronegatively modifying the hydrogel polymer chain, they effectively inhibited salt ion infiltration while activating water molecules for enhanced daytime solar evaporation. More notably, the system employed the residual brine to drive salt-gradient (osmotic) power generation at night via cation-selective transport induced by electronegativity (Fig. 14c). This dual-mode, all-weather SDIE platform exemplifies a synergistic hydrovoltaic mechanism that enables continuous, 24-h water evaporation-driven energy harvesting. Additionally, Deng et al. suggested an evaporation method for fractional crystallization that is driven by a solar thermal gradient (Fig. 14d). To achieve spatial salt isolation, a designed solar absorber creates a steep temperature gradient ($1.8\text{ }^{\circ}\text{C}/\text{mm}$) that simultaneously drives salt concentration and takes advantage of the distant thermal solubility dependencies of NaCl and NaNO_3 . Pure NaCl preferentially crystallizes outside the inner rings of the evaporator over a wide range of NaCl/ NaNO_3 ratios, while the decreased NaCl residues in the brine inside the evaporator allow for the purification of NaNO_3 at the outside edges.

Furthermore, from a 1:1 wt% NaCl/ NaNO_3 effluent, 58.9 % of the NaCl may be recovered as almost pure salts (99 wt%) using multi-stage solar fractional crystallization. In order to advance solar energy, use toward resource recovery, improve economic viability, and advance sustainable development, this study offers an innovative approach [258]. He et al. also introduced a sodium dodecylbenzene sulfonate-modified CB (SDBS-C) absorber to improve salt tolerance and water mobility. The intermediate-state water released by this facilitates efficient evaporation, while the maintained salinity in the residual brine supports energy harvesting through RED-based hydrovoltaic devices. Furthermore, he addressed salt erosion and improved salt tolerance in hydrogels by incorporating ionization electronegativity into the polymer chains, which effectively blocked salt ions from penetrating the

evaporator via Coulomb repulsion. This modification not only reduced salt fouling but also facilitated the activation and release of water molecules through synergistic hydrogen bonding and electrostatic forces (Fig. 14e). The design enabled intermediate-state water to form weaker and unstable interactions with the polymer matrix, allowing easier evaporation due to fewer than four hydrogen bonds per water molecule [41]. As a result, the hydrogel-based solar evaporator exhibited an impressive evaporation rate of $2.9\text{ kg m}^{-2}\text{ h}^{-1}$ in 20 wt% brine, along with excellent salt resistance. Notably, the system maintained high performance ($2.6\text{ kg m}^{-2}\text{ h}^{-1}$) even after 15 days of distorted or protected operation, outperforming several existing evaporators under similar saline conditions [257]. Lastly, a paper-based microfluidic evaporator by Wani et al. [259] utilized photothermal PPy NPs deposited on PVDF/aluminum substrates to support daytime evaporation and all-day electricity generation. Their design ensured salt accumulation in designated regions and maintained salinity gradients across micro-channels, further showcasing the tight coupling between evaporation and SGP-based electricity production. A fibrous MF structure was coated with PPy NPs, forming a highly efficient light-absorbing layer, while maintaining the original 3D porous network of MF (Fig. 14f) [256]. The PPy/PDA@MF composite exhibited excellent optical absorbance even under wetting conditions, supporting stable solar-driven evaporation. Notably, the 3D architecture facilitated the outward migration and accumulation of salt crystals on the exterior surfaces, thereby enabling sustainable salt harvesting and uninterrupted water evaporation. This design also allowed for energy production via salinity gradients, marking a notable advancement in simultaneous freshwater generation and all-day electricity harvesting.

3.4. Effect of temperature gradients

In SDIE thermoelectric technology, one of the main areas of research, interface design, and material optimization, is crucial. To improve the stability and efficiency of solar interfacial evaporative thermoelectric technology, researchers are focused on finding materials with unique features. There is widespread use of the traditional thermoelectric and pyroelectric (Fig. 15a) conversion processes. Pyroelectric materials are a class of polar crystals that generate an electric current or voltage upon a temperature change. This phenomenon, known as the pyroelectric effect, occurs due to the variation in spontaneous polarization as the material experiences thermal fluctuations. Unlike piezoelectric or triboelectric materials, which respond to mechanical stimuli, pyroelectric materials respond solely to thermal stimuli [260]. In triboelectric systems, energy conversion occurs through contact electrification and electrostatic induction. When two materials with different electron affinities come into contact and then separate, a charge separation is created. This leads to the generation of an alternating current as the system cycles between contact and separation [261]. Electrical generation in SDIE is greatly increased by the use of solar energy [34]. Lee et al. constructed a stretchy, hybrid piezoelectric-pyroelectric nano-generator based on a micro-patterned piezoelectric poly(vinylidene fluoride-co-trifluoroethylene) P(VDF-TrFE) polymer, micro-patterned polydimethyl siloxane (PDMS)-carbon nanotube (CNT) composite, and graphene nanosheets, see Fig. 15b. The PDMS-CNT was employed to make the device flexible and also serve as a strong electrode on the base of the device. Because graphene has a high thermal conductivity, it was employed as a top flexible electrode to enable a rapid temperature gradient on the device. The material harvesting ability to withstand temperature fluctuations (ΔT) and mechanical loads (σ) was investigated [262]. To extract the temperature gradient energy between the evaporator and bulk water, Liu et al. created a multi-channel, salt-resistant carbonized grapefruit peel evaporator and combined it with a thermoelectric module (Fig. 15c). The following is the usual structure: the thermoelectric module is mounted on the rear of the evaporator, and electricity is produced by the temperature differential between the evaporator and bulk water. To accomplish continuous interface

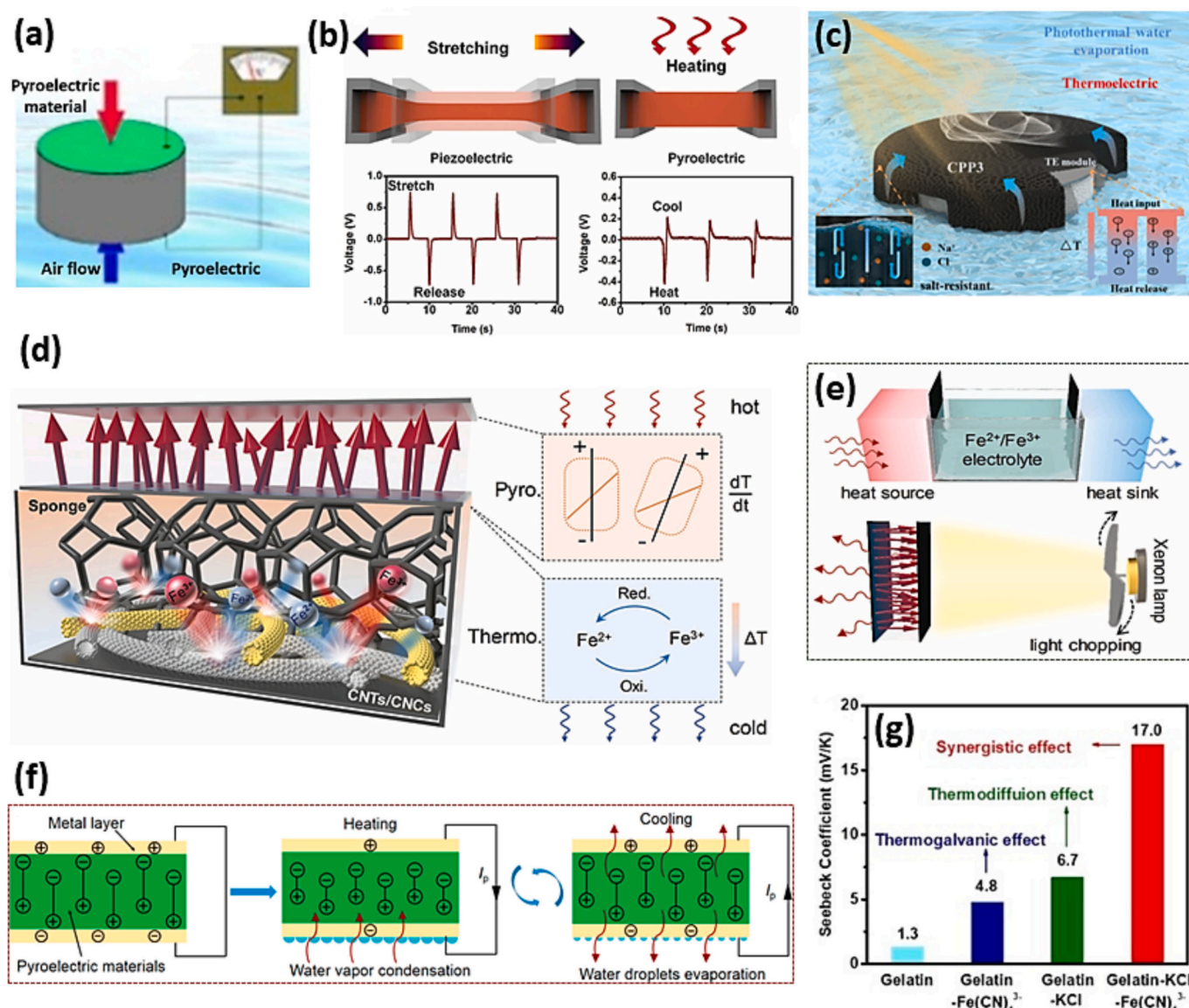


Fig. 15. (a) Diagrammatic representation of a pyroelectric NG powered by water vapor. (b) Pyroelectric output when temperature changes and piezoelectric output when strain is applied. Reprinted under license from [262]. Copyright 2013, Europe PMC. (c) Diagrammatic representation of the thermoelectric module integrated into the SDIE system. Reprinted under license from [263]. Copyright 2021, ACS Publications. (d) Schematic of a hybrid photothermal generator. The upper and bottom figures on the right represent the mechanisms of the thermocell (Thermo) and photothermal pyroelectric generator (Pyro), respectively. (e) Diagrams showing the solar pyroelectric (lower) and thermogalvanic (upper) measurements. Reprinted under license from [264]. Copyright 2018, Wiley. (f) Diagrammatic representation of the piezoelectric NG thermoelectric system's operation. Reprinted under license from [246]. Copyright 2016, Elsevier. (g) Ion migration and the thermogalvanic cell work synergistically. Reprinted under license from [265]. Copyright 2020, Science.

evaporation, water was supplied to the evaporator *via* a channel. The cooperative device can concurrently achieve a power output of 0.5 W m^{-2} and an evaporation rate of $1.39 \text{ kg m}^{-2} \text{ h}^{-1}$ under one sun [34,263]. Fig. 15d shows a schematic representation of the hybrid photothermal generator's operation. The hybrid generator is essentially an integrated sandwich construction made up of a block of PU sponge soaked in ferric/ferrous chloride solution and two ferroelectric PVDF films. On both sides of the PVDF films, a nanocomposite made of cross-linked CNT and CNT is applied, acting as both an electrode and a photothermal absorber. To guarantee proper contact with the two PVDF layers and to stop oxidation and evaporation, the thermogalvanic electrolyte-soaked sponge is sealed with plexiglass. The CNT/CNT composite layer on top of the PVDF film will absorb light and convert it into heat when exposed to radiation, raising the PVDF film's temperature ($dT/dt > 0$). As a result, thermal vibration will cause the dipoles in the PVDF to lose their orientation,

which will lower the level of spontaneous polarization and cause a pyroelectric response. The temperature-dependent redox of ferric/ferrous chloride will create an electrical potential between the electrodes connected to the opposing sides of the electrolyte, or thermocell voltage, as soon as the temperature gradient across the electrolyte is formed. The top PVDF film cools ($dT/dt < 0$) when the irradiation stops or lessens, and when the dipoles realign, the amount of spontaneous polarization will rise, producing a reverse pyroelectric response. In the meantime, the thermocell response will diminish in proportion to the decrease in the temperature gradient. As seen in the upper schematic of Fig. 15e, two pieces of PVDF films coated with CNT/CNT nanocomposite on one side were positioned face to face in a rectangular electrolyte tank to evaluate the thermocell electrodes [264]. Researchers have concentrated on liquid media. Additionally, by applying techniques combining interface

modulation and engineering, researchers aim to improve heat and mass transport processes in the field of interface design and engineering. Cost-effectiveness is a top priority in design, and because insulator materials are so economical, they are the material of choice for pyroelectric materials. For instance, Gao et al. [246] used a commercially available PVDF membrane to create a flexible film evaporator that functions as a piezoelectric nanogenerator (NG). This membrane has a remarkable temperature response and allows waste heat to be converted into electrical power. "Thermal localization" is used to heat the PVDF membrane uniformly. On the Beaufort scale, which is widely used in the natural environment, the average airflow velocity at the piezoelectric NG was 1–2 m/s, or about "force two wind". However, when a low-level vapor flows through the piezoelectric NG, its temperature drops. Thus, a self-sustaining temperature oscillation mechanism that continuously produces electrical energy is established by the piezoelectric NG (Fig. 15f). In practice, the thermogalvanic cell and ion migration may work in concert. The redox couple $\text{Fe}(\text{CN})_6^{3-}/\text{Fe}(\text{CN})_6^{4-}$ was added to the gelation matrix by Han et al., along with additional ion species such as KCl, NaCl, and KNO_3 . Their thermoelectric capacities were greatly exceeded by the overpowering Seebeck coefficient of 17.0 mV/K that was found (Fig. 15g) [265,266]. The temperature self-adaptation of human skin served as the inspiration for Jiang et al.'s [35] thermoregulatory-based evaporator. With a maximum output power of $10\text{--}4\text{ }\mu\text{Wm}^{-2}$ and adaptive temperature management in an SDIE device, the material system that is being presented allows for automatic temperature oscillation during water vapor generation. Designing interfaces and optimizing materials are essential to the development of SDIE thermoelectric technology. Electrospun PVDF/CNT yarns have demonstrated a power output density of approximately $20.7\text{ }\mu\text{W cm}^{-2}$, making them promising candidates for flexible and wearable devices. However, these figures are relatively modest when compared with conventional rigid piezoelectric ceramics such as lead zirconate titanate (PZT), which exhibit substantially higher piezoelectric coefficients (e.g., $d_{33} \approx 374\text{ pC/N}$ for PZT-5H), translating to power densities roughly in the $10\text{--}100\text{ }\mu\text{W cm}^{-2}$ range in optimized devices [267]. In the realm of electrospun PVDF- BaTiO_3 composites, a high-output NG-based on 10 wt% BaTiO_3 embedded in PVDF fibers generated an open-circuit voltage around 50 V and a power density of $\sim 4.07\text{ mW m}^{-2}$ ($\sim 0.407\text{ }\mu\text{W cm}^{-2}$) under vibration stimuli [268]. Although this is lower than ceramics in absolute power density, the electrospun format offers superior flexibility, stretchability, and durability under cyclic mechanical deformation [269]. Furthermore, planar electrospun PVDF/X materials (e.g., GO, BT) typically yield output in the range $0.2\text{--}0.6\text{ }\mu\text{W cm}^{-2}$ during tapping or bending, while yarn-structured composites such as PVDF/CNT show notably higher values ($\sim 20\text{ }\mu\text{W cm}^{-2}$) due to their enhanced mechanical interface and multi-modal deformation behavior. Nevertheless, conventional semiconductor solar interface evaporation has drawbacks. Large-scale deployment of evaporative power production systems is limited since it mostly depends on solar radiation for energy acquisition and works less than optimally in complicated and unpredictable weather conditions. Furthermore, addressing any material leakage during long-term SDIE use is essential to achieving sustainable operation. Therefore, it is imperative to investigate new approaches for sustainable energy harvesting. Inspired by antifreeze beetles, Niu et al. [270] recently created a bionic sandwich structure all-weather evaporator and successfully used it in hydropower coproduction. The clever integration of phase change microcapsules and hydrogel composites to facilitate release while promoting all-weather evaporation is the key characteristic of this novel construction. Furthermore, a hybrid device with exceptional power output performance is produced by integrating the pyroelectric modules with the all-weather evaporator. When eight interconnected SDIE devices are placed outside, they may continuously produce electricity and operate electronic fans, timers, and calculators. In addition to improving overall solar energy consumption efficiency, this bionic solar evaporator makes it easier to produce freshwater and generate electricity in any weather conditions. In addition to improving

solar technology, this study's discovery offers fresh perspectives on how to overcome significant challenges in sustainable energy harvesting.

3.5. Effects of piezoelectrics

In piezoelectric materials, mechanical deformation induces a shift in the positions of internal dipoles. This shift leads to interfacial polarization, which generates an electric potential. The resulting electric field drives the flow of electrons, enabling energy conversion. A cutting-edge method of converting solar energy, solar evaporation piezoelectricity technology combines interfacial evaporation with piezoelectric phenomena and has enormous potential in the clean energy sector. Effective solar energy conversion is made possible by the pressure that the vapor created when the liquid evaporates puts on the piezoelectric material. This mechanical deformation is then transformed into electrical energy by the piezoelectric effect. In particular, the technique includes essential parts, including a liquid medium, a piezoelectric medium, electrodes, circuitry, and a solar interface evaporator. By applying pressure to the piezoelectric material in contact, the vapor produced by evaporation causes mechanical deformation. By joining electrodes and electrical circuits, the electric potential difference created by the separation of positive and negative charges within the piezoelectric material can be used to store electrical energy or power external devices [271]. Wang and colleagues recently produced a transparent and flexible NG (Fig. 16a) by making the first experimental observation of piezoelectricity and the piezoelectric effect in an atomically thin MoS_2 flake [272]. When MoS_2 flakes with an odd number of layers bend, an electrical output can be produced; when flakes with an even number of layers flex, no output is seen. A single-layer MoS_2 device operating at 0.53 % strain produces a 15 mV voltage and a 20 pA current, which translates into a 2 mW m^{-2} power density and a 5.08 % mechanical-to-electrical energy conversion efficiency. Atomically thin MoS_2 's piezoelectricity, high mechanical stretchability, and flexibility show promise for use in implanted devices, wearable technology, electrochemical sensing, and pervasive computing [271]. The fundamental mechanism of the piezoelectric effect is similar to that of the photoelectric effect: when an external force, such as steam power, breaks the central symmetry of the crystal structure, its surface spontaneously produces a polarization charge, creating a piezoelectric potential (Fig. 16b) [245]. The development of piezoelectric NG-integrated WEG systems is limited by the SDIE system's limited mechanical energy harvesting capacity and the low-frequency pulse energy's difficulty in directly application. However, it is undeniable that the piezoelectric NG continues to offer a solution for the SDIE system's collection of small mechanical oscillation energies [271]. There are various benefits to using piezoelectric technology for solar interface evaporation. First of all, this technology can function well in a variety of environmental situations because it is not constrained by light intensity or angle. Furthermore, by doing away with the need to use fossil fuels, solar interface evaporation piezoelectric technology is environmentally benign and sustainable. Zhu et al. [245] have used the pressure that the vapor flow from evaporation puts on the piezoelectric material to generate power for waste heat or vapor-pressure-based energy generation. Additionally, a specially made honeycomb carbon sponge can be converted to SDIE. This offers a chance for SDIE technology to incorporate thermoelectric and piezoelectric modalities. To successfully apply these techniques for producing electricity in real-world settings, more research is necessary. The portability of SDIE is significantly diminished by the external addition of piezoelectric materials. Moreover, Wang et al. [273] created a soft-matter device for the recovery and use of low-grade waste heat. This novel method uses mechanical mobility and autonomous, automatic sustained temperature fluctuations to enable simultaneous thermomechanical energy harvesting at the interface of thermoelectric and piezoelectric mechanics. The thermomechanical-electrical system (TMES), TMES-bot, will continue to reorganize its body into a wheel-like shape or stance as the oscillation amplitude increases. It will eventually successfully flip

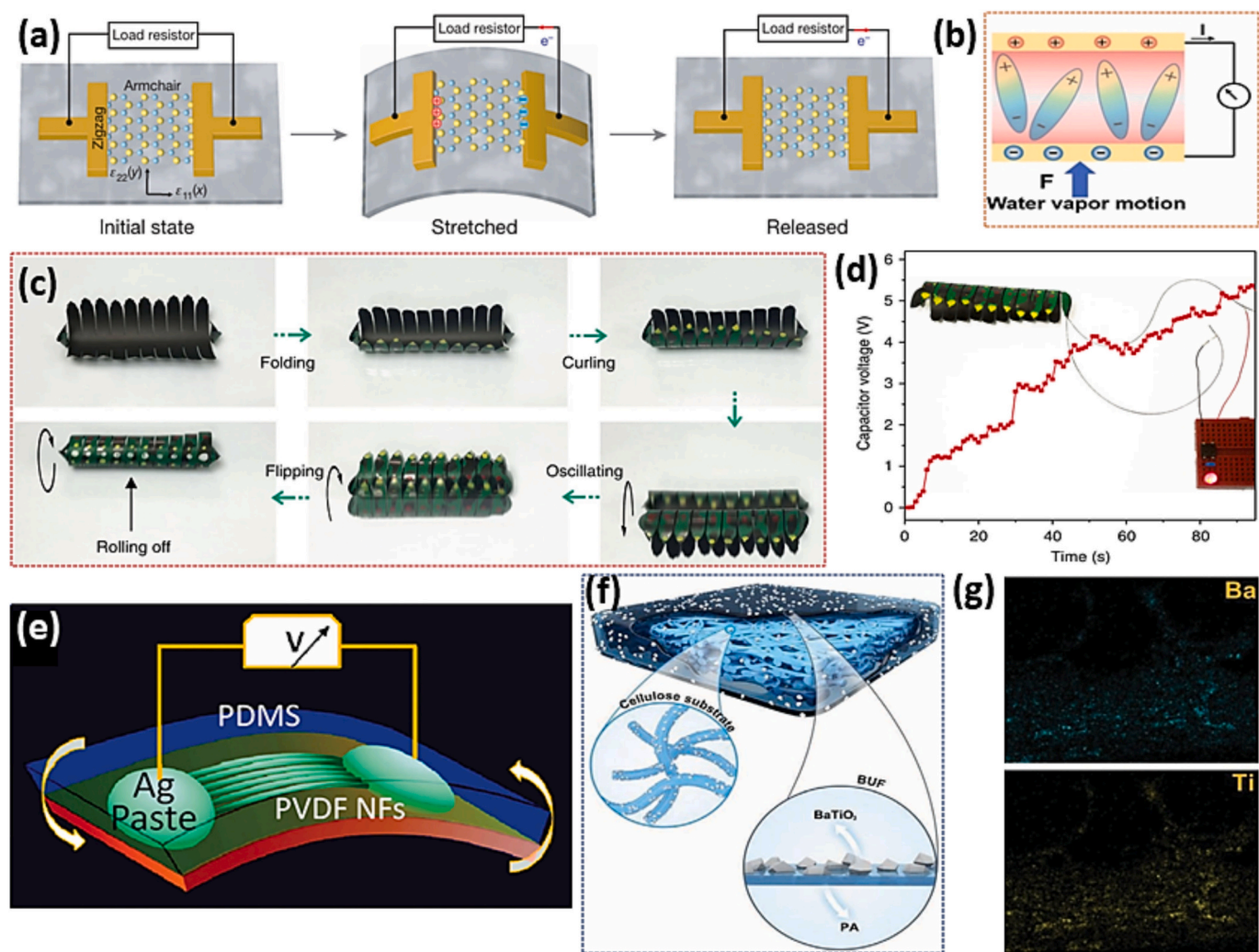


Fig. 16. (a) Piezoelectric NG's operating mechanism is based on the MoS₂ monolayer. Reprinted under license from [272]. Copyright 2014, Nature. (b) The piezoelectric effect mechanism is achieved by using WEG piezoelectric sheets. Reprinted under license from [245]. Copyright 2018, Wiley. (c) TMES-bot's active locomotive evolution for self-defense. (d) TMES-bot's charging feature and an inset image of a lit LED with a charged capacitor. Reprinted under license from [273]. Copyright 2018, Nature Communications. (e) Tensile strain and a related piezoelectric field are produced by mechanically bending the substrate. Reprinted under license from [274]. Copyright 2010, ACS Publications. (f) BaTiO₃ ultrathin nanofilm-based solar evaporator morphology. (g) Images from EDS mapping that display titanium and barium elements in a cellulose matrix. Reprinted under license from [275]. Copyright 2022, Wiley.

and roll to free itself (Fig. 16c). The TMES-bot functions as an active locomotive-adaptive system, changing on its own to replicate the previously outlined anti-predator adaptation pathways by absorbing built-in defense. More intriguingly, our TMES-bot has a thermo-mechanical energy harvesting component. The energy extraction technique uses the pyro/piezoelectric effect to work during oscillation locomotion. An external storage capacitor was successfully charged to 5 V by the TMES-bot, which also illuminated a red LED (Fig. 16d) [273].

For a variety of adaptive mechanical drives, the researchers in this study developed an autonomous TMES that can adjust to low ambient temperatures. The TMES provides a promising method for the formation of a multipurpose, adaptable self-powered system by enabling the simultaneous collection of thermomechanical energy through thermoelectric and piezoelectric effects. Moreover, Hansen et al. PVDF nanofibers were created using *in-situ* mechanical stretch and electrical poling technique at a high bias voltage (> 10 kV), which enables the conversion of nonpolar α -phase to polar β -phase for piezoelectricity. Under repeated long-term reliability testing, a single PVDF nanofiber-based device's output performance ranged from 0.5 to 3 nA of current and 5 to 30 mV of voltage with minimal performance degradation. Additionally, to boost the overall electrical output, Benjamin et al. connected the many

nanofibers in either parallel or serial fashion (Fig. 16e) [274]. Meng et al. [275] have successfully used the technique of one-piece TMES to fully synthesize ultrathin piezoelectric nanofilms and integrate them into solar evaporation systems. The evaporator differs from previous non-piezoelectric evaporators in that the electrical energy it produces can activate nearby water and promote water evaporation. In addition, it has a cycle persistence of 3000 cycles and is more than 20 % more efficient than other evaporators. Even though solar interface evaporation piezoelectric technology has some obstacles to overcome. Furthermore, the shape of the BaTiO₃ NPs embedded in the cellulose skeleton is depicted in Fig. 16f, and the duration of the cellulose substrate's immersion in the BaTiO₃ liquid determines how much of it is present. The BaTiO₃ NPs penetrate the cellulose substrate and cling to the cellulose skeleton through hydrogen bonding interactions as the immersion period increases [276,277]. Ba and Ti are uniformly distributed throughout the cellulose matrix layer, according to elemental mapping by SEM with an EDS detector (Fig. 16g) [275]. Including material selection research and optimization, interface design, efficiency improvement, and sustainability assessment, it is anticipated that this technology will lead to significant discoveries in the field of solar energy conversion and make a substantial contribution to the promotion and

utilization of sustainable energy. The calculations used to determine (Table S1) each of the five examples of somewhat classical computations are based on different SDIE devices, which have varied materials and components. The formula variables make it easy to see how to increase power production efficiency and how many factors impact WEG efficiency. To offer some design suggestions and direction for the future development of WEG, we also compare the data from five different WEG models (Table 4).

4. Conclusion

In conclusion, we provide a thorough examination of the many coupling modes between SDIE and WEG systems. Based on streaming potential, photovoltaic phenomena, frictional electricity generation, thermoelectric effects, and piezoelectric principles, we combine various energy harvesting techniques. Additionally, we examine the mutually beneficial link between sophisticated WEG systems and SDIE technologies, closely examining key elements such as structural management, material selection, and WEG efficiency. We demonstrate the use of multi-mechanism-coupled NG and scaled-up hydroelectric equipment to improve the power generation capabilities of WEG systems. These devices can effectively power microelectronic devices like small fans (1 W), LED lighting, and commercial calculators. Therefore, this study explores the incorporation of dynamic evaporation structures in WEG systems while offering a comprehensive overview of the advantages and limitations inherent in conventional rigid evaporation approaches. Despite the admirable benefits and noteworthy advancements made by WEG systems, the assessment notes that there are still several issues that need to be resolved. A key component of maximizing the complex water-energy relationship and supporting sustainable development initiatives is the installation of an effective WEG system.

5. Challenges and future perspectives

5.1. Challenges

Despite considerable progress in SDIE and WEG systems, several challenges remain that hinder their large-scale practical deployment. These challenges can be broadly summarized and organized as follows (Fig. 17):

5.1.1. Energy conversion bottlenecks

While current photothermal materials exhibit high light absorption ($< 96\%$) and evaporation rates nearing theoretical limits ($\sim 1.47 \text{ kg m}^{-2} \text{ h}^{-1}$), further efficiency gains are constrained by system-level design rather than material performance. The synergy between SDIE and WEG

must be improved through new structural designs and evaporation models that enhance overall energy utilization. Enhancing light management strategies such as spectral selectivity and photon recycling can push efficiency boundaries further. Introducing hybridized systems that integrate solar thermal and photovoltaic effects may offer synergistic energy gains. Minimizing thermal losses through better insulation and localized heating is another key direction [60,270].

5.1.2. Material and device durability

Long-term operation stability under variable environmental conditions (e.g., wind, temperature fluctuations, and salinity) remains underexplored. Salt accumulation on the evaporative surface in 2D evaporators reduces light absorption, clogs vapor channels, and shortens lifespan. More durable materials and self-cleaning mechanisms must be developed. Environmental stress tests, including freeze-thaw, humidity, and saltwater exposure, are necessary for validating long-term performance. Developing antifouling and corrosion-resistant materials can prolong the operational life of the systems. Thermal and mechanical robustness must be optimized for real-world deployment and transportability [45,53].

5.1.3. System cost and scalability

The economic feasibility of large-scale applications is limited by the cost of materials, manufacturing, and maintenance. Since energy efficiency and production cost are tightly linked, striking a balance between affordability and performance remains a central challenge. Economical fabrication methods such as inkjet printing and scalable coating techniques are being explored. Utilizing bio-derived or earth-abundant photothermal materials can lower overall system costs. Lifecycle analysis and recyclability assessments are essential for commercial viability [278,279].

5.1.4. Design of water transport channels and thermal management

The optimization of internal water pathways and thermal confinement mechanisms is critical to minimizing energy loss. Most current studies overlook microscale phenomena during evaporation and focus primarily on photothermal layer performance. An overlooked challenge is the microchannels' long-term operation, which requires anti-fouling surface engineering. Additionally, directional water transport inspired by natural systems (e.g., mangrove roots) can further improve thermal efficiency. Integration of thermally responsive polymers into channel walls can enable dynamic control of water transport based on solar intensity.

5.1.5. Structural optimization: 2D vs 3D architectures

While 2D evaporators are simpler and cheaper to produce, they

Table 4
Comparison of five WEG modes.

WEG models	Durability	Efficiency	Power intensity	Price	Effects on the environment	Growth & development
Streaming potential	Higher, mature technology	Less efficient with restricted progress	$\leq 5 \text{ Wm}^{-2}$	Comparatively low	Higher, more influenced by temperature, wind speed, and humidity	The emphasis of the research is to increase electrode efficiency and reduce processing cost
Photovoltaic effect	Higher, prolonged use	Efficiency increased using the most effective technique	Light intensity	Higher but declining	Low environmental contamination during processing	Increase solar modules' efficiency while lowering preparation costs and choosing eco-friendly materials.
Salinity generation	Medium, Technology needs to be perfected	Least effective	$\leq 10 \text{ Wm}^{-2}$	Lower	comparatively low, but necessary to consider the ratio of freshwater to saltwater	Focuses on creating materials for ion-selective membranes
Temperature gradient effect	Medium, technology must be refined	Less efficient	$\leq 15 \text{ Wm}^{-2}$	Comparatively low	Comparatively low, but mindful of the selection of heat and cold sources	Aims to increase the material's thermal cycle efficiency
Piezoelectric effect	Medium, necessary to refine the technique	Less efficient	$\leq 10 \text{ Wm}^{-2}$	Comparatively low	Comparatively low, however, the mechanical pressure range should be taken into consideration.	Focuses on increasing the piezoelectric materials' sensitivity and energy efficiency

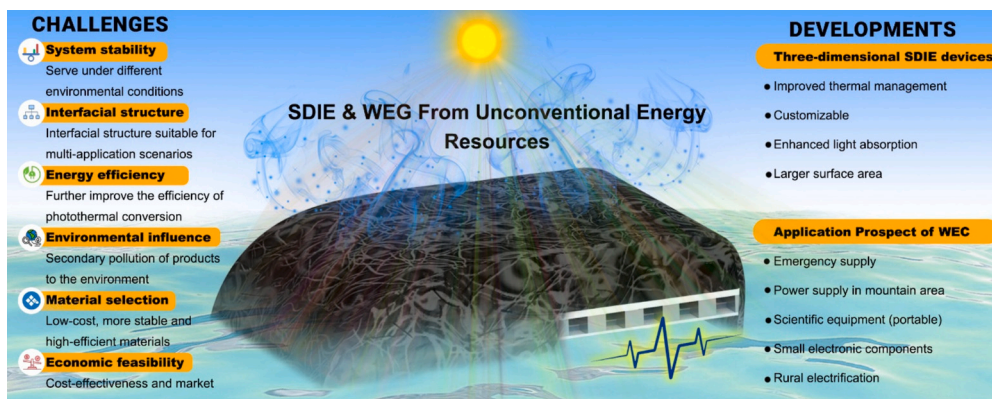


Fig. 17. Challenges and developments in environmentally friendly power generation in the WEG system for upcoming industrialization.

suffer from limited salt-rejection capabilities. In contrast, 3D designs offer higher surface areas and WEG efficiencies, but at the expense of fabrication complexity. Exploring hybrid or hierarchical structures could combine the best of both designs. Research on hierarchical pore structures and self-cleaning surfaces is gaining traction. Using super-hydrophilic coatings or electrostatic repulsion strategies could mitigate salt crystallization. Periodic regeneration or passive rinsing techniques may help restore surface functionality.

5.1.6. Versatility and adaptability

Ensuring the SDIE-WEG system's compatibility with diverse environments and use cases ranging from remote regions to portable electronics essential. Configurable, modular systems with adaptable performance are needed for global scalability. However, scaling these adaptable formats while maintaining uniform performance across devices remains a practical hurdle. Hybrid systems combining photothermal and piezoelectric properties could open dual-mode applications such as simultaneous evaporation and energy harvesting. Future work should also assess adaptability under fluctuating climatic conditions, including humidity and wind exposure.

5.1.7. Need for interdisciplinary approaches

Progress in this field depends on integrating materials science, thermal physics, nanotechnology, and engineering. Collaborative and cross-disciplinary efforts are essential to overcome existing limitations and realize the full potential of SDIE and WEG systems. Collaboration with social scientists can help translate lab-scale technologies into region-specific solutions through community engagement. Advanced modeling from computational physics can accelerate optimization of heat-mass transfer pathways within electrospun matrices. Involvement of policy experts is crucial to streamline regulatory approvals for field deployment in water-stressed regions.

5.2. Perspectives

To advance clean water and energy co-generation technologies, such as SDIE and WEG, certain strategic and interdisciplinary perspectives must be adopted. The following key viewpoints outline personal reflections and generalized future directions (Fig. 17):

- i. *Design simplicity with multi-functionality:* Future SDIE-WEG systems should shift toward simplified architectures with integrated functionality (e.g., modular components that combine photothermal conversion, water transport, and electricity harvesting). This can improve reliability and reduce maintenance costs for real-world deployment.
- ii. *Shift from efficiency to stability and scalability:* While record-high efficiencies have been reported (photothermal conversion

efficiency exceeding 96 %), performance under dynamic environmental conditions remains a hurdle. Future materials research should prioritize stability, anti-fouling performance, and weather adaptability over merely maximizing lab-scale efficiency.

- iii. *From lab to field-focus on cost and manufacturability:* Current material and device designs are often costly and complex. Low-cost fabrication, use of locally available materials, and compatibility with batch production are essential factors for scaling technologies to rural and remote regions. Additionally, policy-level support and public-private partnerships can play a pivotal role in market translation.
- iv. *Interdisciplinary synergy:* Real breakthroughs will emerge from cross-disciplinary integration-material science must work in tandem with environmental engineering, mechanical design, and artificial intelligence-enabled system monitoring. Future prototypes should integrate smart sensing and data-driven optimization to dynamically adapt to environmental shifts, ensuring responsive and resilient performance.
- v. *Application-oriented customization:* A one-size-fits-all model is impractical. Perspectives must evolve toward application-specific SDIE-WEG units-portable units for disaster relief, floating platforms for seawater desalination, and rooftop panels for off-grid energy needs.
- vi. *Standardization and global guidelines:* Lastly, global adoption demands the urgent development of standardized testing protocols and performance benchmarks to guide both academic research and industrial deployment.

In conclusion, the journey from high-performance laboratory prototypes to globally impactful technologies will require collaborative, innovative, affordability-driven design and resilience-focused engineering. The future of clean water and energy lies not just in high efficiency, but in universal accessibility. Future work should shift from material-centric to system-level innovation. The field must prioritize scalable designs, seamless integration with other renewable technologies, and rigorous field-testing under real-world conditions to ensure practical viability. Addressing the outlined challenges through collaborative, interdisciplinary research will be vital to unlocking SDIE and WEG systems for sustainable energy and water solutions globally.

CRedit authorship contribution statement

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Declaration of competing interest

We wish to confirm that there are no known conflicts of interest associated with this publication, and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgement

This work was financially supported by the National Natural Science Foundation of China (Grant No. 52001117). This work is financially supported by the National Natural Science Foundation of China: Comprehensive Energy System Research on Hydrogen Storage Coupled with Coal Chemical Industry in Xinjiang (52266018). Doctoral Initiation Gold Project of Xinjiang Institute of Engineering: Research on Regional Integrated Energy System with Hydrogen Storage (2023XGYBQJ01). Xinjiang Youth Science and Technology Top-notch Talent Project - Training of Young Science and Technology Innovation Talents: Integrated Research on “Source Grid Load Storage” of Comprehensive Energy System with Multi-type Energy Storage for New Power System 2022TSYCCX005. This work was financially supported by the Vietnam National Foundation for Science and Technology Development (NAFOSTED) (grant number 103.02-2021.106) and PHENIKAA Innovation Foundation (PU.2025.PIF.02).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cej.2025.167472>.

Data availability

Data will be made available on request.

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