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Review

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Solar-driven interfacial evaporation: materials design and device assembly

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Abstract
Solar-driven interfacial evaporation (SIE) is an emerging research topic that is gaining attention due to its potential in addressing global water scarcity issues. This review provides a comprehensive overview of base materials, recent innovations in photothermal materials and the design of evaporators for effective water desalination and purification. The recent development of SIE is meticulously discussed, providing a deep understanding of the key performance indicators and state-of-the-art materials. Additionally, this review examines novel strategies that have been reported in the literature for enhancing the efficiency and scalability of SIE systems. These strategies involve using photothermal materials and exploring innovative device configurations. Finally, we discuss the existing challenges and future research directions, emphasizing the potential of SIE in addressing global water scarcity and contributing to a sustainable future.

Keywords: Solar-driven interfacial evaporation, materials design, device assembly, clean water production, photothermal materials, water desalination

INTRODUCTION

Pure water scarcity is a pressing issue affecting humans and animals worldwide, with profound consequences for public health, agriculture and ecosystems[1]. The improper distribution of water resources, coupled with the increasing demands for pure water in various fields, exacerbates this crisis. Climate change intensifies the problem by causing unpredictable patterns of drought and flooding, further straining water supplies. In 2016, approximately 933 million people, which accounted for one-third of the global urban population, experienced water scarcity. This number is projected to rise to 1.693-2.373 billion by 2050, affecting nearly half of the urban global population. India is projected to be the country most affected, as it is estimated that there will be an increase of 153-422 million people residing in water-scarce urban areas. Additionally, the number of large cities facing water scarcity, including 10-20 megacities, is expected to grow significantly[2]. Furthermore, water scarcity affects economies, leading to issues such as food shortages, social tensions, and decreased access to education. Several different technologies have been developed for the purification of saltwater, including electrodialysis[3], membrane distillation[4], solar-driven water evaporation[4], and reverse osmosis[5]. In the search for sustainable energy options, solar energy stands out as a promising solution. Therefore, solar-driven interfacial evaporation (SIE) has garnered the most interest among these techniques due to its distinctive characteristics, including solar energy usage, non-pollution, and cost-effectiveness[6,7]. The recent advancements in solar water purification encompass two critical stages: the generation of solar-driven water vapor and the subsequent collection of this vapor. The process of solar vapor generation is notable for its ability to vaporize at temperatures lower than its boiling point. Traditionally, the natural evaporation of water is considerably slow, typically below 0.3 kg/m^2/h under standard solar conditions. To enhance this process, the use of photothermal materials has been pivotal. These materials, when soaked in water, leverage solar energy to accelerate evaporation. Initially, solar evaporation systems relied on volumetric heating, employing dispersed nanoparticles to absorb solar energy and heat the water. However, this method had limited efficiency (30%-45%) because it required continuous, intense solar exposure to heat the entire body of water[8].

In response to these limitations, the concept of SIE was developed. This innovative approach concentrates heating at the water-air boundary, significantly improving efficiency even under less intense sunlight. It involves strategically placing solar evaporators above water sources, selectively heating only the interfacial water in contact with the evaporator under solar exposure. This selective heating greatly reduces the volume of water that needs to be heated. Importantly, the effectiveness of these interfacial systems can be finely tuned by altering the evaporator structure[9,10]. The structural design of these systems is equally important, as it directly influences the dynamics of energy absorption, heat transfer and water transport. Advanced designs optimize solar energy absorption by employing expansive surface areas or integrating materials with superior solar absorbance. This maximizes the capture of solar irradiance, a key aspect of efficient photothermal conversion. Emerging advancements in materials and structural designs have enabled the creation of systems that can achieve over 90% efficiency in converting solar energy to vapor in solar-thermal evaporation processes. Moreover, the structural design is pivotal in ensuring efficient heat transfer from the photothermal materials to the water interface, facilitating an intimate interplay between the heat-generating elements and the water surface. This ensures that the generated thermal energy is judiciously utilized for water evaporation[7,11]. Furthermore, sophisticated structural designs incorporate mechanisms to minimize thermal dissipation, confining the generated heat to the evaporation zone and enhancing thermal efficiency. Water management, another critical aspect, is influenced by the structural design, ensuring a consistent and controlled supply of water to the evaporative surface through mechanisms such as capillary action or wicking materials. Various structural design innovations have been implemented to address the issue of salt buildup in evaporators. These include the incorporation of hydrophobic coatings, the addition of layers resistant to clogging, and the adoption of designs that avoid direct contact. Each of these solutions plays a crucial role in preventing the accumulation of salt on evaporator surfaces, thereby enhancing the efficiency and reliability of these systems[12,13].

Finally, materials design and device assembly play crucial roles in the efficiency and effectiveness of SIE systems. The structural optimization of photothermal materials enables the harnessing of solar energy with high conversion efficiency. The advanced device assembly allows for the inclusion of multifunctional components. These components enhance energy and water management efficiency and make it easier to commercialize these systems[14,15]. By focusing on advancements in materials design and device assembly, we can enhance the performance of SIE systems. This review article presents a comprehensive overview of the latest progress in the SIE, emphasizing the specific characteristics of photothermal materials and their conversion performance. We explored the solar light absorbers and sophisticated thermal management systems to maximize the performance of SIE. This article aims to inspire the development of cutting-edge SIE technologies by bridging the gap between fundamental research and commercialization.

OVERVIEW OF MATERIALS DESIGN

The efficiency and evaporation performance of SIE depend on specific properties of photothermal materials, including strong light absorption capabilities, high or low thermal conductivity, and suitable wettability and resistance to corrosion and fouling. For instance, commonly used materials include carbon-based materials demonstrated by carbon nanotubes (CNTs)[16] and graphene[17], metal-based materials such as gold[18] and silver[19], metal oxide-based materials, e.g., titanium dioxide[20] and zinc oxide[21], and polymeric materials illustrated by cellulose[22] and polydimethylsiloxane (PDMS)[23]. Besides, MXenes, for example, titanium carbide[24] and molybdenum carbide[25], semiconductor materials including copper sulfide[26] and molybdenum disulfide[27], and metal-organic frameworks (MOFs) such as Cu-benzene tricarboxylic acid (BTC)[28] and zeolitic imidazole framework-8 (ZIF-8)[29] have also been studied. The specifications and light-to-heat conversion mechanism of these photothermal materials are discussed in the following subsections.

Material selection criteria

In the field of SIE, prioritizing the structural optimization of photothermal materials with advanced optical absorption properties is crucial to increase efficiency and promote sustainability. In this regard, nanostructured photothermal materials [Figure 1] have shown exceptional performance due to their ability to localize and concentrate light, resulting in enhanced photothermal conversion efficiency[30-39]. Moreover, the incorporation of phase change materials or photonic crystals in the synthesis provides the ability to dynamically control optical properties. This allows for the customization of spectral selectivity and tunable absorption[40-42].

The thermal properties of selected materials are also significant determinants of their suitability. Notably, thermal conductivity plays a dual role. High thermal conductivity is essential for the effective spread of heat across the material, thus improving the overall thermal efficiency. On the other hand, low thermal conductivity is advantageous in specific layers of the system. This helps in reducing heat loss to the external environment, focusing the thermal energy in the crucial areas for optimized evaporation. Additionally, low thermal expansion is necessary to maintain structural integrity under stress from fluctuating temperatures, thus preventing damage and extending the operational lifespan. Moreover, a high level of thermal stability is required to withstand the temperature extremes encountered in solar-driven evaporation processes, ensuring consistent performance and durability. By meticulously considering these critical thermal properties, researchers can optimize material selection for SIE, resulting in enhanced efficiency, reliability and overall performance[43-48].

The mechanical properties of base substrate materials, including strength, ductility, toughness and fatigue resistance, are also essential factors to consider. Ideally, materials should exhibit high tensile strength and

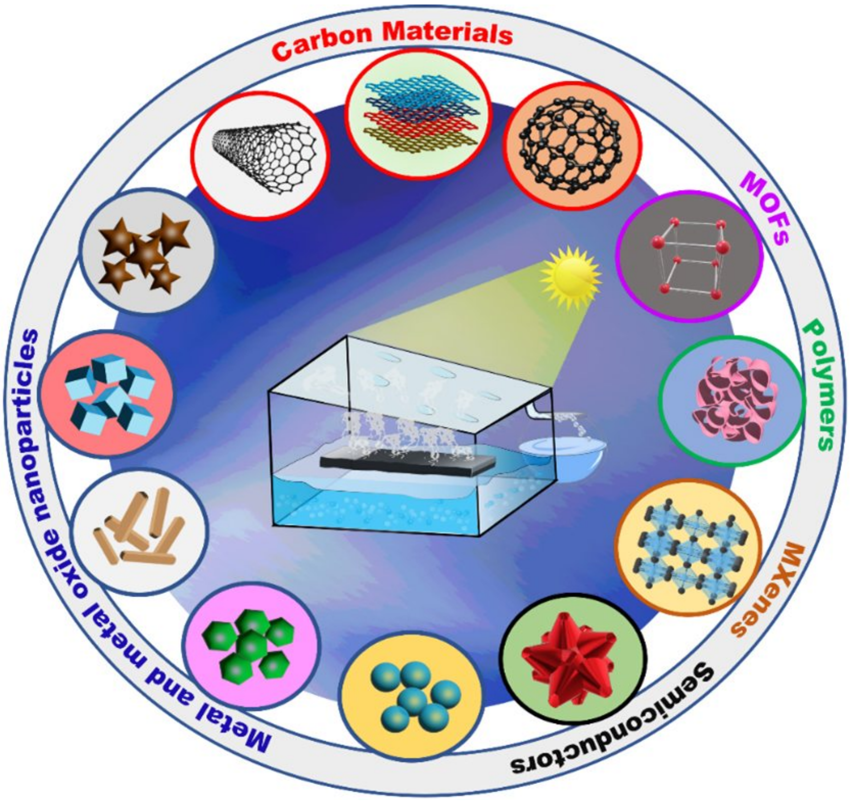

Figure 1. Various types of photothermal materials used in SIE**.**

ductility to withstand the stresses induced by fluctuating temperatures and pressures during the evaporation process. Furthermore, materials with outstanding toughness can resist fractures and deformations, while those with fatigue resistance ensure the system's durability under repetitive loading cycles. The selection of materials for SIE applications depends on finding the right balance among these mechanical properties. This collective enhancement improves the overall performance and sustainability of the technology[49-52].

Material categories

Carbon-based materials

Carbon-based materials, such as graphene, CNTs, carbon black, graphite, and graphitic carbon nitride (g-C_3N_4), are popular choices for SIE applications due to their unique properties, including light absorption, thermal conductivity and chemical stability. For example, graphene and CNTs exhibit impressive thermal conductivity and solar absorption capabilities. On the other hand, carbon black is a cost-effective and highly efficient photothermal material. Graphite stands out for its notable in-plane thermal conductivity and strong light absorption, while g-C_3N_4 is distinguished by its thermal stability and non-toxic nature[53,54]. Carbon-based materials, particularly those with π-bonded structures, exhibit a robust photothermal conversion mechanism rooted in their unique molecular properties. Their conjugated structures enable them to absorb sunlight across the entire solar spectrum effectively. In these π-conjugated systems, the π electrons come together and interact with the p electrons, resulting in a uniform electron cloud density throughout the material. When light is absorbed, the energy from the photons causes the π electrons in the bonded molecular orbitals to move to the π anti-bonding molecular orbitals, which puts them in an excited state. These electrons then release a portion of their energy as heat while returning to their ground state, resulting in the observed photothermal effect. This heat generation, facilitated by the rapid movement of electrons between the HOMO and LUMO orbitals, is pivotal for applications such as SIE[55]. Carbon materials are widely available and surpass other substances in terms of accessibility and abundance. These advantages contribute to their ability to greatly improve SIE, making them a highly promising option for further exploration in related research areas. Their applications span energy storage and conversion, environmental remediation, nano-electronics, composite materials, biomedical applications, catalysis, and wearable technology[56]. The use of carbon-based materials is widespread due to their advantageous attributes. Nonetheless, a significant challenge is their intrinsic hydrophobicity, notably in CNTs and graphene, which impedes effective thermal interaction with water. To mitigate this, several approaches have been implemented. Some ways to improve the water affinity of carbon materials are by integrating them with hydrophilic counterparts, applying hydrophilic functional treatments, or adding oxygen elements. Graphene oxide (GO), a hydrophilic derivative of graphene, serves as a prime example. However, its synthesis can introduce a range of defects such as vacancies and oxygen-based functional groups, which could potentially compromise its structural and functional integrity[55].

Metal-based materials

Metal-based materials, notably metallic nanoparticles such as Au, Ag, and Cu, have been extensively studied for their unique optical properties, primarily attributed to localized surface plasmon resonance (LSPR). When light hits these metallic nanoparticles, the electric field causes the conduction electrons to collectively oscillate with respect to the positively charged lattice. This LSPR phenomenon is highly dependent on nanoparticle geometry and surrounding medium. The resonance condition leads to enhanced absorption and scattering cross-sections for these materials. The absorbed light energy is subsequently converted into thermal energy through non-radiative decay processes. These processes, including the interaction between electrons and phonons, effectively increase the temperature of the material and the surrounding water, making it easier for the water to evaporate[57]. For instance, gold nanoparticles (AuNPs)[58] have demonstrated impressive evaporation rates and efficiencies under 1 sun illumination. Similarly, silver nanoparticles (AgNPs)[19], Cu-based materials[59], and aluminium-based nanoparticles[60] have exhibited notable evaporation rates and efficiencies in various studies. Metal-based materials offer several unique benefits for SIE systems. Firstly, their structural properties are highly adaptable, with precise control over shape and size to meet specific needs[61]. Additionally, certain metals, such as copper-based nanomaterials, possess antibacterial qualities and can catalyze the conversion of CO_2 and decomposition of organic substances, enhancing the multifunctionality of SIE systems[62]. Moreover, these materials exhibit excellent mechanical strength and flexibility, making them suitable as standalone options or as supportive bases for other substances[63].

However, there are drawbacks. Metal-based materials generally incur higher costs compared to other photothermal materials, such as carbon-based options, particularly in the case of noble metals with superior properties. This cost factor limits their widespread application. There are ways to reduce these expenses, such as combining metals with less expensive carbon materials and creating metal structures that are lightweight and have a high level of porosity. This not only decreases the amount of material needed but also improves the absorption of light and the efficiency of photothermal processes. One issue that arises is the vulnerability of certain metal-based materials to corrosion, particularly in harsh conditions such as seawater. To address this issue, it is necessary to delve into stronger metal compositions and apply protective coatings. This will help to enhance longevity and minimize maintenance in such conditions. While certain nanoscale metal materials might lack chemical stability and are prone to oxidation, their durability can be enhanced through core-shell and coating designs. This enhancement leads to long-term stability and reusability in SIE applications[57].

Metal oxide and semiconductor-based materials

Metal oxide materials, notably TiO_2, ZnO, and Fe_3O_4, along with other semiconductors such as silicon, perovskite and gallium arsenide, are making significant strides in SIE and purification due to their unique photothermal properties. Both metal oxides and semiconductors possess wide band gaps that allow them to absorb sunlight efficiently. Upon exposure, they absorb photons whose energies correspond to these band gaps, causing electrons to move from the valence band to the conduction band. When these electrons eventually return to their original state, most of the energy they release is in the form of heat rather than light. Recent studies have shown that incorporating plasmonic nanoparticles or co-catalysts can further amplify the light absorption and photothermal conversion capabilities[64-66]. Notably, Fan *et al.* highlighted that morphological variations of MnO nanoparticles, when tuned via pyrolysis temperatures, could optimize water transport and photothermal conversion in bifunctional solar evaporators made from upcycled waste poly(ethylene terephthalate) (PET) bottles, thereby enhancing evaporation rates and overall efficiency [Figure 2][67]. Semiconductor-based photothermal materials are emerging as a valuable resource in SIE due to their high photothermal conversion rates, robust chemical stability, abundance, and broad industrial application. These photothermal materials also offer antibacterial qualities, durability, and recyclability. One major benefit is their capacity to create electron-hole pairs when photons are absorbed, which helps in producing steam for clean water generation[68]. These advantages extend to various sectors, including electronics, solar energy, LED lighting, and more[69]. However, in SIE, these benefits face challenges such as high-temperature performance issues, doping difficulties, and manufacturing complexities, which contribute to increased costs and scalability limitations[70,71].

Polymers

Deployment of polymeric materials as crucial constituents for design and fabrication has emerged as an innovative direction. With their intrinsic capacity to host a diverse range of properties, polymers have offered a flexible and versatile platform, enabling targeted tailoring of material attributes to optimize solar energy utilization[72]. For instance, hydrophilic polymers can spontaneously adsorb water, facilitating persistent water supply to the evaporation interface, while their structural versatility allows for facile integration with conductive or photothermal nanomaterials to augment light absorption and heat conversion efficiency[73]. Innovative approaches involving stimuli-responsive polymers have opened up possibilities for smart, autonomous system regulation, whereby the water evaporation rate can be modulated in response to environmental conditions. The tailoring of polymer morphologies such as micro-porosity or hierarchical structuring is being explored to maximize light trapping ability and surface area. This not only facilitates vapor escape but also minimizes thermal losses[74]. Meanwhile, fabrication techniques such as 3D printing and electrospinning have enabled the development of intricate multi-component designs. By integrating polymers with other functional materials, these hybrid structures exhibit enhanced performance through synergistic interactions. Polymeric materials are increasingly popular in creating self-floating solar evaporators, offering light weight, easy processing, mechanical stability, porous structure, low thermal conductivity, and adjustable chemical functionalities[75,76]. However, their large-scale practical application faces challenges in terms of cost, scalability, and longevity. Despite promising lab-scale evaporation rates, the efficiency under low-intensity sunlight needs improvement, and issues such as chemical stability, mechanical durability, non-toxicity, and environmental impact require more research and development[8,77].

MXenes

MXenes are a class of two-dimensional (2D) transition metal carbides, nitrides and carbonitrides. In contrast to traditional materials, the distinctive layered structure of MXenes allows for customizable surface properties, excellent electrical conductivity, strong hydrophilicity, and strong mechanical properties. These

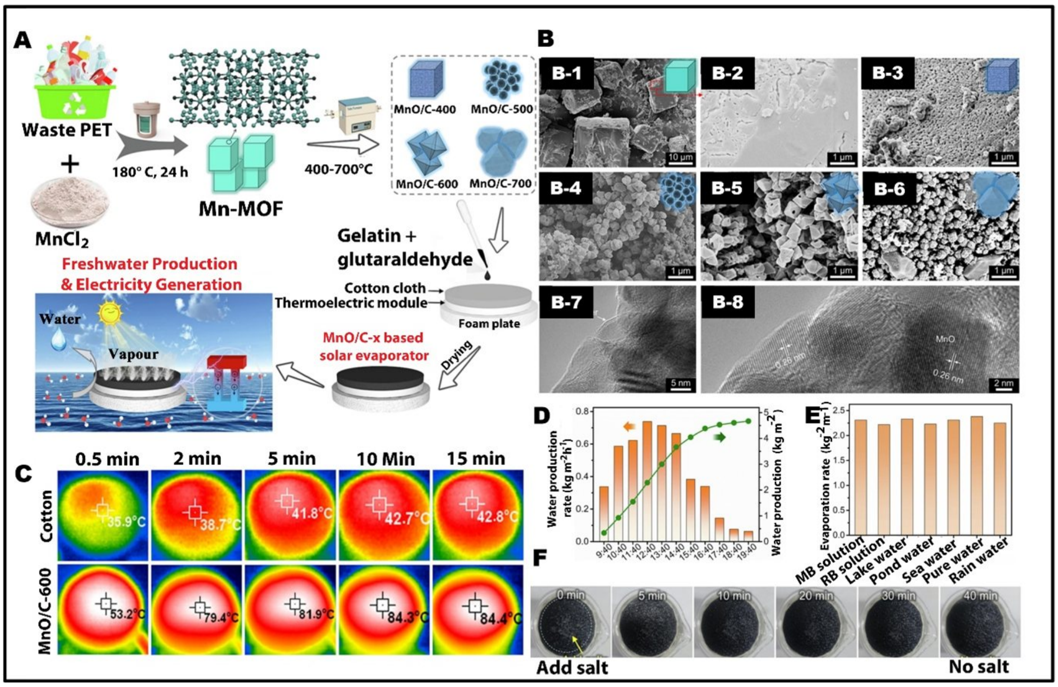

Figure 2. (A) Illustration of the process for fabricating flexible MnO/C-x membrane for solar evaporation and thermoelectric power production. (B) SEM micrographs of (B-1 and B-2) Mn-MOF, (B-3) MnO/C-400, (B-4) MnO/C-500, (B-5) MnO/C-600, and (B-6) MnO/C-700. (B-7 and B-8) HRTEM micrographs of MnO/C-600. (C) IR images of cotton fabric and MnO/C-600 membrane exposed to 1 Sun radiation. (D) Rates and cumulative quantities of water production. (E) Evaporation rate of MnO/C-600 employing varying water sources. (F) Images show the salt ablation effect after adding NaCl to the MnO/C-600 evaporator's top surface. Reprinted with permission from ref.[68]. Copyright 2023 Elsevier.

characteristics make MXenes highly effective in converting light into heat and localizing it efficiently. Exploiting these qualities, researchers have engineered MXene-based nanocomposites, hybrid materials and coatings that have demonstrated exceptional performance under direct solar illumination[78]. Furthermore, the hydrophilic nature of MXenes facilitates water transport to the photothermal conversion layer, ensuring a constant supply for evaporation. This eliminates the limitation of prolonged water diffusion pathways, thus leading to a higher evaporation rate[79]. Moreover, their compatibility with various fabrication methods allows for the creation of complex architectures that can efficiently manage light absorption, heat generation and vapor diffusion. Nevertheless, the production of these items presents considerable obstacles, mainly because of the potential risks to the environment and human health caused by the use of hazardous chemicals during the etching process[79]. Further research and development are essential to overcome their production challenges and fully exploit their potential[80].

Metal-organic frameworks

MOFs are consistently revolutionizing the solar water evaporation field with their unique and customizable material design. These porous materials, made from metal ions or clusters connected by organic linkers, have incredibly large surface areas that are essential for efficient water evaporation. A central aspect of MOFs in SIE is their light-to-heat conversion mechanism. When MOFs are exposed to sunlight, their intricate structure allows them to absorb specific wavelengths efficiently. The absorbed photons excite electrons within the MOFs, leading to localized heating. This localized heating is a result of non-radiative decay processes, where the excited electrons release energy in the form of heat. The high surface area of MOFs ensures that this generated heat is effectively transferred to the surrounding water, facilitating rapid evaporation[81]. By cleverly integrating hydrophilic functional groups and photo-responsive moieties into

MOFs, their hydrophilicity and light absorption properties are significantly improved, resulting in increased water evaporation rates[8]. Moreover, their customizable structure allows for tailored band gaps and selective light absorption, which can be exploited to optimize their photothermal properties. Another striking feature of MOFs lies in their ability to be composited with other materials such as graphene or CNTs, engendering hybrid architectures that leverage the strengths of each component[82]. From interfacial heating to volumetric heating, these innovations offer a new landscape of possibilities in SIE. By consistently exploring and utilizing these adaptable materials, MOFs have a bright future in spearheading the next wave of SIE systems. However, it is crucial to recognize the limitations inherent in MOFs, particularly in terms of electrical conductivity, structural stability and durability under different environmental conditions[83].

The significance of materials design in SIE applications is underscored by the diverse categories of materials, each boasting unique properties that contribute to their effectiveness in this context. The careful selection and manipulation of materials can result in increased water evaporation rates and purification efficiencies. Furthermore, the ability to fine-tune the properties of these materials through alterations in morphology or composition, as in the case of MnO nanoparticles, allows for the optimization of their performance in specific applications.

DEVICE ASSEMBLY STRATEGIES

The assembly of the device directly influences the SIE efficiency and performance. The assembly of an evaporation device entails precise arrangement and connection of different components, each crucial to the overall functionality of the system [Figure 3]. Optimal assembly can maximize the capture and conversion of solar energy, consequently boosting the efficiency. This involves strategic integration of elements such as solar absorbers and evaporators, which directly govern the capacity of a device to evaporate water using solar energy. Conversely, improper assembly could result in suboptimal performance, energy wastage and reduced evaporation rates due to issues such as poor energy transfer, ineffective insulation and unnecessary energy loss. Therefore, it is crucial to refine assembly strategies in order to enhance the performance of SIE systems.

Maximizing solar absorption

To optimize solar absorption, several strategic approaches can be employed. These include the use of broadband solar absorbers and the incorporation of solar concentrators such as parabolic troughs or Fresnel lenses. In addition, researchers have investigated the design of floating structures that can follow the sun's path, altering the surface of the absorber material to reduce reflection and developing multi-layered structures that are optimized for different wavelengths. Spectral splitting techniques are employed to direct specific wavelength ranges to materials that are best suited for absorption. Effective thermal management can be achieved using thermally conductive materials. Additionally, plasmonic enhancement is realized through the incorporation of metal nanoparticles or nanostructures that support LSPR[84,85]. Exploring various methodologies to enhance solar absorption, recent research in this field has emphasized the development of intricate structures with exceptional light-trapping properties, as illustrated in Figure 4. Jonhson *et al.* conducted a study on a 3D-printed porous silica mesh framework with hydrophilic-modified graphene[86]. The modified graphene, known as MG@Silica, exhibits exceptional light absorption properties thanks to the nanopores it contains. The presence of nanopores in the material helps to lower the effective refractive index and create more surface area for light to be trapped. This results in a reduction of the angular dependence of incoming light and a decrease in light reflection. Additionally, they function as optical microcavities, trapping light via multiple light scattering and reflection processes, potentially leading to improved thermal evaporation efficiency.

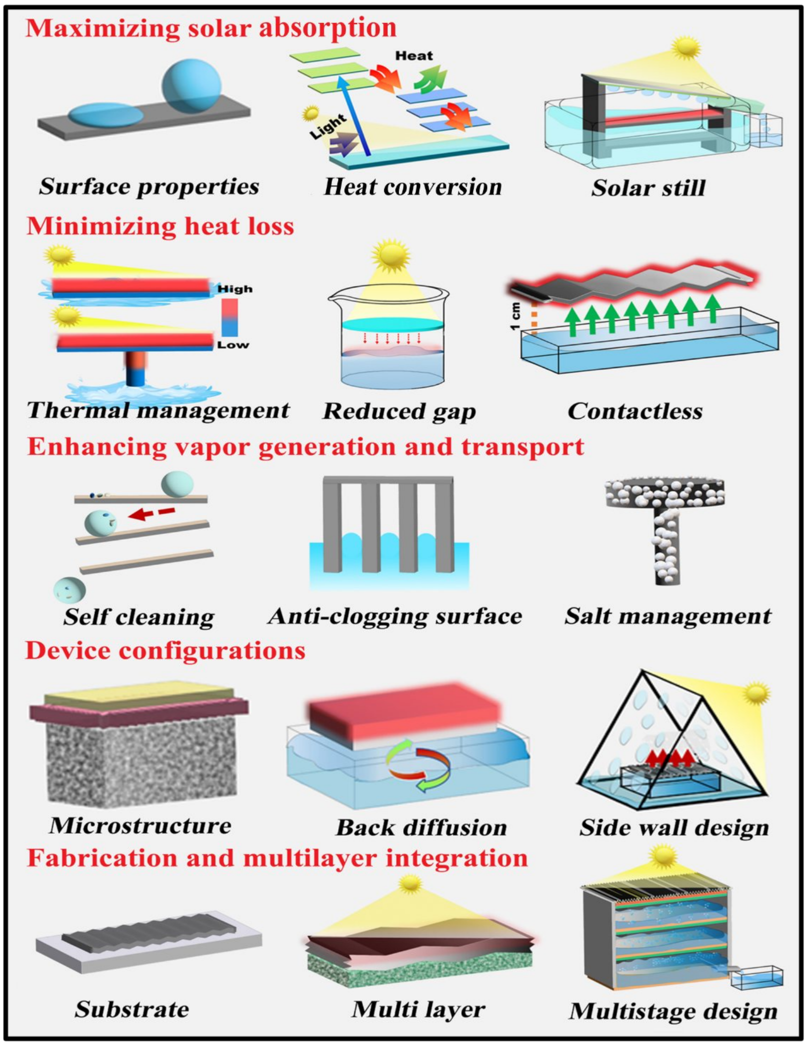

Figure 3. Illustrations of device assembly strategies to achieve clean water production from sea water.

In a lab-scale prototype, Menon *et al.* introduced a selective absorber/black emitter designed to optimize absorption and minimize emission[87]. This design enhances solar absorption, leading to improved evaporation efficiency. The addition of a reflective foil inside the water tank enhances the system performance by redirecting any unabsorbed solar radiation back to the absorber. An acrylic wall surrounds the inner pocket of a tank, acting as a barrier to reduce thermal losses. This ensures that a significant portion of the captured solar energy is used for heating the water, promoting evaporation. In addition, a copper aperture positioned above the absorber helps to eliminate unwanted light, resulting in more precise data collection and a better understanding of the factors that influence solar absorption efficiency.

Minimizing heat loss

Key strategies for achieving enhanced performance include optimizing the design and materials of the solar absorber. Ideally, the absorber should have high light absorption and low thermal conductivity to ensure efficient sunlight-to-heat conversion while minimizing heat dissipation. The use of nanofluids or other advanced heat-transfer fluids can boost thermal conductivity and heat retention during the evaporation process. In addition, ensuring proper thermal insulation for the evaporator setup helps to reduce heat loss to the surrounding environment. By integrating heat recovery systems or phase-change materials into the

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Figure 4. Illustration of various solar water evaporators with different surface structures.

design, it is possible to capture and recycle the latent heat released during condensation. This further reduces overall heat loss and bolsters the performance of SIE systems[88-90].

Enhancing vapor generation and transport

Enhanced vapor generation and transport can be achieved through the incorporation of advanced nanostructured materials, which also optimize the light absorption capacity and thermal properties of the system. The resulting improved photothermal conversion efficiency not only maximizes solar energy utilization but also creates a localized high-temperature environment for rapid vapor generation. In order to optimize vapor transport, the use of superhydrophobic and hydrophilic surfaces can be employed to promote effective water vapor release. This helps to minimize vapor entrapment and the potential for backflow[91-93]. Xia *et al.* report that the device features a glass microfiber-supported $Cu_{2-x}Se/Nb_2CT_x$ nanocomposite solar absorber and absorbent cotton as its water transmission pathway[4]. The unique structure of water evaporation devices, featuring a rough surface and glass microfibers with low thermal conductivity, effectively reduces light reflections and minimizes heat loss to the surrounding environment. This enhances the photothermal conversion efficiency of devices. Moreover, the absorbent cotton with vertically aligned microchannels and intrinsically hydrophilic properties ensures effective water transfer via capillary forces. The solar vapor evaporation device demonstrates a remarkable ability to absorb light, transport water efficiently, and manage heat effectively. As a result, the device maintains a consistently high evaporation rate regardless of the intensity of the light source.

In addition, the study conducted by Feng *et al.* reveals intriguing discoveries that challenge the conventional understanding of SIE processes [Figure 5][94]. It demonstrates that the surface roughness of a solar absorber is a more decisive factor in SIE than its light absorption capacity. This is evident in the behavior of Fe_3O_4 nanoparticles, which, despite exhibiting the lowest light absorptivity, show the highest evaporation rate due to their increased surface roughness. The investigation uncovers a dynamic interplay between capillary

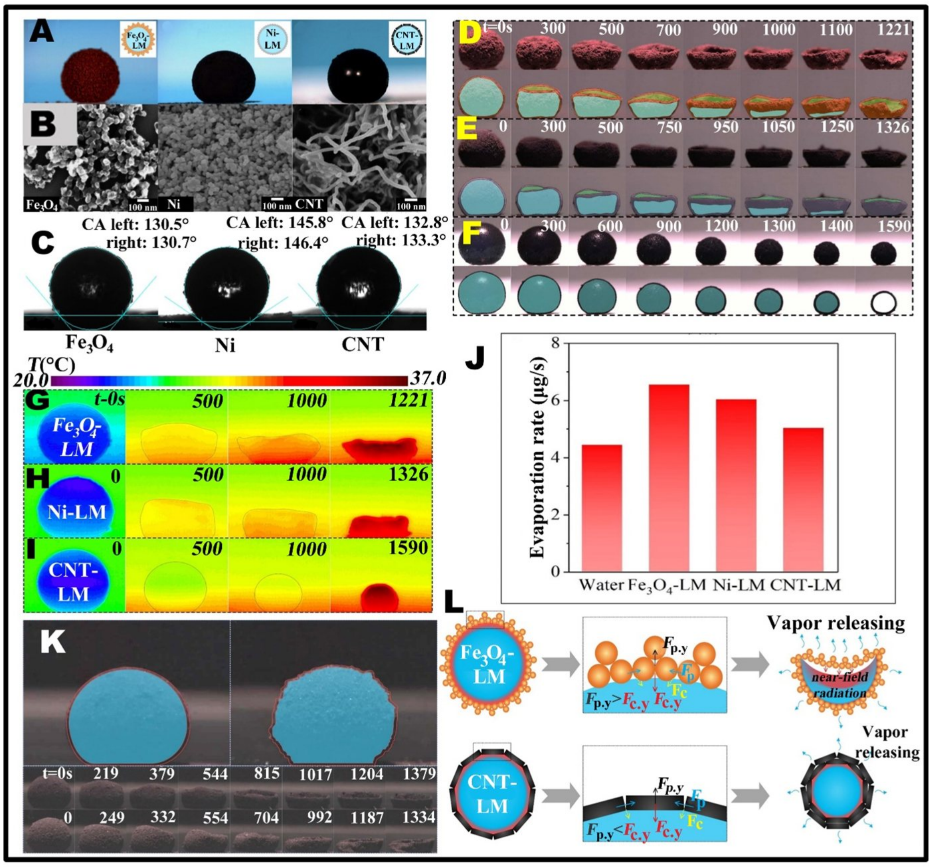

Figure 5. (A) Photographs, (B) SEM micrographs, and (C) contact angle images of the liquid marbles comprised of Fe_3O_4, Ni NPs, and CNTs, respectively, aligned vertically. Pictorial evidence and image analysis of evaporating liquid marbles with (D) Fe_3O_4, (E) Ni, and (F) CNT are also depicted. Tracking the surface temperature evolution is achieved via an infrared (IR) camera for (G) Fe_3O_4-LM, (H) Ni-LM, and (I) CNT-LM. (J) Demonstrates the evaporation rates. (K) Depicts morphology images of LM created through both the imprinting and rolling methods, as well as typical snapshots of a Ni NP-evaporating liquid marble. (L) elucidates the evaporation processes of LMs enveloped by either Fe_3O_4 NPs or CNTs. Reprinted with permission from ref.[95]. Copyright 2023 Elsevier.

forces and interparticle interactions influenced by surface roughness, which results in varied evaporation dynamics. It is worth noting that the study reveals the enhanced effects of a textured surface and a specific arrangement of nanoparticles on the concentration of heat and electromagnetic fields when exposed to light. This results in a boundary with high temperature and accelerated evaporation. The results of this study have significant implications for the development and production of small-scale heatable evaporators or reactors. These advancements enable a diverse array of processes with accurate temperature and kinetic control.

Device configurations

Device configurations play a significant role in minimizing heat loss, maintaining ideal water temperature, and enhancing energy conversion. Various types of floating devices such as solar stills, photothermal materials and advanced energy management systems can be employed to optimize the performance of SIE systems. Specifically, both single-layer and bilayer structures have a notable impact on SIE. Single-layer structures comprise a sole layer of photothermal material that absorbs sunlight, transferring the generated heat to the liquid-vapor interface to promote evaporation. This design offers simplicity, cost-effectiveness and ease of fabrication, making it a popular choice for small-scale applications[95,96]. However, single-layer structures face several challenges such as low light absorption and limited heat localization which restrict their overall evaporation efficiency. On the other hand, bilayer structures comprise two distinct layers: a light-absorbing layer and a thermal-insulating layer. The light-absorbing layer efficiently captures solar energy and transfers it to the liquid-vapor interface, while the thermal-insulating layer minimizes heat loss to the bulk liquid and the environment[97-99]. This design results in a more efficient heat transfer, leading to enhanced evaporation rates. The separation of light absorption and heat insulation functions allows for the optimization of each layer, contributing to the overall performance improvement of the SIE system. Despite the increased complexity and cost of manufacturing bilayer structures compared to single-layer ones, their exceptional efficiency and versatility make them a compelling choice for large-scale solar-driven water purification and desalination applications. In addition, there are two innovative methods for utilizing the sun's energy in different applications: solar stills and solar concentrator-based systems. Solar stills are passive devices that operate on the principles of evaporation and condensation to effectively produce purified potable water. They work by trapping solar radiation within an enclosed chamber, where it heats the contaminated water, causing it to evaporate. The water vapor then condenses on the cooler surface of the still and is collected as fresh water[100,101]. This technology offers a sustainable and cost-effective solution, especially for remote or disaster-stricken regions where access to clean water is limited.

However, systems that utilize solar concentrators are specifically engineered to harness the power of sunlight by directing it towards a concentrated area, thereby maximizing its energy output. Using mirrors or lenses, these systems collect and concentrate sunlight onto a specific target, such as a heat-absorbing material or a photovoltaic (PV) cell[102,103]. This concentrated solar energy can then be converted into thermal energy or electricity, depending on the application. Solar concentrator systems can be found in large-scale solar power plants and in smaller-scale applications such as solar cookers and solar water heaters.

Fabrication and multilayer integration

Several techniques are employed in the fabrication of SIE devices, each offering distinct advantages. Self-assembly[104] is a bottom-up approach that facilitates spontaneous organization at the nanoscale, enhancing photothermal properties. Layer-by-layer (L-b-L) deposition[105] ensures uniformity and allows for the fine-tuning of material properties. Electrospinning[106] is notable for producing nanofibrous structures, making it ideal for high-surface-area components that enhance evaporation rates. Additionally, 3D printing[107] stands out for its design flexibility, enabling rapid prototyping of intricate device architectures and the integration of diverse materials. Together, these methods provide precise control over material distribution and alignment within the device, promoting optimal heat management and water transport. Furthermore, integrating multiple functional layers, such as photothermal converters, hydrophilic wicking layers and hydrophobic vapor channels, within a single SIE device ensures efficient energy harvesting and water recovery[108]. Moreover, a synergistic strategy combining innovative fabrication techniques and precise multilayer integration is required to achieve effective and scalable systems in order to fully utilize the water-energy nexus through SIE. Ongoing research in this field aims to address key challenges, such as long-term stability, cost reduction and scalability, to pave the way for widespread adoption of SIE technology for sustainable water desalination and energy generation.

RECENT ADVANCEMENTS IN SOLAR-DRIVEN INTERFACIAL EVAPORATION

Significant progress has been made in water purification, renewable energy, and environmental sustainability thanks to recent advancements in SIE. These advancements have been driven by the introduction of innovative materials, advanced device designs, and bio-inspired concepts. By optimizing device configurations, including floating[109], membrane-based[110] and 2D designs[111], these systems have become more robust and scalable, making them suitable for large-scale applications. Additionally, the integration of energy storage and conversion systems has facilitated simultaneous electricity generation and fresh water production, enabling innovative off-grid, self-sustaining applications and diversifying renewable energy sources.

Emerging trends in materials and structures

In recent studies, researchers have been investigating different materials to enhance the efficiency of SIE. These materials include but not limited to poly(vinyl alcohol) (PVA), cellulose, wood, MOFs, and covalent organic frameworks (COFs). These materials offer unique advantages including adaptability and hydrophilic properties, which enhance SIE efficiency. Research on these various materials is helping to improve the efficiency of converting solar energy into thermal energy for water treatment purposes[112].

PVA, a low-cost, biocompatible and easy-processable polymer with a high affinity to water molecules, is often used to fabricate solar evaporators in the form of hydrogels[113]. Various absorbers are embedded into PVA networks to form solar hydrogel evaporators. Recently, Guo *et al.* utilized polymethyl methacrylate (PMMA) particles as a template to create uniform and size-controlled channels in PVA-based evaporators, resulting in 40% accelerated SIE rates compared to control samples prepared by freeze-drying[114]. Tu *et al.* created SIE evaporators using PVA/reduced carbon dots spherical microgels, which were inspired by natural leaves[115]. These evaporators achieved a vapor generation rate of 1.58 kg m^{-2} h^{-1} and can potentially reach 2.18 kg m^{-2} h^{-1} according to their theoretical framework. However, PVA may have limitations in mechanical strength and long-term stability under continuous solar irradiation. Although PVA-based solar evaporators have potential, it is important to prioritize further research in order to enhance their durability and efficiency in different environmental conditions. Cellulose-based materials such as bacterial nanocellulose, plant-derived cellulose, commercial cellulose paper, and cellulose nanofiber (CNF) membranes have also been used to construct SIE systems. These materials can function as hydrophilic substrates, thermal insulation layers, or both functions can be combined in one place simultaneously[116]. Furthermore, wood materials with vertically aligned channels and hydrophilic walls are ideal platforms. Surface-carbonized balsawood and modified basswood have been used as solar evaporators, displaying faster salt exchange and effective prevention of salt accumulation[117]. Xie *et al.* innovatively applied a polypyrrole (PPy) coating to the spikes of a natural plant, *Setaria viridis*, creating an efficient and sizable evaporation surface[118]. This approach proved to be both environmentally sustainable and potentially cost-effective for SIE. By adjusting the height and quantity of these coated spikes, the researchers were able to achieve a notable SIE rate of 3.72 kg m^{-2} h^{-1} under one sun, demonstrating the efficiency of the method in practical conditions[118]. However, the study also acknowledges certain challenges. The scalability of using natural plant materials such as *Setaria viridis* on a large scale is a significant concern, especially considering the potential variations in material availability and consistency. Moreover, the long-term durability of these materials in real-world applications remains uncertain. The performance of the PPy-coated spikes might vary under different environmental conditions, such as changes in humidity, temperature, and light intensity, which could influence the consistency and effectiveness of the evaporation process. Jiang *et al.* incorporated GO flakes into bacterial nano cellulose (BNC) hydrogels, producing bilayer evaporators. BNC not only offers channels for water transportation but also reduces heat dissipation to the water beneath it[119]. In the ongoing investigation of water evaporation techniques, a recent study presents a novel method for SIE by utilizing a double-layered evaporator [Figure 6]. This structure is made from a combination of bacterial cellulose and vinyltrimethoxysilane, showcasing both superhydrophilic and superhydrophobic properties. Remarkably, this evaporator achieves impressive water evaporation rates of 1.91 and 4.20 kg m^{-2} h^{-1} under laboratory and outdoor solar conditions (1 sun irradiation). This aerogel-based evaporator is structurally robust, exceptionally lightweight and exhibits excellent salt resistance[120]. The innovative strategy in the design and construction of materials with tunable properties, relying on a single molecular unit, is promising for future applications in water purification and beyond.

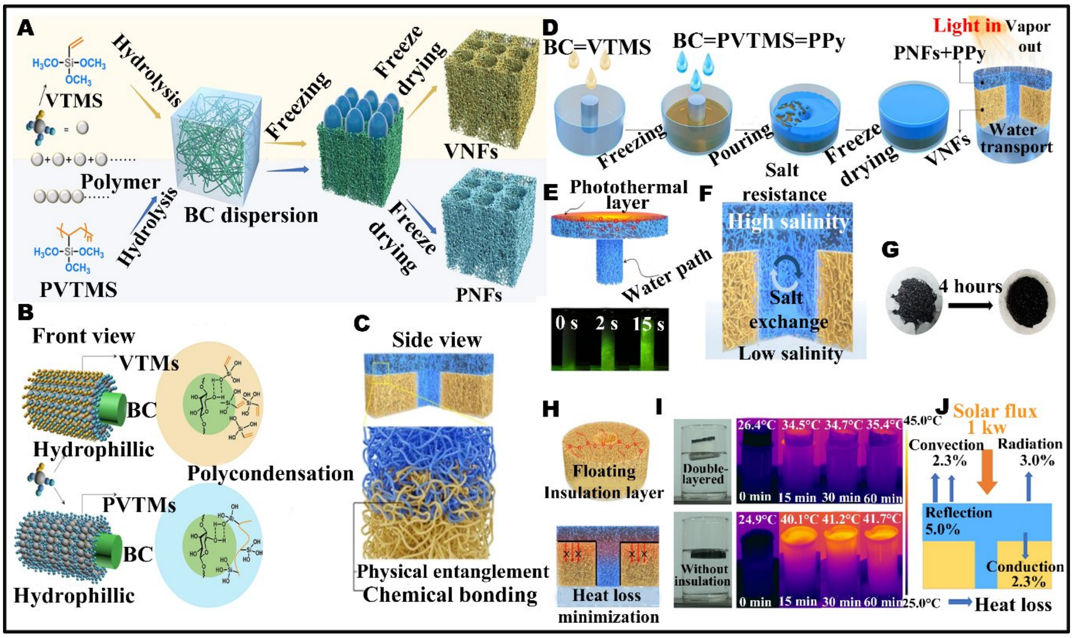

Figure 6. Illustrating the creation and properties of wettability tunable hybrid aerogels (A) Fabrication steps for superhydrophobic VNFs (vinyltrimethoxysilane (VTMS)-based nanofibrous aerogels) and superhydrophilic PNFs (polysiloxane-based nanofibrous aerogels) using VTMS and BC nanofibers. (B) Siloxane's molecular orientation on BC nanofibers. (C) Depiction of the physical linkage between VNFs and PNFs at the evaporator's interface. (D) Procedure for incorporating an evaporator device. (E) PNFs-PPy and water movement in pure PNF representations. (F) Salt transport mechanism for self-cleaning in evaporators. (G) Photographic evidence of salt resistance in the evaporator. (H) Illustration of a VNFs insulator reducing downward heat loss. (I) Thermal images of double-layered evaporator and single-layered PNFs-PPy under sunlight for 60 min. (J) Heat dissipation chart for the evaporator. Reprinted with permission from ref.[121]. Copyright 2023 Springer Nature.

Li *et al.* developed a hybrid membrane by encapsulating Cu-BTC nanorods with a polyaniline (PANI) layer, which served as both a protective layer and a solar absorber[121]. The Cu-BTC/ polyvinylidene fluoride (PVDF) membrane with PANI coating showed enhanced stability in both water and seawater. It also achieved an impressive SIE rate and efficiency of 90.8% under 1 sun. MOFs, with their micropore size, can act as molecular sieves to separate small guest molecules, making them suitable for evaporating clean water from volatile organic compound (VOC)-contaminated sewage. Peng *et al.* tackled this problem by a composite membrane that involved the growth of a ZIF-8 layer on a PANI-coated polyethersulfone (PES) membrane[122]. The aperture size of ZIF-8 allows it to effectively filter out the majority of VOCs present in the evaporated steam. Additionally, its water stability has been improved through a partial ligand-exchange reaction. The resulting hybrid membrane achieved a high VOC rejection efficiency and SIE rate under one sun and could even handle high-concentration VOCs. The critical analysis reveals that each methodology, while demonstrating innovative approaches, is accompanied by inherent challenges. The bilayer evaporators developed by Jiang *et al.*, utilizing BNC and GO flakes, exhibit superior water evaporation rates, an attribute crucial for regions grappling with water scarcity[119]. These evaporators, leveraging solar energy, could significantly impact water purification processes. However, the scalability and cost implications of these materials may limit their application in economically constrained regions, a factor that cannot be overlooked in global implementation strategies. In the realm of treating industrial wastewater, the introduction of the composite membrane by Peng *et al.* has brought about a notable breakthrough[122]. This membrane stands out for its ability to selectively reject VOCs, making it a valuable addition to the field. Yet, its complex fabrication process and potential fouling issues raise concerns regarding its practical applicability on a larger scale. From our perspective, the technologies developed by Jiang *et al.* and Peng *et al.* hold considerable promise, particularly in the context of industrial wastewater treatment, given their high efficiency and specificity[119,122]. However, the challenges of cost-effectiveness and scalability must be addressed to realize their full potential. A comparative assessment indicates that while Jiang *et al*.[119] offers evaporators potentially more suited for large-scale industrial applications, Peng *et al*.[122] demonstrates a membrane with VOC rejection capabilities, likely more beneficial in specialized industrial settings. Additionally, the membrane developed by Li *et al*., with its enhanced stability in varied water conditions, presents a versatile solution potentially applicable in diverse geographical regions[121].

COFs are typically embedded in porous matrices such as PVA gels[123], PDMS sponges[124], or polytetrafluoroethylene (PTFE) substrates[125]. These frameworks possess an extended π-conjugated system that enables broad light absorption, although their absorption primarily encompasses the lower wavelength portions of the visible solar spectrum. For enhanced light absorption, monomers can be used that contain specific dye molecules such as 1,4,5,8-tetrakis(phenylamino)anthr-acene-9,10-dione (TPAD), squaraine (SQ), or diketopyrrolopyrrole (DPP). TPAD-COF, SQ-COF, and DPP-COF have all shown impressive light absorption capabilities and efficient energy conversion[125]. While COFs serve as photothermal materials, they do not perform as effectively as carbon-based materials such as graphene and CNTs. However, their adjustable porous and chemical structures make them intriguing for other functional components in solar vapor generators. By optimizing the COF ratio in dual-region hydrogels (CGHs) that comprise hydrophobic reduced GO (rGO) and hydrophilic COF-loaded rGO regions, a high SIE rate and light-utilizing efficiency can be achieved[126]. A croconium-based molecule, CR-TPE-T, which exhibits efficient photothermal conversion due to its biradical characteristic, has been prepared. When paired with a polyurethane (PU) substrate, these evaporators achieved an SIE rate of 1.27 kg m^{-2} h^{-1}. In addition, researchers have made advancements in solar evaporators by utilizing aggregation-induced emission (AIE) molecules in 3D fiber aerogels. This has resulted in a significant increase in the rate of solar-induced evaporation, reaching 1.43 kg m^{-2} h^{-1} with an impressive efficiency of 86.5%. In another approach, phosphomolybdic acid was combined with porphyrins to create 2D dendritic nanosheets with enhanced photothermal capabilities, achieving an SIE rate of 2.23 kg m^{-2} h^{-1} and 90.9% energy efficiency under one sun[127,128].

Inspired by the structure of black hair, an arched solar evaporator with hydrophilic photothermal fibers was constructed for desalination application with proficient salt rejection due to its distinct surface properties and the innovative convex device architecture. The surface of black hair is replete with hydrophilic groups, which play an essential role in attracting and retaining water, forming a confined liquid film when water contacts with the hair. Subsequently, capillary forces and the Marangoni effect drive the liquid flow above the cuticle, generating a free-flowing liquid layer. This mechanism enhances the efficiency of water transport, expedites liquid flow, and maintains a constant cycle of water replenishment and circulation. The constant flow of water over the hair surface prevents the accumulation of salt crystals on the photothermal layer, enabling effective salt rejection[129]. Zhao *et al*. developed a solar evaporator fabricated from hierarchically nanostructured gels (HNGs) derived from porous carbon, through the hydrothermal carbonization of chitosan[130]. This structure exhibited significant solar absorption, leading to enhanced evaporation efficiency and reduced heat loss. The structure also facilitated rapid water transport, ensuring a continuous supply of water to the evaporation surface and, producing clean water at a rate of 3.2 kg m^{-2} h^{-1}. Under natural sunlight, the HNG demonstrated the capability to produce fresh water at a daily yield of 18-23 liters per square meter. The integration of croconium-based molecules and HNGs, along with the unique surface properties of black hair-based evaporators, marks a significant breakthrough in the field. This development has led to high SIE rates and effective salt rejection. The creation of sophisticated materials such as croconium-based molecules or HNGs is often complex, requiring precise conditions and methodologies. This complexity can lead to challenges in reproducing these materials consistently, which is a fundamental requirement for practical application. The studies by Wang *et al*. and Yu *et al*. serve as exceptional examples of novel photothermal materials in the SIE[131,132]. Wang *et al.* have achieved notable advancements in synthesizing higher-metal nitride nanosheets, including Mo_5N_6, W_2N_3, Ta_3N_5, and Nb_4N_5, using amine-functionalized transition metal dichalcogenide nanosheets as precursors[131]. Their work highlights the extraordinary capabilities of these materials for steam generation, notably achieving a rapid temperature rise to 80 °C in just about 24 s under simulated sunlight, coupled with an impressive solar evaporation rate of 2.48 kg m^{-2} h^{-1} and an efficiency of 114.6%. Similarly, Yu *et al.* have focused their efforts on enhancing SIE for seawater desalination[132]. They synthesized 2D $MoN_{1.2}$ nanosheets integrated with rGO to form $MoN_{1.2}$-rGO heterostructures, effectively lowering vaporization enthalpy. This results in a notable improvement in evaporation rates, reaching 2.6 kg m^{-2} h^{-1}, surpassing the theoretical limit of conventional 2D evaporators and outperforming other transition metal nitride-based evaporators. Both studies are marked by meticulous scientific detail and rigor, underscoring the potential impact of these materials in advancing sustainable technologies. They present significant advancements yet also highlight the need for further research into scalability, long-term stability, and environmental impacts of these materials. Overall, these investigations contribute substantially to the advancement of efficient and sustainable technologies in SIE, marking a notable progression in the field of novel photothermal materials.

Advanced device designs

Advanced device designs for SIE stand out as transformative innovations. They combine the natural power of sunlight with cutting-edge technologies. Li *et al.* devised a method that involves combining CNTs with CNFs to create tunable nanocomposite inks, which are then applied to ethanol-diffused polystyrene (E-PS) films[133]. A one-step thermal treatment induces device shrinkage and substrate foaming, creating microscale crumpled textures. These textures enhance water supply and light absorption, while mesoscale pores minimize thermal conduction and radiation. This synergistic design yields a high evaporation rate and efficiency, even with a low loading of photothermal materials. Another novel evaporator made from carbon derived from bamboo leaves was designed using light trace simulation by arranging and carbonizing the bamboo leaves and finally modified with polyacrylamide (PAM). The vertically arranged carbon structure enhances light absorption by extending the light path and increasing the light-absorbing area. The PAM hydrogel is distributed evenly between the vertical carbons, allowing for quick water delivery and reducing the distance for evaporation. This evaporator achieves an ultrahigh light absorption rate of 96.1%, a water evaporation rate of 1.75 kg m^{-2} h^{-1}, and a solar-to-vapor efficiency of 91.9% under one sun irradiation. The device effectively performs seawater desalination, heavy metal ion removal and dye separation during water evaporation and is suitable for outdoor applications and repeated recycling[134].

Zhao *et al.* combine carbonized Co-based MOF (ZIF-L) and natural wood aerogel to fabricate an efficient and stable system[135]. Carbonized ZIF-L serves as the photothermal layer, absorbing solar radiation for photothermal conversion, while the wood aerogel transports seawater to the evaporation interface and ensures the self-floating capabilities of devices. A key feature is its resistance to salt deposition and automatic salt discharge ability, which was achieved through the macroporous channels and pits in the wood aerogel. Sodium alginate is used as a binder to improve the adhesion of the photothermal layer to the aerogel. The evaporator achieved an evaporation rate of 1.52 kg m^{-2} h^{-1} and an impressive evaporation efficiency of 92.42% under 1 sun illumination, making it suitable for continuous SIE. The novel evaporator design combines a PPy-impregnated nylon thread photothermal layer with an octadecane/carbonized PPy nanotube aerogel composite material. This innovative design achieves a high evaporation rate of 2.62 kg m^{-2} h^{-1}, an excellent solar-to-vapor efficiency of 92.7%, and demonstrating the ability to suitable for all-day evaporation. The evaporator exhibits high salt resistance, maintaining efficiency above 85.3% even in a high-concentration saline solution (20%) and functioning effectively in a 3.5% brine solution for 6 h without performance degradation or salt precipitation[136]. Natural luffa and PPy was used to design a SIE device, focusing on regulating water content by utilizing hydrophilic hierarchical channels within the luffa.

These channels transform excess water from a bulk state to a film state on the porous skeleton, optimizing the performance of devices. The unique fiber arrangement and porous structure of the luffa increase the contact area between water and air, facilitating steam escape and enhancing the evaporation rate. This design emphasizes the importance of hierarchical channels in water regulation for high-efficiency SIE[137]. A magnet-dominated photothermal device (MPD) with a spiny surface has been developed through the direct assembly of magnetic nanoparticles in the presence of a magnetic field [Figure 7]. The one-step fabrication process eliminates the need for harmful reagents and simplifies the process. The adjustable spiny morphology enhances light absorption via multiple reflections and allows for easy recovery from damage. With high solar absorbance (96.1%) and light-to-heat conversion efficiency (over 94%), the MPD accelerates water evaporation under solar irradiation to over 1.70 kg m^{-2} h^{-1}, approximately 3.5 times higher than the natural evaporation rate[138]. Using a magnetic field, MPD successfully created a high-efficiency evaporator, showcasing its potential as a promising device for freshwater generation.

The cutting-edge design of the 3D evaporator includes a solar absorber layer on its top surface, which efficiently converts light into heat. Below the absorber, vertically aligned microtube bundles (MTBs) are strategically placed to connect saline water to the solar absorber. Equipped with hydrophilic microchannels, the MTBs effectively pump saline water through capillary force and facilitate the flow of excessive salt back into the bulk water. This unique structure not only ensures efficient water and salt transport but also recovers conductive heat for water evaporation, resulting in a significant enhancement of overall efficiency. Following the five-day rooftop experiment, the MTB-based evaporation system was subjected to testing in a floating configuration in the Red Sea, which has a salt content of approximately 4.3%. This test aimed to showcase its practical potential for seawater desalination[139]. The evaporator design utilizes interconnected porous hydrogels (IPHs) synthesized via the sacrificial assembly template (SAT) method, which allows for the production of lightweight, mechanically stable hydrogels with tunable pore size and high interconnectivity. By incorporating activated carbon particles as a solar absorber, IPHs demonstrate excellent solar absorption and good heat localization. The pore size of the hydrogels significantly influences the water transport rate through the matrix, with larger pore sizes resulting in faster transport. The experiments showed that IPHs with different pore sizes had water transport rates that ranged from 0.62 to 621.9 g min^{-1}. The optimized IPH attained higher solar-to-vapor conversion efficiency, approximately 90%, with an evaporation rate of 2.8 kg m^{-2} h^{-1}. Additionally, it exhibited outstanding anti-salt-fouling properties and the capability to eliminate common heavy metal ions and organic dyes[114].

The methodology used by Li *et al.* demonstrates impressive evaporation efficiency[133]. However, the complexities associated with the nano-ink formulation and substrate interactions during thermal treatment may influence the reproducibility and scalability of the results. The bamboo leaf-derived carbon evaporator, despite its high light absorption and multifunctional capabilities, confronts issues related to the consistency of the carbon structure post-carbonization, which is crucial for maintaining performance metrics. This also raises questions about the long-term structural integrity under repeated use. The use of carbonized ZIF-L with wood aerogel by Zhao *et al.* introduces an eco-friendly approach with enhanced salt resistance[135]. However, the integration of these materials at a nanoscale level poses challenges in achieving uniformity across larger surfaces, a key factor for consistent SIE performance. Moreover, the long-term stability of the wood aerogel in harsh saline environments and its ability to maintain structural integrity while preventing salt accumulation remains an area requiring further exploration. The design of the PPy-impregnated nylon thread photothermal layer provided a longer operation time and enhanced resistance to salt. However, the interfacial stability between the photothermal layer and the aerogel composite, especially under continuous solar irradiation and in high-salinity conditions, is a critical aspect that needs rigorous assessment. This is imperative to ensure sustained efficiency without degradation of photothermal properties or structural

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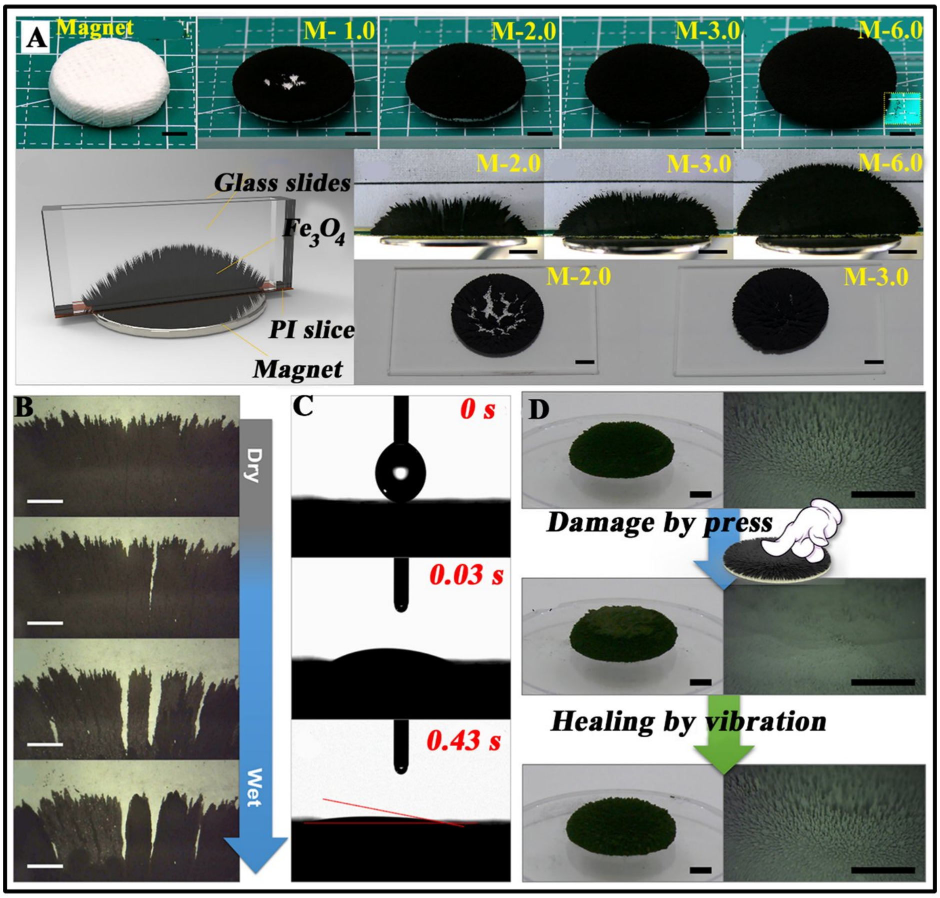

Figure 7. (A) Depictions of the magnet in air-laid paper and the MPD with varying Fe_3O_4 nanoparticle densities, including schematics, optical views of Fe_3O_4's spiny shape, and surface images of M-2.0 and M-3.0 post-water wetting, with a 4mm scale bar. (B) Visual transformation of Fe_3O_4's spiny structure during wetting. (C) Water contact angles on the Fe_3O_4 layer before and after the application. (D) Optical images of prepared M-3.0 showcasing its spiny structure, the loss from finger pressure, and restoration via vibration. Reprinted with permission from ref.[139]. Copyright 2021 John Wiley & Sons.

breakdown. The luffa and PPy-coated device, while innovative in optimizing water regulation, confronts the challenge of maintaining the hydrophilic-hydrophobic balance within the hierarchical channel structure. This balance is essential for consistent steam generation and escape, and any disparity could significantly affect the evaporation rate and efficiency. In the case of the MPD, the challenge lies in precisely controlling the nanoparticle assembly to achieve the desired spiny morphology. This morphology is critical for light absorption and heat conversion efficiency. Furthermore, understanding the long-term impact of magnetic field exposure on the structural and functional stability of the device is crucial, especially in outdoor environments. Efficient capillary action for continuous water transport is a crucial scientific challenge in the case of the 3D evaporator with MTBs. It is important to manage salt backflow effectively to prevent salt accumulation and maintain efficiency. This requires a delicate balance in the microtube design and the hydrophilic-hydrophobic properties of the materials used. Finally, the IPHs present a challenge in tuning the pore size for optimal water transport without compromising the structural integrity and mechanical stability of the hydrogel. The interplay between pore size, solar absorption, and heat localization directly influences the solar-to-vapor conversion efficiency and anti-salt-fouling properties, necessitating precise material engineering.

Reconfigurable graphene-wrapped Fe_3O_4 (Fe_3O_4@G) nanoparticles, known for their unique magnetic responsiveness are employed to construct a magnetically responsive conic array (CA) assembly within the solar evaporator[140]. By leveraging the reversible assembly properties of these nanoparticles under the influence of a magnetic field, a dynamic and reconfigurable structure is formed. The strategic combination of macro magnets with CA assemblies leads to the development of a sophisticated hierarchical assembly that significantly enhances the evaporator's performance. This design approach not only improves evaporation rates but also provides excellent salt resistance, water transport and recycling capabilities. The lab-scale prototype uses a solar umbrella to improve solar evaporation efficiency through surface-based heating and radiative heat localization. Positioned above the water surface to achieve a large view factor, the solar umbrella features a commercially available selective solar absorber and a spray-on black paint emitter. This design results in an over 100% enhancement in evaporation rates compared to volumetric heating, and it achieves a 43% solar-thermal efficiency under 1 sun. The system is passive, non-contact and eliminates the risk of fouling and contamination from wastewater streams. Hence, it is ideal for long-term implementation in brine-disposal ponds to achieve zero liquid discharge[87]. Wang *et al.* developed a fabrication strategy that involves a L-b-L assembly process to create an MXene/CNTs/Cotton fabric-based SIE system[141]. The process begins with the preparation of MXene nanosheets and amino-modified CNTs which exhibit negative and positive zeta potentials, respectively. The cotton fabric is alternately dip-coated with MXene nanosheets and CNTs solutions (MC), forming a porous MC film. As the number of L-b-L cycles increases, the composite fabric exhibits a proportional increase in mass per unit area. Under one sun illumination, the evaporation rate achieves 1.35 kg $m^{-2}h^{-1}$ for water and greater than 1.16 kg $m^{-2}h^{-1}$ for textile wastewater. In another study, researchers used tannic acid (TA) and iron (III) to construct a 3D-printed interfacial solar evaporator with a conical array surface structure. This design enhances light harvesting capacity through multiple reflections and anti-reflection effects [Figure 8]. By optimizing the height of the conical arrays, the evaporator achieves an evaporation rate of 1.96 kg m^{-2} h^{-1} under one sun illumination and photothermal conversion efficiency of 94.4%. The evaporator exhibits excellent desalination performance, recycle stability, anti-salt properties, underwater oil resistance and adsorption capacity for organic dye contaminants, making it suitable for multipurpose water purification applications[142].

Zhang *et al.* successfully addressed the trade-off between thermal localization and salt rejection, which was a prevalent issue in previous wick structure-based evaporators [Figure 9][6]. They achieved this by decoupling the processes of solar-thermal conversion, thermal localization and passive water supply, thereby enhancing the efficiency of the system while maintaining optimal performance. The prototype using common materials has a solar-to-vapor conversion efficiency comparable to wick-based evaporators and salt rejection performance similar to contactless evaporators. The study emphasizes the importance of engineering passive fluidic flow and developing a mechanistic model that couples salt transport, fluidic flow and heat transport to guide evaporator design. The macrochannels in the thermal insulation were engineered to trigger natural convection due to the salinity gradient. The convective flow significantly drives salt rejection while inducing negligible additional heat losses. This model-driven, quantitative design approach can serve as general guidelines for solar evaporation devices and potentially improve biofouling resistance. Confined water layers were integrated into passive solar evaporators to enhance desalination reliability and promote zero-liquid discharge in wastewater treatment.

Similarly, Zhao *et al.* have reported on a technique for creating distillation membranes with vertically aligned channels and a gradient of hydrophilicity[143]. This is achieved through the use of engineered defects in COF films. These functional variations enable a selective water transport pathway and precise liquid-vapor phase change interface. The COF membranes demonstrate a flux of 600 L m^{-2} h^{-1} with 85 °C feed at 16 kPa absolute pressure, nearly triple the performance of current state-of-the-art membranes. The study

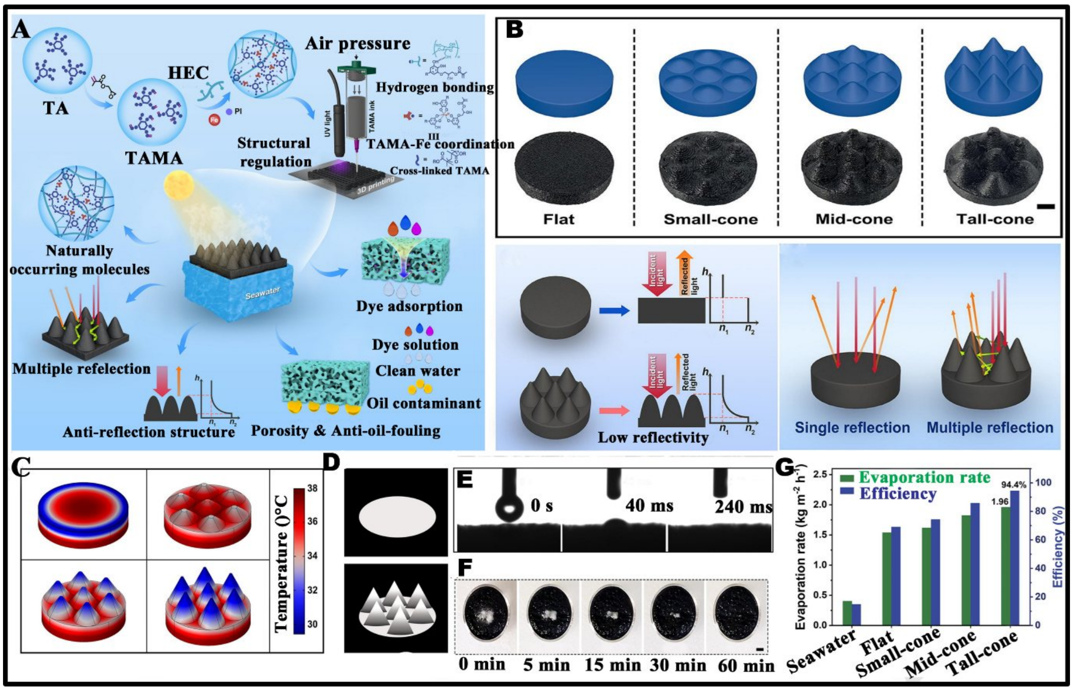

Figure 8. (A) Graphical representation of preparation, structure, and resilience of a 3D-printed TAMA evaporator. (B) Typical models of evaporators and their related 3D-TME specimens at scale bar 5 mm. (C) COMSOL-simulated temperature distribution on 3D-TME surfaces with varying cone heights under standard sunlight. (D) Numerical models show light patterns for 3D-TMEs on flat and tall-cone surfaces. (E) Images show water angle tests on the 3D-printed sample. (F) 3D-TME images with salt, at different intervals, under standard sunlight. (G) Graphs display evaporation rates and energy efficiencies for seawater and 3D-TMEs. Reprinted with permission from ref.[143]. Copyright 2023 Elsevier.

found that both COF layer thickness and etching time significantly impact desalination performance. The COF membranes effectively remove metal ions and pollutants, to obtain the purified water. Furthermore, the engineered COF membranes prevent salt crystallization and outperform commercial PTFE membranes. The results suggest that these gradient 2D COF membranes are promising candidates for water purification and desalination using waste heat sources.

Ultralong hydroxyapatite nanowires (HNs) and glass fibers (GFs) are combined to create a high-temperature-resistant paper, while black NiO nanoparticles are used as the photothermal material. The hydrophobic layer of the Janus paper is formed by modifying the HNs with sodium oleate, which prevents salt accumulation and enhances the salt-resistant properties of the evaporator. This innovative design not only exhibits high water evaporation efficiency but also demonstrates compatibility with other photothermal materials, making it a versatile and promising solution for solar-driven desalination and water purification applications. This innovative paper demonstrates a remarkable water evaporation efficiency of 83.5% under 1 kWm^{-2} irradiation[144].

The Fe_3O_4@G nanoparticle-based CA assembly offers dynamic, reconfigurable structures with enhanced evaporation and salt resistance. However, a core scientific challenge is ensuring the long-term stability and repeatability of the magnetic responsiveness under varied environmental conditions, which is crucial for the consistent performance of this dynamic system. The innovative design of solar umbrella evaporators markedly boosts evaporation rates through surface-based heating, but it faces the challenge of maintaining the structural and functional integrity of the selective solar absorber and emitter under continuous and intense solar exposure, which could lead to performance degradation over time. In the MXene/CNTs/

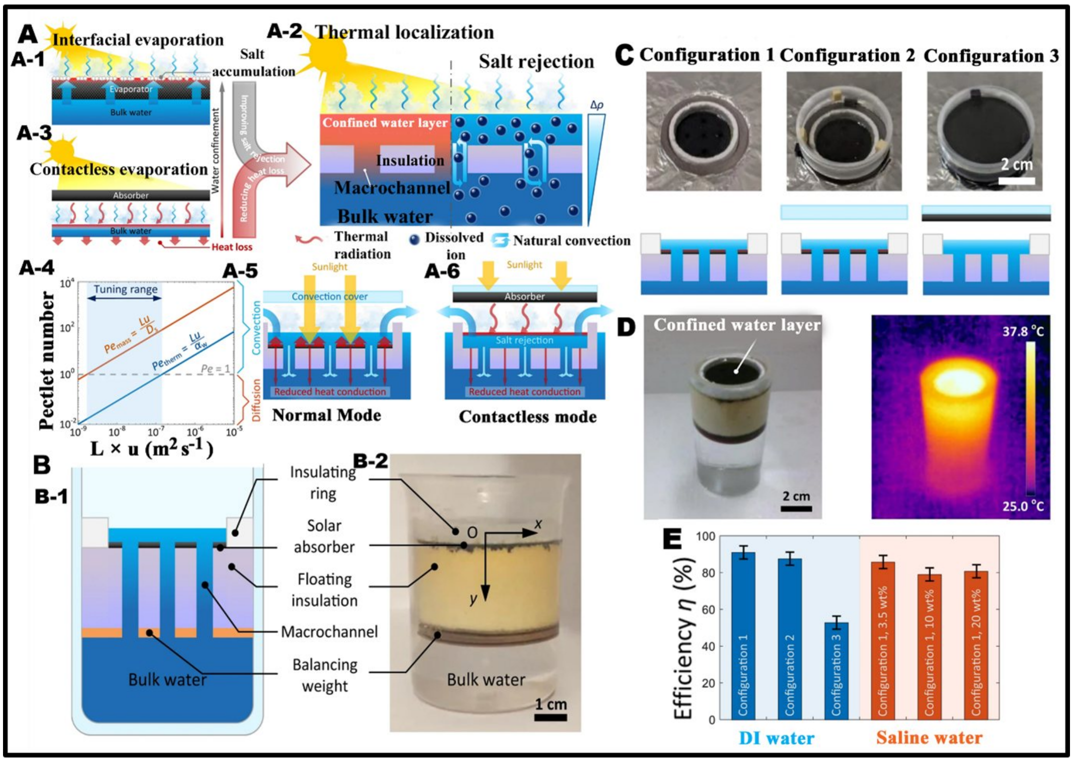

Figure 9. (A) (A-1) Depiction of a wick-based solar evaporator for interfacial evaporation, (A-2) heat localization, salt rejection via wick-free bounded water layer, heat loss minimization through self-floating insulation, and mechanisms for salt rejection using convection in water channels, (A-3) increased heat loss in contactless evaporation with a separated solar absorber and air gap, (A-4) Variance of Peclet numbers with flow condition (L × u) indicating convection or diffusion dominance, Use of confined water layer in normal (A-5) and contactless (A-6) evaporator modes. (B) Confined water layer prototype: (B-1) schematic, (B-2) actual image. (C) Three solar evaporation setups: the first two with basic solar-to-thermal conversion, with the second having a convection shield, and the third being contactless with an air gap. (D) Photo and IR view of the reservoir with the confined water layer. (E) Efficiency assessment across setups and salinities. Reprinted with permission from ref.[6]. Copyright 2022 Springer Nature.

Cotton fabric-based SIE system, while the L-b-L assembly enhances evaporation rates, the primary scientific hurdle lies in achieving a uniform and stable integration of MXene nanosheets and CNTs onto the cotton fabric. This uniformity is essential for maintaining consistent evaporation performance, and any variability can significantly affect the system efficiency. The conical array surface structure of 3D-printed interfacial solar evaporators improves light harvesting, but optimizing the geometry of these arrays for maximal light absorption and minimal reflection is a delicate and complex task, requiring precise fabrication techniques. The evaporator addressing thermal localization and salt rejection presents a breakthrough in decoupling key processes for enhanced efficiency. However, the scientific intricacy here involves engineering macrochannels in the thermal insulation to optimize salt rejection via natural convection while minimizing additional heat losses. This requires a sophisticated understanding of the interplay between fluid dynamics, heat transfer, and salt transport. The distillation membranes with vertically aligned channels in COF films, though highly effective in desalination, confront the challenge of precisely controlling the COF layer thickness and etching time. These parameters are critical for performance optimization but are challenging to manage consistently, especially in large-scale applications. Furthermore, maintaining the functional integrity of these membranes under varying operational pressures is a significant concern. Lastly, the high-temperature-resistant paper with HNs and GFs addresses the issue of high evaporation efficiency under intense irradiation. However, the main scientific challenge lies in the consistent modification of the HNs with sodium oleate to ensure uniform hydrophobicity, crucial for sustained salt resistance and evaporation performance.

Bio-inspired concepts

Researchers have been drawing inspiration from biological patterns in plants, animals, and microorganisms to develop advanced evaporation materials and structures. By emulating nature's time-tested strategies and designs, bio-inspired concepts offer innovative solutions to optimize sunlight absorption, heat localization and water transportation. These include photothermal nanocomposites, 3D water pathways, and self-healing surfaces. These bio-inspired approaches not only enhance the energy efficiency of solar evaporation but also contribute to minimizing environmental impacts. For instance, biomimetic structures have been leveraged to achieve effective light-to-heat conversion and thermal management, which, in turn, minimizes energy waste. Additionally, these bio-inspired solutions can serve as blueprints for fabricating scalable and low-cost evaporation systems.

Shi *et al.* introduced novel design strategies for an all-day fresh water harvesting device by combining fog collection and interfacial solar steam generation through engineering 3D micro-topologies on the surface of PVA/PPy hydrogel membranes [Figure 10][145]. By incorporating 3D micro-tree arrays with branched micro-cones, this system efficiently captures fog, transports droplets in a specific direction, and ensures quick drainage. It utilizes bioinspired design principles to achieve these functions. This setup achieves a fog collection rate that is 115% higher than the commercially used Raschel mesh and 61% higher than a cactus stem, emphasizing the potential of hydrogel 3D printing for environmental applications. The authors found that surface microstructures improved solar steam generation by providing a large surface area for thermal conversion and water evaporation, with conical structures being promising candidates due to increased light absorption area and reduced vapor flow resistance. The findings indicate potential strategies for enhancing interfacial solar steam systems by manipulating surface structures. This approach can be applied to other materials, particularly recently developed hydrogels with strong hydratable and light-absorbing properties. The gel membrane prototype, featuring micro-tree arrays that are 4 mm tall, 0.8 mm in diameter, and separated by 1.2 mm, displayed an impressive solar water evaporation rate of 3.64 kg m^{-2} h^{-1} under 1 sun. Furthermore, durability studies conducted in a lab setting revealed the remarkable stability of membranes over a period of 20 months. In a rooftop prototype, the tested bi-functional microstructured hydrogel membranes were able to produce approximately 185 mL of fresh water over the course of eight days. The daily water collection efficiencies were around ~34 L m^{-2}.

Following that, inspired by natural plant transpiration, a study designed a wooden cone evaporator by successively loading tannins and iron ions on the delignified wood (DW) surface [Figure 11]. Alkaline sulfite treatment of wood removes partial lignin and hemicellulose, enhancing flexibility and hydrophilicity. The unique hierarchical porous structure of wood enables swift water transportation and exceptional heat insulation. The 3D cone evaporator showcased an impressive evaporation efficiency of 1.79 kg m^{-2} h^{-1} when exposed to direct sunlight, surpassing the performance of conventional 2D evaporators. Furthermore, the DW-TA-Fe^{3+} device exhibited mildew resistance, making it practical and cost-effective. As a result of this feature, the device can maintain its satisfactory biostability even when submerged in water for 30 days[146].

However, a few important questions need to be addressed, including the durability of the technology over extended periods of time and in different environmental conditions, the possibility of implementing it on a larger scale for desalination plants, the potential environmental effects of using chemically treated wood, and the adaptability of the technology with regards to different types of wood or other natural materials. Addressing these issues in future research could help to further improve the technology and better understand its potential for real-world applications. Furthermore, new designs are being employed in

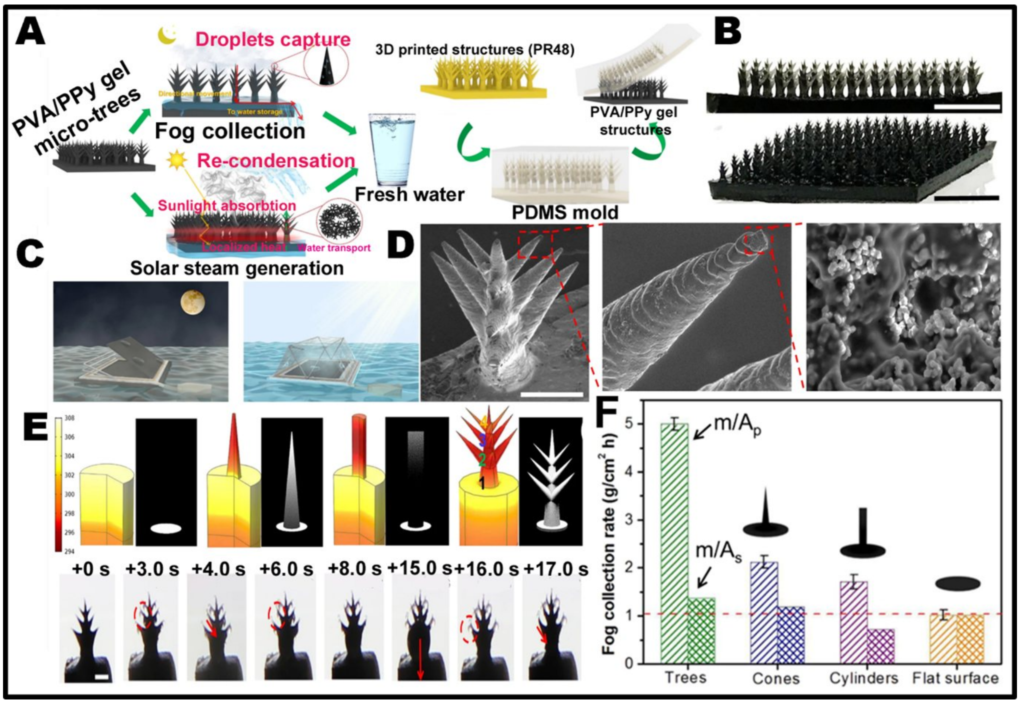

Figure 10. (A) PVA/PPy hydrogel membrane with micro-topologies and its schematic illustration. (B) Represents the fabricated PVA-PPy gel micro-tree array. (C) 24/7 water collection diagram of the floating device. (D) SEM images of tree topology. (E) Simulated patterns and temperature gradients for different micro-topologies and photographs of the fog collection process on a gel tree (a red circle indicates the formation of the droplet while a red arrow indicates the motion of the droplet), (F) Consistent fog collection rates of different membranes. Reprinted with permission from ref.[146]. Copyright 2021 Springer Nature.

various fields. Examples include the use of the lotus leaf effect for self-cleaning and the concept of vascular networks for efficient water transport. Such creative approaches are proving to be crucial in enhancing the performance of evaporation devices. They also ensure their robustness in various environmental conditions[147]. In essence, the confluence of these novel materials and innovative device designs is ushering in a new era for SIE technology. This amalgamation of advancements not only holds the promise to significantly enhance the efficiency and functionality of current solar evaporation systems but also represents a significant step towards a more sustainable and water-secure future. The combined efforts of material scientists, engineers, and innovators are contributing to an exciting journey that could fundamentally change how we utilize solar energy in the context of water treatment and management.

Dang *et al.* introduced a salt-resistant evaporator (SRE) designed using computational fluid dynamics simulations to optimize its geometry for higher hydraulic conductivity and diffusion flux, thus enabling robust convection [Figure 12][148]. This configuration employs well-aligned multiscale channels, facilitates quick brine transfer and enables real-time salt excretion, ensuring continuous regeneration of the evaporator. Notably, the use of carbonized rattan, a sustainable biomass material, is a significant point due to its natural composition of regular multiscale channels, making it an excellent choice for SRE construction. The study claims impressive results with the rattan-based evaporator demonstrating a high evaporation rate of 1.47 kg m^{-2} h^{-1} and efficiency of 91% in a highly concentrated brine (20 wt% NaCl) under 1 sun. Importantly, it maintains performance consistency over continuous weekly operations, indicating long-term system stability. This opens the door for large-scale application of solar desalination for high salinity brine. The approach by Shi *et al.*, utilizing 3D micro-tree arrays on PVA/PPy hydrogel membranes, grapples with the intricate balance between fog capture efficiency and solar steam generation[145]. One of the

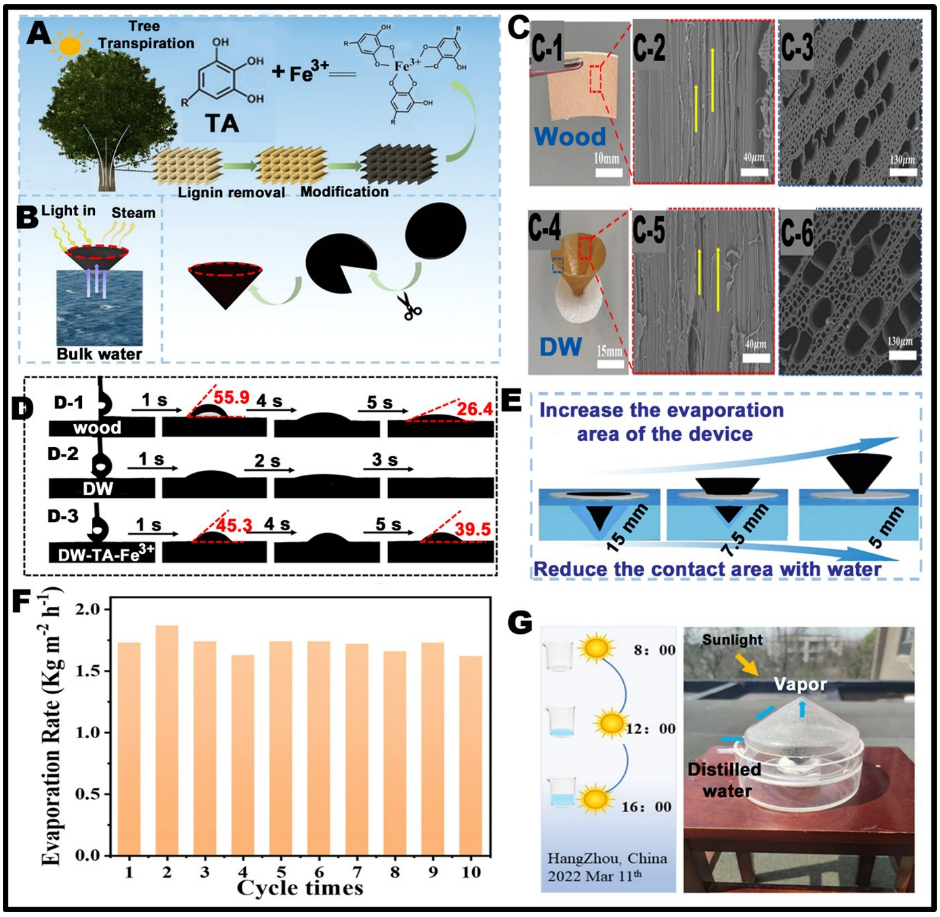

Figure 11. (A) Illustration of creating a photothermal conversion wood veneer. (B) A three-dimensional model of a wood cone evaporator. (C) Depictions featuring: (C-1) and (C-4) Visual representations of wood and DW. (C-2) and (C-3) SEM images showcasing wood and DW in a tangential section. (C-5) and (C-6) SEM visuals of DW and wood cross-sectioned. (D) Contact angle images of the (D-1) wood, (D-2) DW and (D-3) DE-TA-Fe^{3+}. (E) Design of the device at variable underwater depths. (F) Performance analysis of the DW-TA-Fe^{3+} over multiple cycles. (G) Field test for water evaporation. Reprinted with permission from ref.[147]. Copyright 2023 Springer Nature.

main challenges is to carefully design the micro-topologies of the hydrogel to ensure efficient water flow and ideal thermal properties for evaporation. Additionally, it is important to address the issue of maintaining the structural integrity of the hydrogel during the hydration and dehydration cycles it undergoes. The wooden cone evaporator inspired by plant transpiration, which employs DW enhanced with tannins and iron ions, confronts the challenge of maintaining the chemical and structural stability of the wood. This involves ensuring that the treatment does not compromise the porosity and hydrophilicity of wood, essential for its evaporation efficiency. In the study by Dang *et al.*, SRE encounters the primary scientific hurdle of sustaining the hydraulic conductivity and diffusion flux in the multiscale channels[148]. Ensuring consistent performance in high salinity conditions is of utmost importance to prevent channel clogging or compromise due to salt accumulation. Furthermore, incorporating carbonized rattan presents the task of balancing the inherent variations in its channel structure with the requirement for consistent performance throughout the evaporator. These specific scientific challenges underline the complexity of optimizing material properties and structural design to enhance the functionality and efficiency of these advanced water harvesting systems.

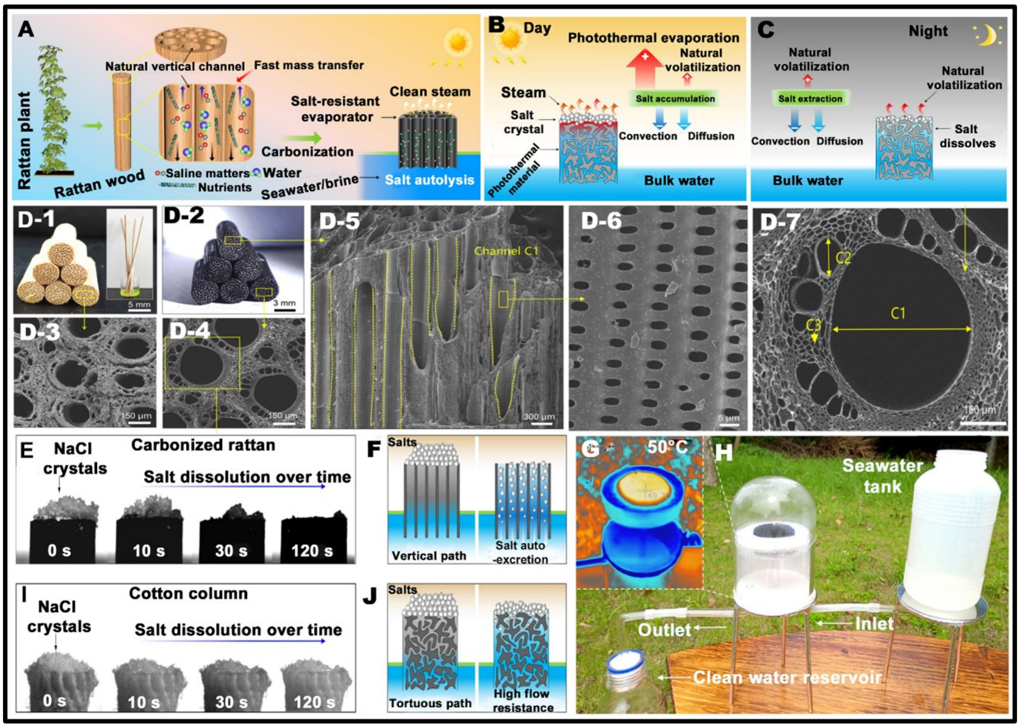

Figure 12. (A) Process of creating orderly, multi-level porous carbon-based photothermal material. (B) Schematic of the daytime evaporation and volatilization outpace convection and diffusion. Ionic species of salt experience enrichment and accumulation. (C) Night-time convection and diffusion exceed natural volatilization, diluting and expelling salt ions. (D) (D-1) Picture of natural rattan and inset depicts a reed diffuser, (D-2) carbon-treated rattan, (D-3) and (D-4) SEM micrographs of the top section of natural and carbonized rattan, respectively, (D-5) SEM micrograph of the side section of the carbonized rattan, (D-6) SEM micrograph of the wall of the channel C1 and (D-7) Close-up view of SEM micrograph of carbon-treated rattan. (E) Salt expulsion experiment photos using carbonized rattan. (F) Salt expulsion depicted through vertical (G). The SRE device represents the temperature distribution after 10 min of irradiation. (H) Real-time optical image of the SRE integrated device in outdoor environment. (I) Salt expulsion experiment photos using carbonized cotton column. (J) Salt expulsion depicted through a tortuous path. Reprinted with permission from ref.[149]. Copyright 2023 Elsevier.

Hybrid systems

A hybrid system combines two or more technologies to create a more efficient and versatile setup. The advantages of these systems include greater energy efficiency, increased evaporation rates, simultaneous electricity generation and superior use of solar power which makes them a key player in advancing sustainable solutions.

PV-thermal (PV-T) systems, which ingeniously combine PV and solar thermal technologies, have emerged as a promising solution for simultaneous electricity and heat generation[149]. This hybrid approach enables efficient utilization of solar energy while optimizing overall system performance. Simultaneously, the combination of solar-driven desalination and power generation has proven to be a successful solution for tackling water scarcity and energy challenges[150-152]. Therefore, Duan *et al.* developed an innovative hybrid energy system (HES) using CNT-based prototypes[153]. The HES effectively addresses the issue of discontinuity and instability in renewable energy generation. It features a freshwater production device that can generate freshwater at a rate of 0.84 kg $m^{-2}h^{-1}$, with excellent purification and desalination capabilities. Additionally, they created a solar charging system with a maximum output of 5 V, suitable for charging mobile devices and power banks during sunny conditions. Zhou *et al.* designed a hydrogel-based system for simultaneous water purification, electricity and hydrogen production[154]. The researchers have utilized a unique 3D pillared PAM/CNT hydrogel with optimal hydrophobic modifications to facilitate a precise balance between water absorption and evaporation. This method leads to an impressive photothermal efficiency of 96% at the liquid/vapor interface. The holistic design of systems showcases the harmonious generation of purified water and renewable energy under natural conditions, employing thermoelectric generators as thermal insulators. These are sandwiched by PAM-based evaporators and PAM/CNT-based solar absorbers, ensuring efficient cooling and heating. The system can produce a consistent electrical output power of 4.8 W/m^2, which can power water splitting to generate hydrogen at a rate of 0.3 mmol/h. The studies conducted by Duan *et al.* and Zhou *et al.* have identified distinct advantages and disadvantages[153,154]. Duan *et al.* introduce an innovative HES that integrates freshwater production with solar energy harvesting and includes a solar charging system, enhancing its utility[153]. However, this system faces challenges in efficiently managing energy distribution between its dual functions and requires further investigation into its performance across varying solar intensities. Zhou *et al.* present a hydrogel-based system that achieves high photothermal efficiency, effectively balancing water absorption and evaporation, which is crucial for water purification and energy production[154]. One drawback of this system is the requirement for meticulous optimization of its PAM/CNT hydrogel composition to ensure efficiency. Furthermore, incorporating thermoelectric generators adds further complexity to the overall design. When examining evaporation dynamics, comparing the rates of evaporation under different levels of sunlight can offer valuable insights. "0 Sun" evaporation, occurring without the influence of direct sunlight, relies on ambient heat and air movement and is crucial for understanding ecological and meteorological phenomena in low-light conditions. Conversely, "1 Sun" evaporation, which occurs under standard solar conditions, serves as a fundamental benchmark in scientific research, allowing for the evaluation of evaporation processes under average sunlight exposure. These contrasting conditions help in comprehensively understanding the intricacies of the water cycle and its varying responses to different environmental factors. Dao *et al.* developed an innovative nanogenerator inspired by the *Limnobium laevigatum* plant[155]. The *Limnobium laevigatum*-inspired nanogenerator (LLN) is a device that incorporates a special combination of multi-walled CNTs (MWNTs) coated on cellulose paper, which is then placed on top of Polystyrene foam. Engineered to float on water, the LLN exhibits exceptional capabilities in both electricity generation and water evaporation. Under 1 sun conditions, it generates 248.57 mW/m^2, while in 0 sun conditions, its output is 107.38 mW/m^2. Additionally, it achieves a water evaporation rate of 1.48 kg/m^2/h in sunlight and 0.58 kg/m^2/h in the dark. The study also finds optimal performance with a 50 μm thick MWNT layer in a 0.6 M NaCl solution, indicative of its potential efficiency in seawater-like environments. In another study, Dao *et al.* investigate a nature-inspired hierarchical evaporator using MWNTs, focusing on its water evaporation and electricity generation capabilities[156]. The evaporator showcases a notable water evaporation rate of 1.364 kg/m^2/h under 1 sun conditions and 0.450 kg/m^2/h in the absence of sunlight (0 sun). In terms of electricity generation, the device achieves power densities of 176 μW/m^2 under 1 sun illumination and 94 μW/m^2 in dark conditions when utilizing Zn wire electrodes. With gold nanowire electrodes, the power densities are 14.50 nW/m^2 under 1 sun and 6.48 nW/m^2 under 0 sun. This study highlights the importance of electrode materials and their placement in enhancing the efficiency of these nanogenerators. The studies by Dao *et al.* on the LLN and the hierarchical evaporator using MWNTs demonstrate commendable advancements in solar energy and water evaporation technologies[155,156]. The high energy output and evaporation rate of LLN under optimal sunlight conditions are noteworthy. However, it presents challenges in ensuring the stability of the MWNT coating, a critical factor for sustained functionality. The adaptability of a hierarchical evaporator to different lighting conditions is a significant advantage, yet its performance is constrained by the dependency on specific electrode materials, highlighting an area for further material optimization. These insights reflect the complexities and potential areas for refinement in developing efficient and versatile energy-harvesting systems.

POTENTIAL APPLICATIONS OF SCALABLE SIE

Scalability allows the technology to be used in a variety of settings, from small-scale household applications to large-scale industrial or agricultural operations. This flexibility is key in making the technology accessible and useful in different contexts. Wu *et al.* introduced a novel double-layered vertical solar sea farm system (DVSSF), which represents a significant advancement in scalable SIE[157]. This system ingeniously combines the process of SIE with agriculture, using a two-tier structure. The lower section is dedicated to generating clean water through the solar evaporation of seawater. This produced water is then moved upwards to the upper layer, which contains soil for crop cultivation. This ingenious design allows for the direct growth of various vegetables, including broccoli, lettuce, and Pak Choi, on the sea surface. Impressively, these vegetables achieved a germination rate above 80%, illustrating the efficiency of the design. The DVSSF stands out due to its minimal need for geographical resources and maintenance, presenting a viable solution to the pressing challenges of diminishing clean water and arable land. Similarly, Guo *et al.* developed a sustainable method to convert waste face masks, a significant byproduct of the COVID-19 pandemic, into effective photothermal evaporators for water purification[158]. Capitalizing on the unique interwoven structure of the masks, the team applied successive surface treatments with PVA and PPy, enhancing the capacity of the material for water absorption and solar energy capture, achieving an impressive 97% solar absorption efficiency. This modified face mask-based system demonstrates a notable solar steam efficiency of 91.5% and achieves a seawater evaporation rate of 1.39 $kg/m^2/h$ while also effectively resisting salt accumulation over extended periods. The purity of the condensed water from this system is sufficiently high, making it suitable for both drinking and agricultural use, thereby facilitating the possibility of ocean surface farming. A key innovation of this research is the development of a floating photothermal device that showcases the feasibility of autonomous solar-powered ocean farming. This device successfully cultivated crops such as turnips, irrigated by water derived from the solar evaporation process of the modified face masks.

Both these technologies illustrate the potential of scalable SIE in contributing to sustainable development goals. They leverage renewable energy sources, promote waste reduction through repurposing, and offer scalable solutions that can be adapted to various scales and contexts, from small communities to larger industrial applications. The implications of these technologies extend beyond their immediate environmental benefits. Through the implementation of alternative methods for fresh water generation and agriculture, they have the potential to significantly contribute to improving food security, particularly in regions that are heavily affected by climate change and environmental degradation. Additionally, the autonomous nature of these systems, particularly highlighted in the floating photothermal device by Guo *et al*., indicates a shift towards more self-sufficient and sustainable practices in resource management[158].

CURRENT CHALLENGES AND OPPORTUNITIES

SIE technologies have shown considerable advancements in recent years. However, several challenges still need to be addressed. One of the foremost challenges in materials design lies in the development of photothermal materials that are not only highly efficient in solar energy absorption but also demonstrate stability and durability in various environmental conditions. The efficiency of these materials in converting solar energy to heat directly influences the overall performance of solar evaporation systems. Researchers are currently dedicated to improving the light-absorption capabilities and thermal conductivity of these materials, all while keeping costs low and being environmentally friendly. This has led to a growing interest in exploring nanomaterials such as graphene-based composites, which offer high light absorption and thermal conversion efficiencies. However, the scalability of these materials for wide-scale applications and their long-term environmental impact are significant concerns.

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Additionally, the design of multilayer structures in device assembly presents intricate challenges. These structures, typically composed of a light-absorbing layer, a water transport layer, and a thermal insulation layer, must be finely tuned to work in harmony. Every layer plays a crucial role, ensuring optimal solar absorption, minimal heat loss, and efficient water transportation to the evaporation site. The challenge lies in optimizing the integration of these layers to enhance the overall system efficiency. This requires a delicate balance in material properties, for instance, ensuring that the water transport layer provides adequate capillary action for water supply while the thermal insulation layer effectively reduces heat loss to the environment. Moreover, thermal management remains a critical hurdle in device assembly. Effective thermal management strategies are essential to maintain the temperature gradient necessary for efficient evaporation. This involves not only selecting materials with high thermal stability but also designing the system architecture in such a way that it maximizes heat retention in the evaporation zone.

In the context of opportunities, the current landscape offers considerable scope for innovation in both materials design and device assembly. There is a significant potential for the development of novel nanomaterials and hybrid composites that could offer enhanced photothermal properties, improved stability, and reduced environmental impact. Innovations in surface chemistry and nano-engineering could lead to breakthroughs in material efficiency and longevity. In device assembly, the opportunity lies in creating more integrated and efficient systems. Advances in the design of multilayer structures and improved thermal management techniques could substantially increase the efficiency of solar evaporation systems. Furthermore, the drive towards sustainable and eco-friendly materials opens up avenues for research into bio-inspired and green materials that not only perform efficiently but also align with environmental sustainability goals.

CONCLUSION AND FUTURE PROSPECTS

This review article highlights the significant advancements in the photothermal materials design and device assembly and offers a thorough analysis of different materials such as plasmonic materials, semiconductors, and carbon-based materials. It highlights the significant potential these materials have in improving the performance of SIE. Furthermore, the article delves into the intricacies of device assembly and optimization, emphasizing integrating advanced materials with smart designs, such as self-floating devices and hierarchical structures. These innovative designs can address challenges such as thermal loss, heat localization, and vapor escape. The continuous progress in this field offers a glimpse into a sustainable future where solar-powered water purification can significantly alleviate the water crisis and contribute to a greener, more resilient world.

As the global demand for clean water and renewable energy sources continues to grow, exploring the future prospects of SIE becomes even more critical. Anticipated directions in materials design, device assembly, and potential applications are set to revolutionize this technology. Future research in materials design is expected to focus on the discovery of novel materials with enhanced light absorption, tunable wettability and improved thermal management properties, in addition to incorporating self-cleaning or anti-fouling capabilities. Potential materials include 2D materials, MOFs, and nanoporous polymers, which could enable higher evaporation rates and energy conversion efficiencies. Combining SIE technology with other renewable energy systems, such as PV or thermoelectric generators, can create synergistic effects that maximize overall energy utilization and output. Developing integrated systems will not only improve the efficiency of water production but also diversify the applications of this technology, including electricity generation and thermal energy storage.

To facilitate widespread adoption, future research should focus on the development of scalable and modular device designs that can be easily fabricated, assembled and customized according to specific application requirements. Moreover, incorporating smart control and monitoring systems will allow for real-time performance optimization and fault detection, further enhancing the robustness and reliability of SIE systems. Future research should aim to optimize these processes by minimizing energy consumption, reducing environmental impacts, and promoting circular economy principles such as resource recovery and waste minimization. In addition to water production and treatment, SIE technology can be applied to other fields, such as food processing, pharmaceuticals, and agriculture.

On the other hand, with indications of ice present in the polar regions of celestial bodies such as the Moon and Mars, SIE could serve as a valuable tool for converting this ice into drinkable water. This process would reduce the need for water to be transported from Earth, which currently involves substantial cost and resource-intensive supply missions. Furthermore, the same principle could also be applied to extract other useful resources. Thus, the deployment of SIE in space research encourages not only the sustainability of long-term human habitation beyond Earth but also the feasibility of further space exploration. Ultimately, the future of SIE technology is filled with potential, offering a promising solution to the increasing global need for clean water and renewable energy. This will undoubtedly contribute to a more sustainable future.

DECLARATIONS

Authors' contributions

Conceived the manuscript: Balu Sk, Liu S
Wrote the manuscript: Balu Sk
Reviewed the manuscript: Xing R, Latthe SS
Contributed to the discussion of the manuscript: Cheng S, Liu S

Availability of data and materials

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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