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REVIEW

Navigating Solar Thermal Desalination: A Comprehensive Review of Materials Selection Criteria

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Abstract
Global water scarcity, intensified by climate change and population growth, necessitates sustainable freshwater solutions. Solar thermal desalination offers promise due to its energy efficiency, yet optimizing system performance hinges critically on material selection, particularly for photothermal absorbers and their substrates. While extensive research addresses photothermal nanomaterials, substrate materials vital for structural integrity, thermal management, and interfacial stability remain underexplored. This review comprehensively examines current advances in solar evaporator components, evaluating photothermal materials and substrates against key selection criteria: thermal conductivity, stability under harsh conditions, scalability, and compatibility. We analyze diverse substrate materials (e.g., metals, ceramics, polymers, bio-based, and aerogels) and their synergistic roles in enhancing evaporation efficiency and durability. Critical gaps in large-scale feasibility, long-term stability under variable solar flux, and cost-performance trade-offs are identified. The review also highlights emerging trends such as 3D-printed substrates and bio-inspired designs to overcome salt accumulation and fouling. By addressing these challenges and outlining pathways for scalable implementation, this work aims to advance robust, economically viable solar thermal desalination technologies for global freshwater security.

Keywords Desalination · Solar desalination · Photothermal materials · Substrate materials · Sustainability

Introduction

The scarcity of freshwater is a serious problem worldwide, especially in some specific regions of the world; hence, desalination is an essential technology [1]. It means the technique used to filter salts and other minerals from seawater to obtain safer water for use in drinking or farming. Since water scarcity on the earth has become a pressing issue because of the expanding population, industrialization, and climate change affecting freshwater resources, desalination has become an essential alternative source of freshwater [2]. Distilling involves the evaporation of seawater to get steam, which is then condensed to get freshwater, while membranes (e.g., reverse osmosis) filter seawater through moveable walls to get rid of salts and other impurities [3]. Both technologies can solve water shortage issues and have improved in terms of cost-effectiveness over time. Nevertheless, the following problems exist: high energy consumption, negative impacts on the environment as evidenced by brine discharge, and the continuous enhancement of technology to lower costs and promote sustainability. The current direction of research and development involves improvements in the efficiency of membrane materials, new techniques of desalination such as solar-heated desalination, and the integration of new environmentally friendly nanomaterials to enhance performance [4]. This is because the numbers of people and demands on available freshwater are set to increase in future, and they will turn to a process as efficient and adaptive as desalination to respond to climate change challenges [5].

Solar thermal desalination, particularly using the photothermal evaporator, could be regarded as one of the major

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steps forward in sustaining global water scarcity issues [6]. This technique uses sunlight to drive the desalination process; the photothermal materials that are used in this method can convert solar energy into heat. The photothermal evaporator is considered one of the essential components of this technology, capturing sunlight and generating localized heating at the surface of the photothermal evaporator [7]. The localized heat leads to evaporation, hence the splitting of water from salt solutions. Based on this, nanostructured materials contribute to the improvement of the photothermal characteristics of the evaporator and help in achieving higher light-trapping efficiency and fast heat transfer to the water [8]. Substrate materials are also important in the photothermal evaporator since they offer structural support and thermal stability while maintaining the interfacial contact of the photothermal materials with the saline water [9]. Choosing appropriate materials for the mentioned photothermal layer and substrate requires such characteristics of materials as thermal conductivity, stability in extreme conditions, and compatibility with further processing [10]. The benefits of solar thermal are diversified, thus giving it an edge in desalination over other techniques that infer heavy dependence on fossil energy forms. Secondly, solar desalination can be especially useful in regions where conventional water and electricity supply systems are not developed [11]. In this context, solar desalination remains a promising technology due to its outlook for affordability and sustainability in future as several technological enhancements are discovered and innovated [12]. Figure 1a, b shows, which was extracted from the Elsevier data, the research trend and the technological advancements for sustainable desalination.

Some of the most recognized materials for photothermal conversion in solar thermal desalination using a photothermal evaporator are carbon-based materials such as graphene and carbon nanotubes due to their high light capture and heat transfer capacity [13]. Gold, silver, and copper metal nanoparticles are also used because of their properties associated with surface plasmon resonance, the increase of light absorption, and localized heating and have good light absorption properties when in its nanoform of metal oxides such as titanium dioxide (TiO_2) [14]. These materials are important in enabling the process of adopting solar power in the production of heat for evaporation. The substrate material can be metal, for example, stainless steel, aluminum, Luffa, graphite, coconut fiber, aerogel, or copper [15]. They are chosen based on their ability to provide mechanical strength, corrosion resistance, and thermal conductivity to the photothermal layer to support the dissipation of heat from the saline water. Flexible materials include polyethylene terephthalate (PET) and polyimides that can be developed with the compounds to make designs that respond to the importance of heat [16]. Some of the ceramics, like silicon carbide and alumina, have good thermal conductivity and higher strength, which allows the components to be used for heavy-duty performance in hostile operating environments [17]. Bio-based materials like Luffa and coconut fiber are also used for the seek of low cost and environmentally friendly manner. The selection of materials is crucial for boosting the efficiency, reliability, and cost-effectiveness of solar thermal desalination systems. This drives continuous research into new materials and assembly procedures to ensure a consistent supply of clean water [5].

Despite significant advancements in photothermal materials (e.g., MXenes, plasmonic metals, carbon nanostructures) and hybrid solar-membrane systems [18–20], several critical gaps continue to impede the widespread scalability and commercial viability of solar desalination. A fundamental trade-off persists in photothermal materials between efficiency, stability, and cost. For instance, novel materials like bismuth copper oxysulfide, while excellent

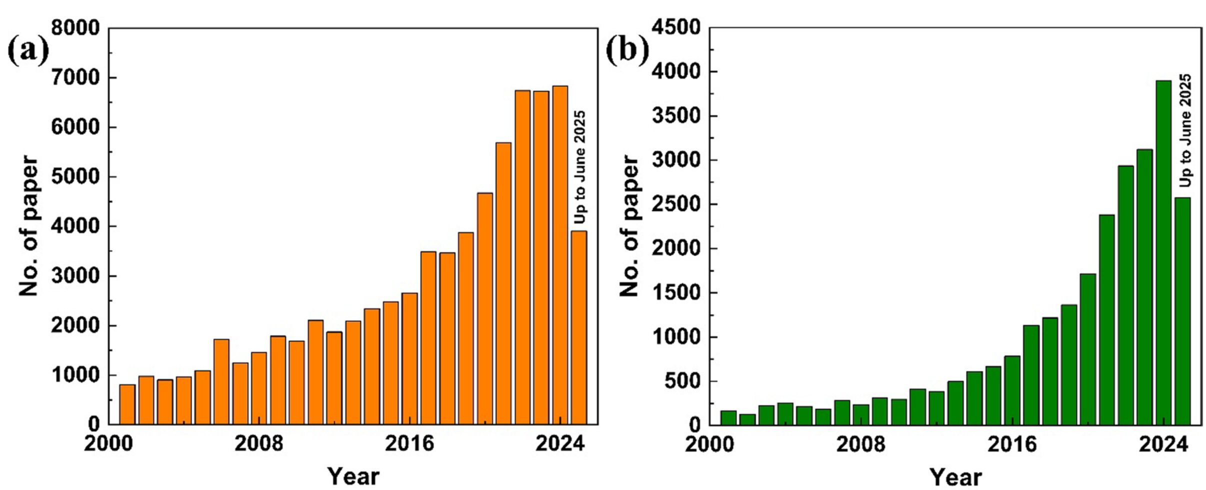

Fig. 1 Research trend of **a** desalination and **b** solar thermal desalination based on Elsevier data

at light absorption and localized heating, often degrade under variable solar intensity or harsh environmental conditions [21]. Similarly, while cost-effective alternatives such as bio-derived carbon exist, they frequently lack the necessary durability for long-term deployment [22, 23]. Compounding these material limitations, salt fouling remains a pervasive issue, leading to surface clogging despite innovative surface engineering strategies like energy-mass-path decoupling. This persistent fouling directly impacts the efficiency and longevity of the desalination system [22].

Beyond the materials themselves, substrate design presents its own set of challenges, primarily struggling with thermal and hydraulic inefficiencies. Current substrates often fail to adequately confine heat, resulting in significant conductive losses to the bulk water. Even advanced 3D and multisurface designs require further refinement to overcome these losses. Furthermore, water transport mechanisms, such as hydrogel-assisted capillary action, prove unreliable under high salinity or fluctuating conditions, thereby limiting critical evaporation rates [24]. These individual challenges are further exacerbated by system-wide issues. The performance of solar desalination systems often drops significantly under real-world variability in solar flux and brine concentration. Scaling lab-based prototypes to industrial applications remains largely unproven, highlighting a significant hurdle in commercialization. While hybrid systems offer improvements in brine management, they frequently overlook crucial thermal energy recovery. Moreover, the absence of standardized efficiency metrics across the industry makes comprehensive comparison and optimization difficult [25–28]. Critically, material innovation often progresses in isolation from substrate engineering and system integration [29]. This siloed approach hinders the development of holistic solutions that are essential for addressing the cost-efficiency-scalability paradox. This paradox, where high performance frequently sacrifices affordability or durability, represents the foremost barrier to the widespread adoption of solar desalination technologies.

The present manuscript aims to solve the issues regarding the substrate materials. This review work discussed some of the widely used substrate materials in terms of their advantages and drawbacks. The substrate materials also explain the role of the substrate materials in detail to understand the selection criteria, including their affinity with photothermal materials to guarantee the highest heating transformation rates and resistance to harsh operating conditions. In addition, new trends in the production of substrate components using 3D printing technology could lead to the design of individual substrate designs suitable for specific applications in solar desalination, which is a continuous process of enhancement of solar thermal desalination processes. This manuscript also aims to give insights in terms of the commercialization of desalination technology using photothermal evaporation.

Strategies for Desalination

To lower salt concentrations to below the 500×10^{-6} drinking water limits set by the World Health Organization, surplus salts and other dissolved compounds must be removed from brackish or saltwater through the desalination process [30]. Figure 2 represents the invented desalination technique based on three major processes, which are evaporation, filtration, and crystallization. Desalination has been used for millennia, but in recent decades, its popularity has grown due to increased water shortage and demand in areas like the Middle East and Africa [31]. The three main methods of desalination are membrane filtration, thermal evaporation, and crystallization. However, the crystallization method is not popular and viable in the current day.

Evaporation and Condensation

Many methods are used in evaporation and condensation desalination; each of them has strengths and weaknesses. MSF and MED employ thermal energy in multiple plates to evaporate and condense seawater, but they are infamous for power-hungry and efficient operational issues [32]. In thermal vacuum compression, one uses mechanical compression to increase efficiency, but the downside is that it is expensive to maintain [33]. Techniques such as solar steel and solar chimney desalination use solar energy but avert some limitations, including the availability of space and weather conditions [34]. Solar stills and the HDH methods imply the immediate use of sunlight or moist air for evaporation and condensation but with efficiency and scalability challenges [35]. However, despite these criticisms, improvements in the technologies continue to occur to make these processes more efficient and thus less costly to produce freshwater from seawater and brackish sources.

Different approaches to desalination, such as evaporation and condensation, have many advantages and pre-stalled difficulties. MED and MSF systems are excellent in their production capacity, which allows them to be recommended for large-scale production [36]. However, both methods are rather energy-consuming processes that need a significant amount of heat and electricity to be effective. The feature of energy efficiency in thermal vapor compression (TVC) is mechanical compression, thereby reducing operating costs [37]. However, as the varieties of mechanical parts become more complex, there appears to be a necessity for more frequent maintenance and even possible mechanical failure. Solar steel and solar chimney desalination methods are energy-efficient techniques with solar energy as the

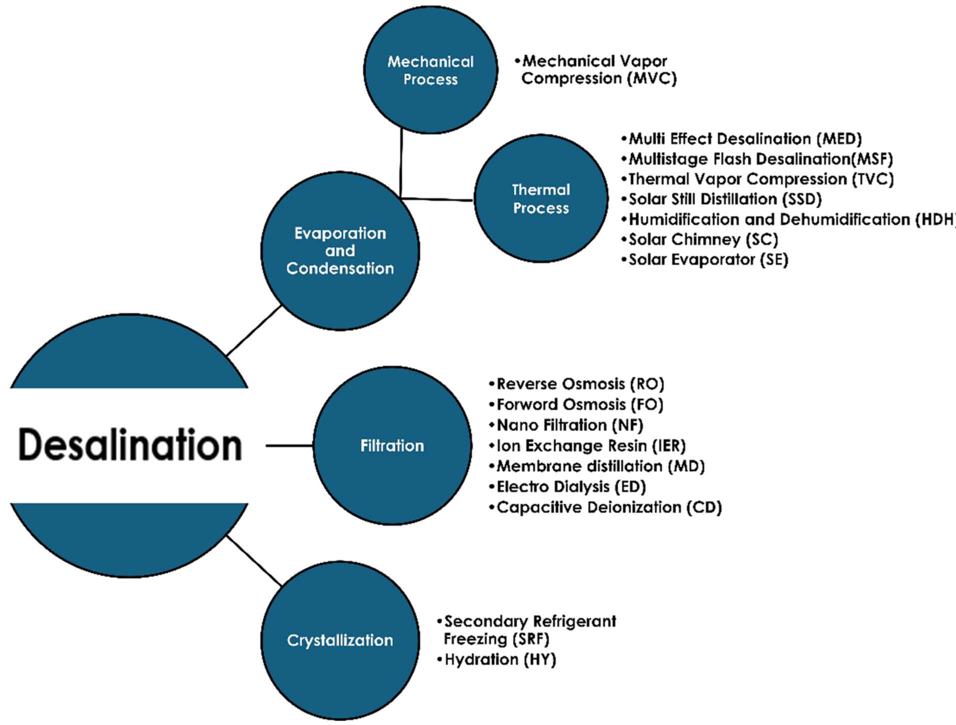

Fig. 2 Desalination technique based on three major processes of evaporation, filtration, and crystallization

primary power source, which decreases the need for supplemental power [38]. However, such methods need a large area to be laid out, and their dependability can be affected by weather conditions. Solar stills and HDH techniques display simplicity and the possible decentralization of water production methods [39]. However, they exhibit generally lower efficiency and problems with scalability and predominantly depend on the availability of light and humidity. Nonetheless, current research and development, as well as technological innovations, are focused on enhancing these techniques so that the process of desalinating seawater and brackish water can be made more economical.

Figure 3 represents some of the research work that focuses on the evaporation and condensation method. Figure 3a–c presents a 3D solar evaporator using PVA sponge, zwitterionic hydrogel, and MWCNTs for efficient salt-resistant desalination. It achieves 3.35 kg/(m^2·h) in 10 wt% brine under 1 kW/m^2 solar input, shows antibacterial properties, and meets WHO standards in outdoor tests, offering a robust solution for seawater and wastewater treatment [40]. Another similar study (Fig. 3d-g) presents a green, biomimetic solar evaporator using nanocellulose, chitosan, and carbon nanotubes, leveraging the Donnan effect for salt resistance. Featuring vertically aligned channels, it achieves a high evaporation rate of 3.382 kg/(m^2·h) under 1 sun (1000 W/m^2) and ensures long-term stability in saline conditions, offering sustainable desalination solutions [41]. In addition, Fig. 3h–k introduces a temperature-responsive hydrogel evaporator using NIPAm, Am, and polypyrrole for efficient solar desalination. It dynamically shifts surface wettability to minimize heat loss while ensuring a continuous water supply. The system achieves an evaporation rate of 3.48 kg/(m^2·h) with 91.8% efficiency under 1 sun (1000 W/m^2) and maintains ~ 90% performance over 25 cycles in 12.5 wt% brine without salt crystallization, offering a promising strategy for sustainable and stable solar-driven water purification [42].

Filtration

Desalination by filtration involves a broad group of efficient technologies providing for the filtration and separation of salts, impurities, and other compounds from water employing membranes, ion exchange resins, and electrochemical methods [43]. Reverse osmosis (RO), which is the most popular, uses pressure-driven semi-permeable membranes that are quite successful in removing salts from seawater and brackish water, albeit at the expense of power consumption and brine disposal [44]. Forward osmosis (FO) is a water treatment method based on osmotic pressure; it has less energy consumption compared to RO, but it also has some obstacles in large-scale implementation and FS production rates [45]. Nanofiltration (NF) employs membranes with pore sizes intermediate to those of UF and RO to filter out ions and organics while not needing as much energy as RO but needing well-controlled pre-treatment to prevent fouling. Ion exchange resin (IER) technology encourages the exchange of ions in water, which is applicable for the

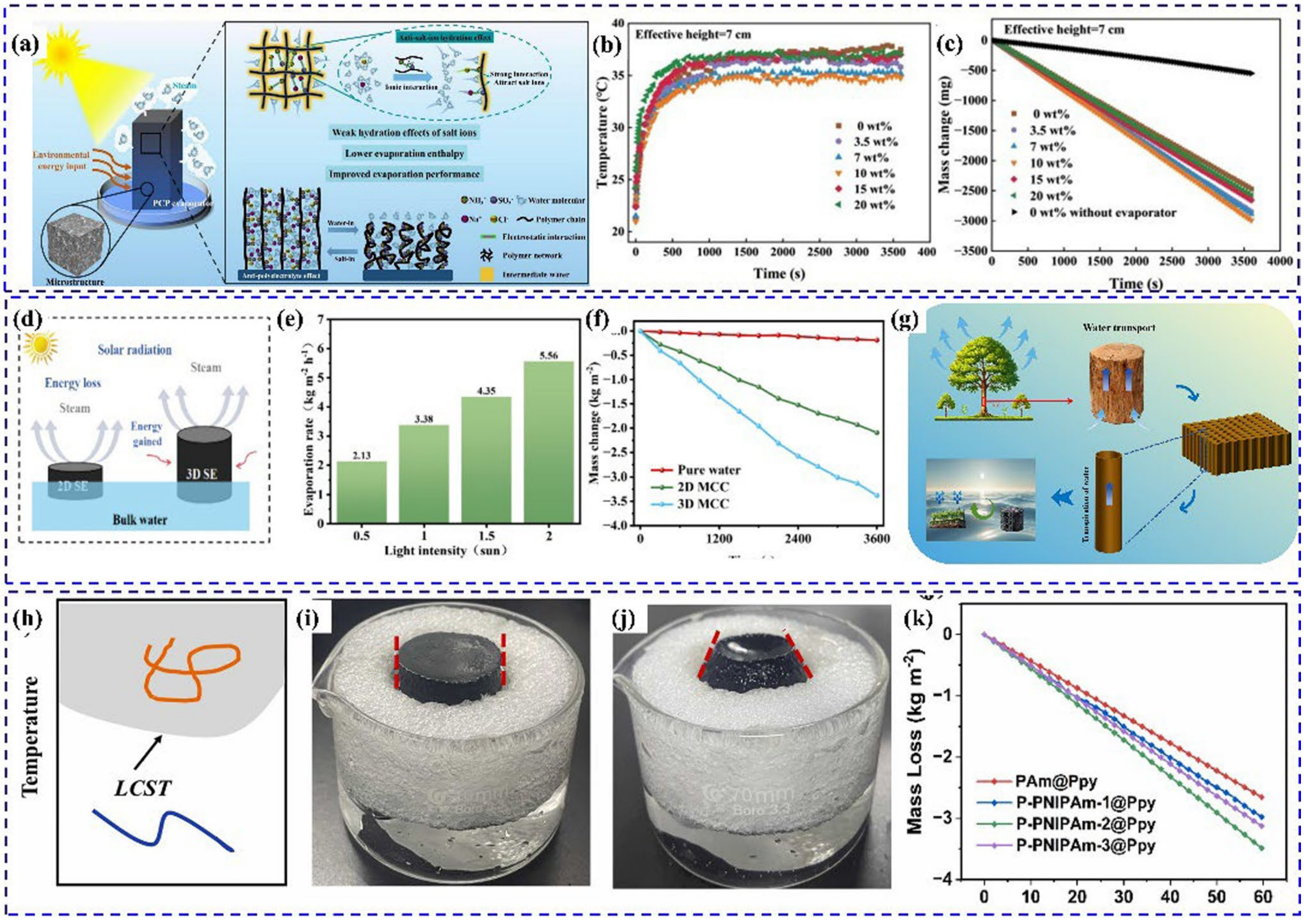

Fig. 3 **a–c** Evaporation and condensation process using a PVA sponge. Reproduce with permission from Ref. [40]. Copyright 2025 Elsevier. **D–g** Desalination performance of nanocellulose, chitosan, and carbon nanotubes. Reproduce with permission from Ref. [41]. Copyright 2025 Elsevier. **H–k** Desalination using a temperature-responsive hydrogel evaporator composed of N-isopropylacrylamide (NIPAm), acrylamide (Am), and polypyrrole. Reproduce with permission from Ref. [42]. Copyright 2025 Elsevier

elimination of some contaminants, but the process can be regenerated but cannot be well-utilized in high-salinity water. Desalination by membrane distillation (MD) involves utilizing hydrophobic membranes to transport water in the gaseous phase, leading to moderate energy requirements and the capability of treating high-salinity waters, but with major issues of membrane deterioration and fouling [46]. Both electrodialysis (ED) and capacitive deionization (CD) use electrical fields or capacitive techniques for ion removal and have the advantages of selectivity and/or energy reuse; however, the electrodes need renewal or refreshment and have lower freshwater production ratios than RO [47]. These methods, in total, present a spectrum of innovation toward attempting to remediate the deficiency of freshwater with continuing improvements in effectiveness, contending costs, and a variable range of applications toward the copious requirements for water treatment internationally. A breakthrough in fabricating artificial water channel (AWC)-based COF membranes via colloid-assisted self-assembly, achieving Å-scale separation with high water-to-salt permselectivity. Figure 4a-c presents the HC_6-$TpPa_2$ membranes exhibit excellent salt rejection, high permeance, and superior anti-swelling, anti-fouling, and long-term stability, advancing bio-inspired membrane technology for efficient desalination [48]. Similarly, another study develops Ti_3C_2Tx MXene membranes with cyclodextrin-embedded polyester networks via TMC-induced interfacial crosslinking, enhancing structural stability and salt rejection (Fig. 4d–f). α-CD-modified membranes showed optimal performance, achieving up to 93.96% salt rejection and high water permeability. Molecular dynamics simulations revealed ion transport behavior, offering a robust desalination solution [49]. Different methods of desalination through filtration technologies are characterized by various strengths and weaknesses, but they are all not without some major difficulties. RO performs exceptionally well in the rejection of saline and solutes in water and, as such, can be effectively used to produce fresh water.

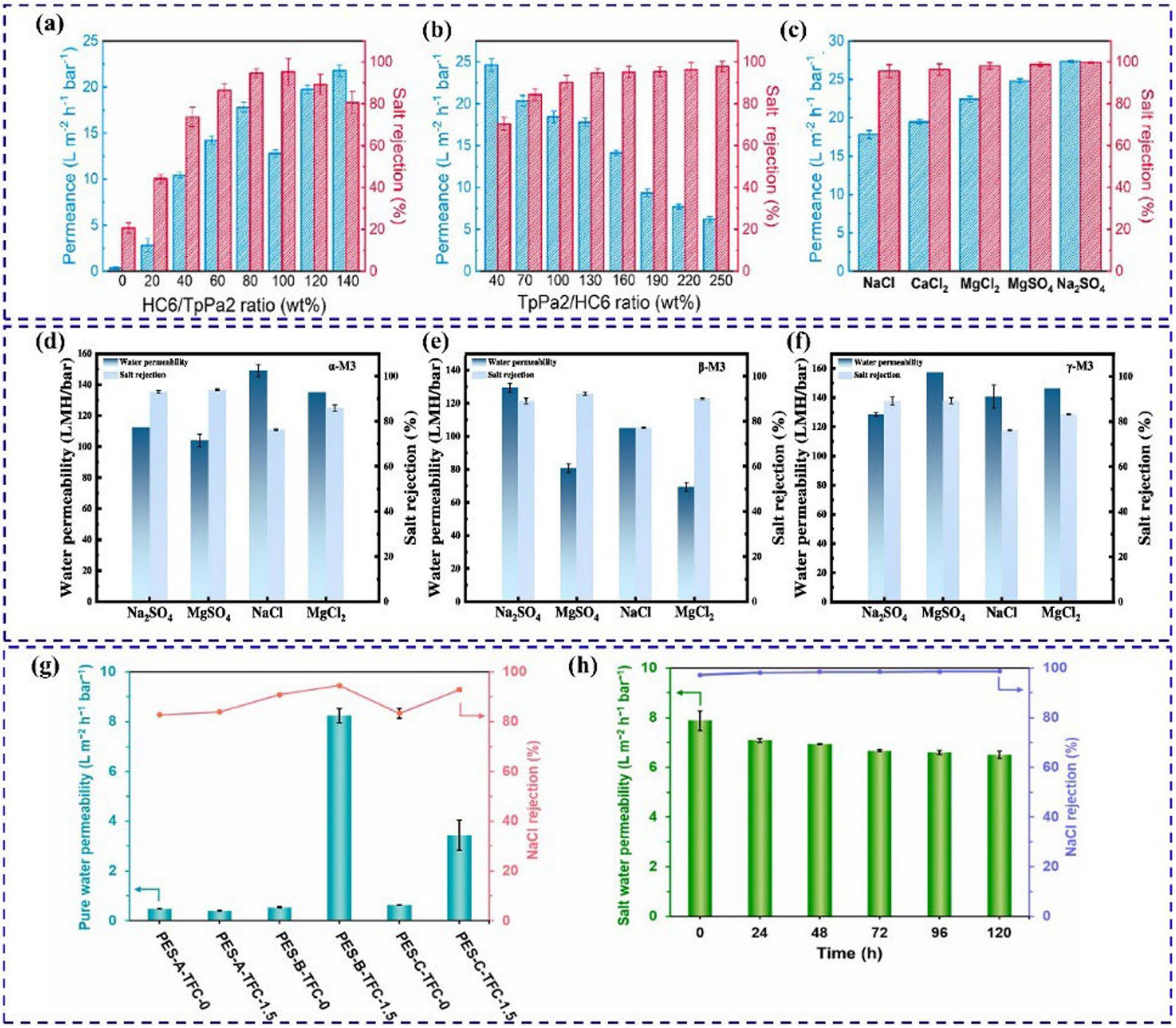

Fig. 4 **a** Salt rejection and water permeance of HC_6–$TpPa_2$ membranes at varying HC6/$TpPa_2$ ratios, with $TpPa_2$ fixed at 13 mg. **b** Performance of membranes with different $TpPa_2$/HC_6 ratios, using 10 mg of HC_6. **c** Permeance and salt rejection of HC_6-$TpPa_2$ membranes measured at 25 °C. Reproduce with permission from Ref. [48]. Copyright 2025 Elsevier. **d**–**f** Salt rejection efficiency of α-M3, β-M3, and γ-M3 membranes when tested with 1000×10^{-6} solutions of Na_2SO_4, $MgSO_4$, NaCl, and $MgCl_2$. Reproduce with permission from Ref. [49]. Copyright 2025 Elsevier. **g** Comparison of separation performance between RO membranes with and without DOTAP incorporation. **h** Long-term operational performance of the PES-B-TFC-1.5 membrane. Reproduce with permission from Ref. [52]. Copyright 2025 Elsevier

RO, however, presents notable disadvantages. Its operation demands high power input due to the high-pressure requirements, and a significant drawback is the need for careful disposal of concentrated brine. While FO is less energy-intensive than RO through membrane thickness and can be integrated with waste heat, the drawback of the process is lower NFRs and difficulties for the regeneration of the draw solution. Nanofiltration (NF) retains ions and small organic species and requires lower operating pressures than RO but requires pre-treatment to avoid membrane fouling and carries higher operating costs [44]. IER methods like strong-acid cation exchange resin (SAC) and strong-base anion exchange resin (SBA) are efficient for selective demineralization of water with the possibility of resin regeneration; however, these are less suitable for the treatment of high-salinity water and require many chemicals and regeneration processes. While MD also provides advantages, including energy efficiency and the enhancement of treating high-salinity water, there are some disadvantages that MD cannot avoid, including durability and the difficulty of scaling up membrane distillation [50]. ED and CD technologies accommodate the selectivity in ion removal and potential for energy recovery, but they have a relatively lower FWR compared to RO, and both require periodic electrode or resin regeneration [51]. Altogether, these methods depict a range of innovations for sustained freshwater production, where each of them has benefits complementary to stationary and operational technical challenges that are under constant research for enhanced practical application. Some of the examples are the study which investigates the synergy between substrate properties and synthetic liposomes in enhancing hollow fiber reverse osmosis (RO) membranes (Fig. 4g, h). By optimizing pore size (8.5 nm) and porosity and integrating DOTAP vesicles, the membrane achieved improved polyamide layer formation, boosting water permeability (0.48 to 8.30 L/(m^2·h) bar) and salt rejection (82.8% to 94.5%) under low pressure. The findings emphasize the critical role of substrate-nanomaterial interactions in optimizing interfacial polymerisation for high-performance, scalable desalination membranes [52].

Crystallization

Crystallization for desalination includes SRF and HY, each of which is a process aimed at driving salts out of water. SRF uses secondary refrigerants or cooling agents to cause the precipitation of salts from seawater or brackish water [53]. There are multistage flash (MSF) that uses heat and pressure to cause salt to crystallize in water; thermal vapor compression (TVC) which requires heat; and solar refrigeration which employs the use of solar power to cool. These methods are useful in attaining high FFR, but they consume a lot of energy to run and deal with salty wastewater. On the other hand, HY methods focus on something where chemical and/or electrochemical processes are used to flocculate salts from water, wherein the solution is enhanced using additives or an electric field is applied to cause flocculation [54]. This approach is flexible when it comes to the selection of ions of interest, but it comes with some chemical handling and disposal issues. Thus, both SRF and HY can be seen as fitting into the large objective of sustainable production of freshwater using technology, considering certain accommodations on energy consumption, waste management, and system complexity in water desalination processes.

Crystallization for desalination includes SRF and HY, each of which is a process aimed at driving salts out of water. SRF uses secondary refrigerants or cooling agents to cause the precipitation of salts from seawater or brackish water [55]. This study (Fig. 5a, b) explores how mechanical stirring affects freeze desalination (FD) performance using a custom-designed, jacketed cylindrical crystalliser. A 35 g/L NaCl solution underwent radial directional freezing under various stirring conditions. Without stirring, salt rejection increased brine density and caused ice to accumulate at the top. Stirring at 60 r/min disrupted thermal and solute gradients, improving salt removal efficiency from 59% to 67% without reducing ice yield [56]. There is multistage flash (MSF) that uses heat and pressure to cause salt to crystallize in water; thermal vapor compression (TVC) which requires heat; and solar refrigeration which employs the use of solar power to cool. These methods are useful in attaining high FFR, but they consume a lot of energy to run and deal with salty wastewater [57]. On the other hand, HY methods focus on something where chemical and/or electrochemical processes are used to flocculate salts from water, wherein the solution is enhanced through additives or an electric field is applied to cause flocculation. This approach is flexible when it comes to the selection of ions of interest, but it comes with some chemical handling and disposal issues [58]. Thus, both SRF and HY can be seen as fitting into the large objective of sustainable production of freshwater using technology, considering certain accommodations on energy consumption, waste management, and system complexity in water desalination processes. Another study (Fig. 5c–e) investigates the impact of ultrasonic vibration on seawater freeze desalination performance. Using a custom-designed ultrasonic-assisted crystallizer, experiments compared desalination efficiency with and without ultrasonic vibration. Results show that ultrasonic vibration improves desalination by forming smaller ice crystals, increasing salt removal efficiency by 18.18% to 67.86%, especially at higher salinities [59].

In thermal desalination, contaminants are removed from saltwater by evaporating it with heat and then condensing the vapor back into freshwater. This procedure uses techniques including vapor compression (VC), multiple-effect distillation (MED), and multistage flash (MSF). In contrast, membrane desalination uses electric potential or pressure to push saltwater through a semi-permeable membrane, rejecting contaminants. These methods include membrane distillation (MD), electrodialysis (ED), and reverse osmosis (RO). Based on variables such as feed water quality, energy consumption, environmental effect, capital and operating expenses, and product water quality, each desalination technique has advantages and disadvantages. Table 1 provides an overview of the benefits and drawbacks of the main desalination methods.

The selection of the most suitable desalination technology is a multifaceted decision, influenced by factors such as the availability and cost of energy sources, the quality and quantity of feedwater, desired product water specifications, environmental regulations, social acceptance, technical viability, reliability, and economic sustainability [66]. Table 1 provides a comparative overview of several desalination methods, highlighting their respective benefits and drawbacks. Each technology possesses inherent strengths. While RO generally offers superior output efficiency, its

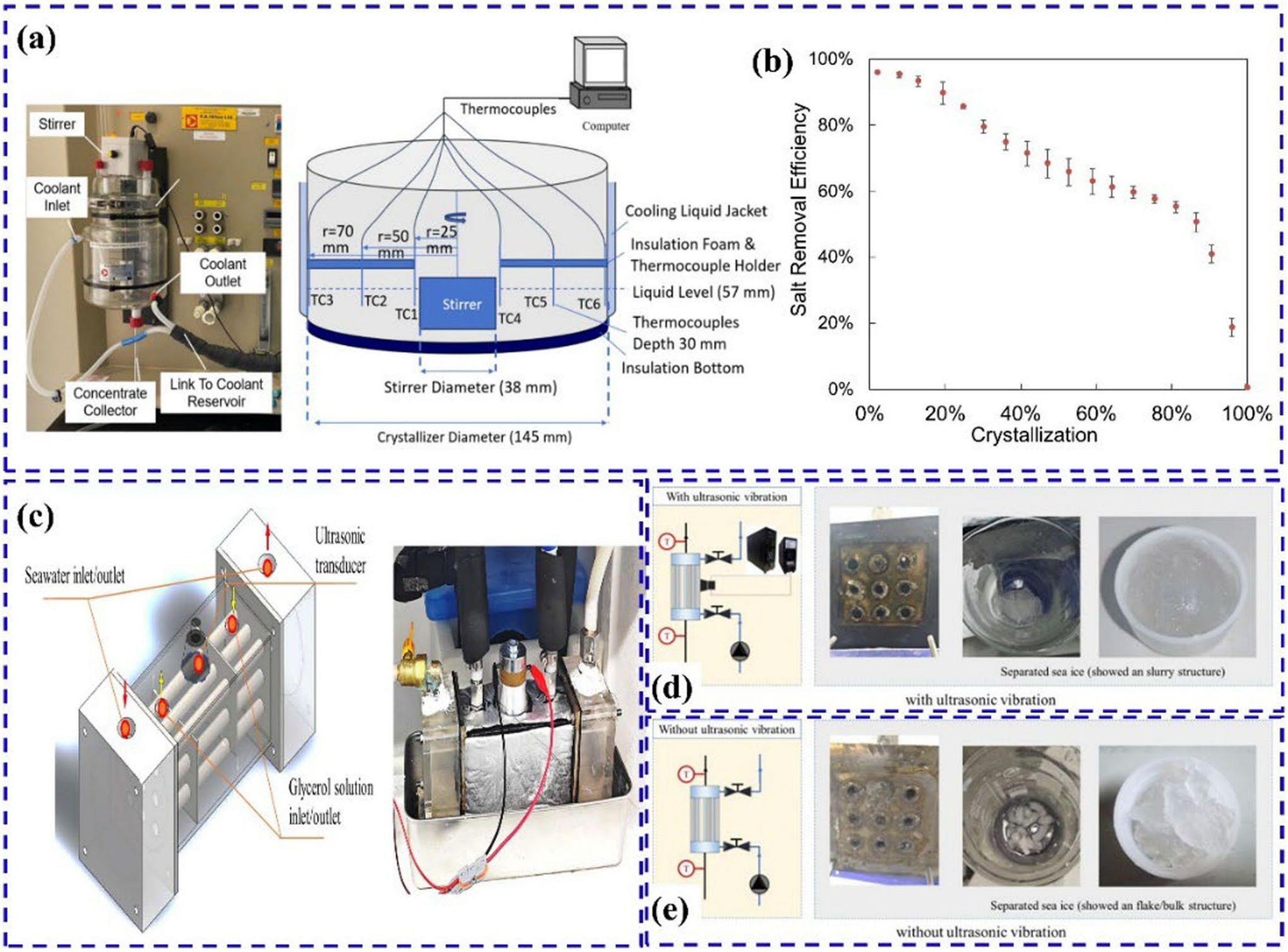

Fig.5 **a** Illustrations and setup of the freeze crystallizer system, including a diagram of the jacketed vessel with the stirrer and thermocouples, as well as the corresponding, and **b** salt removal efficiency as a function of crystallization. Reproduce with permission from Ref. [56]. Copyright 2025 Elsevier. c Diagram and actual image of the ultrasonic-assisted freeze crystallization system designed for seawater desalination. Experimental results showing the sea ice formation efficiency under the effect of d ultrasonic condition and e without ultrasonic conditions [56, 59]. Reproduce with permission from Ref. [59]. Copyright 2025 Elsevier

operational and investment costs are significant concerns due to its high-pressure requirements. Conversely, ED and MD are characterized by lower energy consumption, yet they typically necessitate substantial initial capital investment to establish operations. This balance between efficiency, energy demand, and capital outlay underscores the complex trade-offs involved in selecting an optimal desalination solution.

A promising field of study for water treatment is nanocomposites-based desalination. The application of nanocomposite materials that combine nanoparticles with other components to enhance their properties has been discovered to be very advantageous for desalination operations. Filtering membranes utilized in the desalination process included nanocomposites. Furthermore, they employed in an interfacial solar evaporator to improve desalination efficiency [27]. These nanocomposite membranes offer improved processability, rapid decontamination, a greater surface area, thermal stability, and selectivity for eliminating different types of contaminants.

Strategies for Solar Desalination

An extensive study into the use of solar electricity for steam generation has led to the development of the operating concept of a parabolic solar steam generator with the use of a solar absorber. The solar absorber, which is the central component of this system, is often made of extremely sophisticated materials with excellent absorptivity. These materials are efficient in generating heat from the sun. The design dictates which solar absorber is inserted into a solar collector, which can be a dish, a parabolic trough, or a flat-plate collector. Subsequently, the extreme heat is transmitted to the working fluid, which is typically water, and is pumped

Table 1 Advantages and disadvantages of different desalination methods

Sl	Description	Advantages	Limitations	Ref
1	Solar still	Eco-friendly Produces high-quality water Utilizes local materials Operates at a low cost with minimal maintenance	Low efficiency Requires a large area for installation	[60]
2	Solar chimney	Ecological sustainability Low water production costs Allows for the recovery of valuable by-products like salt	Large area and high capital investment Demands significant expertise and substantial construction materials	[61]
3	MSF	High efficiency and reliability Suitable for large-scale production High-quality distillate with minimal or no need for feed water pre-treatment Low operational complexity	High energy consumption Significant capital costs due to its heavy and complex plant design Corrosion issues can arise from high-temperature operations Low equipment lifespan	[62]
4	MED	No pre-treating the feed water It also consumes less thermal energy Energy efficient	Heavy and costly to install and maintain Corrosion issues	[63]
5	RO	Flexible and well-established operation Environmentally friendly Can be designed as a portable	Susceptible to biological fouling over time Their high-pressure operation drives up energy costs Membranes typically have a relatively short service life Increasing long-term expenses	[64]
6	HDH	Operational flexibility Suitability for decentralized applications It can utilize any form of low-grade energy, such as solar or waste heat, making it highly adaptable Low installation and operation costs	High capital cost and elevated water production expenses Operation requires many stages, which increases system complexity Higher maintenance and space requirements	[65]

through the absorber. Steam is produced when the working fluid's boiling point is reached because of the energy absorbed [67]. The resulting steam may be utilized for a variety of purposes, including the synthesis of hydrogen and drinking represent in Fig. 6a, b**.** To achieve optimum efficiency, tracking devices may be fitted to maintain the solar collector's orientation at the exact angle of the sun, enabling the system to utilize its full potential energy output throughout the day. By adding thermal insulation and a selective coating on the absorber to reduce heat losses, the solar steam generator's efficiency may be increased. Therefore, this mechanism may be viewed as a practical and environmentally good way to produce energy, supporting the trend toward clean and renewable energy sources worldwide.

Plasmonic Heating

Novel solar thermal vibration molecular technology can transform solar energy into a usable form of energy, like steam. This approach is based on the principles of molecular dynamics and vibration mechanics and uses a fast-heating methodology. To efficiently gather solar light and convert it into heat, a certain material is made, often a thin film or a nanomaterial. When the material is exposed to sunlight, it undergoes rapid temperature variations, which lead to random thermal vibrations among its molecules. This amount of energy is then used to phase-change the working fluid, typically water, into steam. Because the molecular vibrations technique works at a tiny level rather than bulk heating as in previous approaches, it is a simpler and more efficient way to transform solar energy into steam. The proposed method can increase energy conversion efficiency and scalability, making it an appealing way to advance solar thermal steam generation [68]. This technology is one of the advancements in solar energy augmentation for a variety of uses, such as industrial processes and electricity generation.

To effectively absorb and transfer solar energy, the thermal vibration technique in the solar steam-generating application needs materials that meet certain parameters. Graphene is a material that is quickly going to be a viable option due to its exceptional thermal conductivity and capacity to absorb solar radiation [69]. Its single layer of hexagonal structure gives it the ability to quickly sense chemical vibrations and temperature changes when exposed to sunlight. Graphene and carbon nanotubes are an excellent choice because of their tubular structure, which enables them to transport and absorb heat energy with remarkable efficiency. Researchers are drawn to them because of their remarkable traits. Because of their superior thermal stability and fast temperature response, titanium dioxide and zinc oxide were found to be the best metal oxides for this method [70]. Additionally, some polymers that have the right stability and heat conduction can be employed. The choice of material, which considers factors such as overall cost-effectiveness, thermal

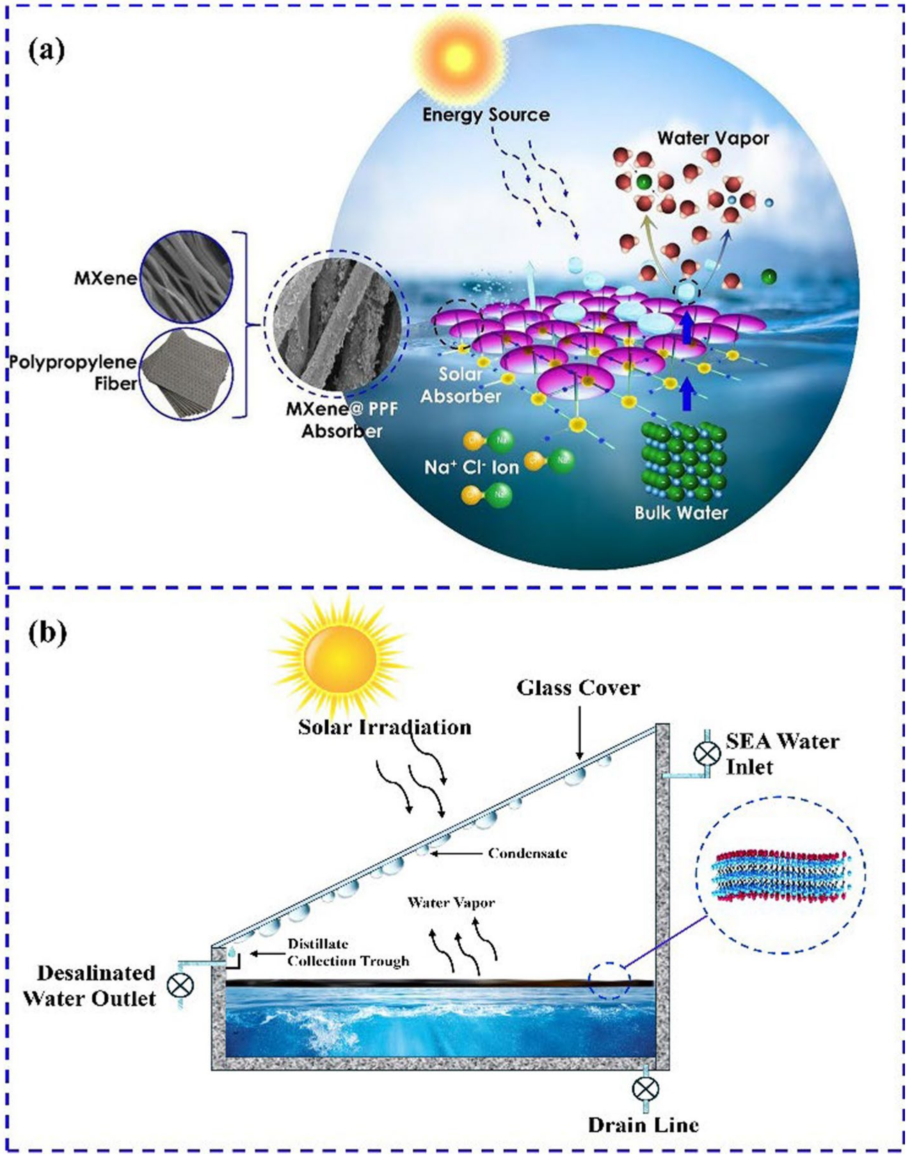

Fig. 6 **a** Mechanism of solar thermal desalination using composites. Reproduce with permission from Ref. [18]. Copyright 2024 Elsevier. **b** The setup for the solar thermal desalination experiment

efficiency, and stability in the face of sporadic temperature variations, is the most important one. As research advances, the optimization of these materials becomes increasingly important to fully realize the potential of the thermal vibration method for solar steam generation and open the door to sustainable, clean, and efficient energy production. Figure 7 illustrates several photothermal processes.

By using the minute vibrations that molecules undergo when exposed to light radiation, this technique claims to perform better than traditional methods. Because of the exact molecular dynamics and usage of nanomaterials, the approach can convert sunlight into steam more accurately and efficiently, which opens the prospect of greater scalability and flexibility in numerous applications [26]. The creation of materials that can withstand the severe environment of strong solar radiation and sudden temperature swings without losing their efficiency is still being researched, though. The intricacy of the technological challenges entailed in transforming molecular vibrations into meaningful labor increases, with early costs for material development and system calibration often being higher. The thermodynamic challenges associated with this technology and the continuous research and innovation aimed at this goal are crucial to fully realizing the potential of the trembling of the molecules method and paving the way for an energy-efficient and sustainable solar steam generation system.

Electron–Hole Generation

Through the electron excitation of the molecules, solar steam is created in this way of using solar energy to generate green power. Excitation of electrons within specially

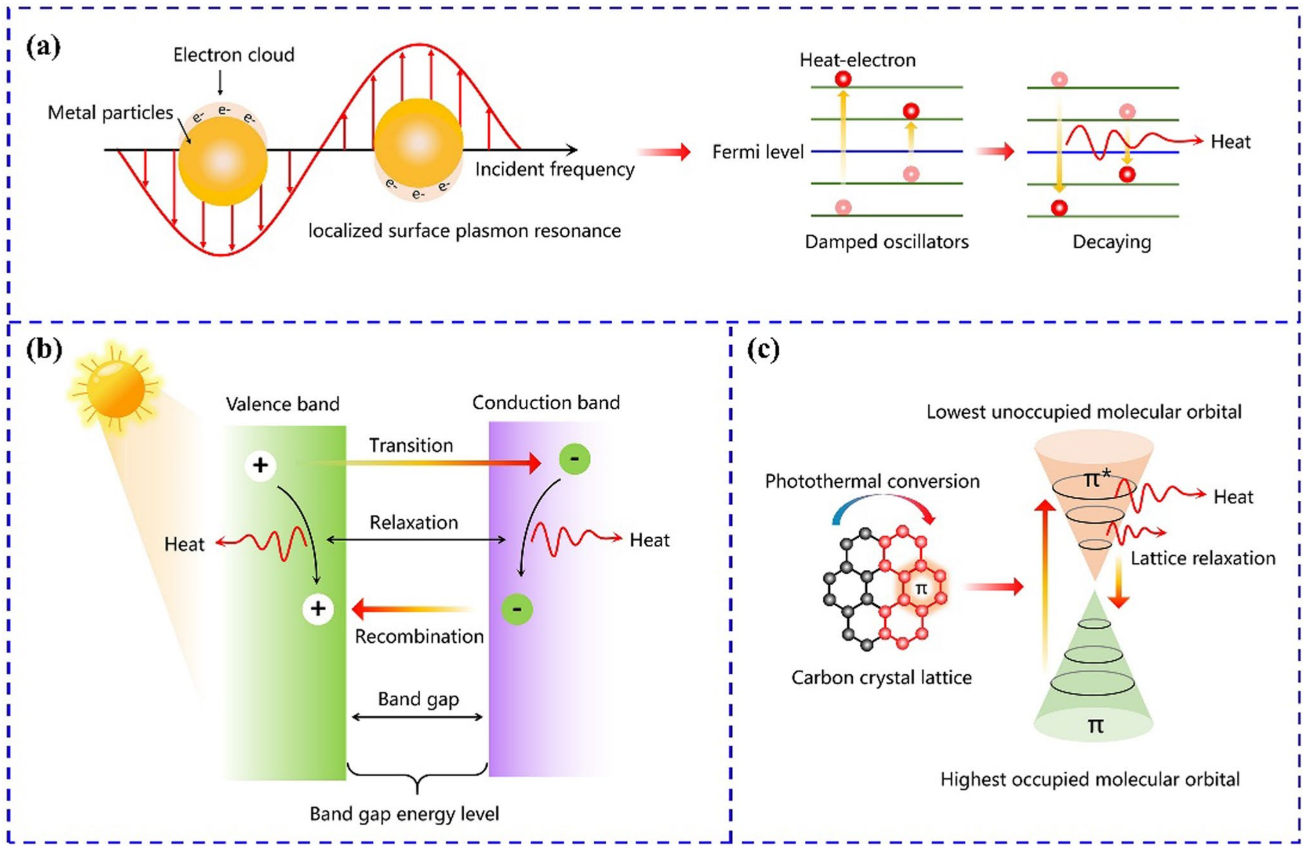

Fig. 7 Different methods of photothermal conversion mechanisms. Reproduce with permission from Ref. [71]. Copyright 2024 Elsevier

prepared molecules by sunlight results in the conversion of energy into heat and the production of steam. These materials represent a class of materials that have been precisely designed at the nanoscale to efficiently harvest and process solar radiation. When these materials are exposed to sunlight, they undergo electron excitation, which increases the electrons' energy. The energy released will be transformed to heat by the relaxation of these excited electrons later [72]. The thermal energy produced is then used to warm a suitable working fluid, often water, to produce steam, which is useful for a variety of tasks including industrial processes and the generation of electricity. Among the many advantages of the elision excitation of molecules technology are direct contact, higher conversion efficiency, and a high degree of molecular functioning. Although research and development are still in their early phases, the proposed technique offers promise for future growth in the field of solar steam generation. In addition, it is more environmentally friendly and sustainable than conventional energy sources. Using materials that are suitable for this approach, such as those with certain optical and electrical characteristics that permit photon absorption and electron excitation, is one of its advantages [73].

For the electron excitation approach, materials such as silicon (Si) and gallium arsenide (GaAs), well-known semiconductors for their ability to absorb photons and create electron–hole pairs when exposed to sunlight, are often explored. Due to their tunable bandgaps, semiconductor nanocrystals known as quantum dots can absorb light at certain wavelengths. Because of the size dependence of their electronic characteristics, they are suitable for effective light absorption and the subsequent activation of electrons. Zinc oxide (ZnO) and titanium dioxide (TiO_2) are two metal oxides that have semiconductor properties. They may undergo electron excitation when exposed to sunlight. Usually, solar-to-chemical conversion uses these components [74]. Additionally, there is a class of materials known as organic materials, which comprises conjugated polymers and small molecules that may also be made to undergo an electron excitation process. The choice of materials is determined by several parameters such as cost, stability, absorption spectra, and electron excitation efficiency. It also has a high potential for efficiency because of the direct electron excitation capability in carefully designed molecules, which enables it to convert solar energy into heat faster than existing methods. This method's molecular-level functioning may reduce heat loss and allow for precise regulation of energy conversion processes [75].

Thermal Vibration

Noble metals (e.g., silver and gold), as well as other plasmonic materials, have special features that are utilized in the plasmonic heating process [76]. Here, precisely manufactured nanoparticles, which usually form as nanospheres or nanorods, are selected for strong plasmonic resonances in the required spectrum, commonly in the visible or near-infrared. Because these nanoparticles readily absorb light under sunshine, light energy is focused and gathered via plasmonic resonances, resulting in localized heating in the region of the nanoparticles. The substance that has been heated locally is then introduced into the water that surrounds it, resulting in temperature rises and phase changes that generate steam [77]. The effective generation of plasmonic solar steam by the plasmonic heating approach is contingent upon the careful selection and design of plasmonic materials at the intended wavelength. Noble metals are the most utilized engineering materials because of their potent plasmonic properties; nevertheless, to produce structures that are more effective and beneficial, current research is concentrating on other materials, such as semiconductors. The method of creating solar steam using plasmonic-heated molecules has advantages and disadvantages [78].

Because plasmonic materials, particularly noble metals such as gold and silver, have large resonances in the visible and near-infrared spectrum, it is possible to efficiently absorb solar radiation and convert it to heat, which is why the resulting high potential efficiency is such a wonderful benefit. Steam is produced when the energy transformation process is carefully adjusted when nanoparticles are changed in the localized heating mode. Due to its flexibility and scalability, this technology may be used in a wide range of systems, from small personal computers to large industrial systems [79]. Nevertheless, there are several drawbacks, such as the materials' aging over time and their price in noble metals. Despite the potential usefulness of plasmonic materials, their cost may make certain large-scale applications unfeasible. It is also critical to consider how long these materials will endure in the severe environment of continuous solar radiation. The engineering difficulties in incorporating plasmonic nanoparticles into practical solar steam-generating systems must be considered.

Table 2 represents the advantages and disadvantages of different photothermal mechanisms where plasmonic heating offers several advantages, including strong absorption, rapid surface temperature increase, and high efficiency, making it beneficial for reducing heat loss. It is also scalable and adaptable for various applications. However, it comes with notable disadvantages, such as high costs, the tendency to degrade over time, and limitations in economic viability. Additionally, its implementation on a large scale can be challenging, hindering broader adoption. Electron excitation offers advantages such as broad spectral absorption, low cost, ease of preparation, and better chemical stability. However, it also has its drawbacks, including the need to withstand the stress of repeated excitation, challenges in optimization, and limited integration of materials, which can restrict its practical applications. Thermal vibration offers potential energy conversion, operates on a microscopic level, and requires less time for heating, making it efficient in certain applications. However, it also faces disadvantages, such as limitations in material selection, high system calibration costs, the need for specialized manufacturing materials, and the requirement for material optimization, which can complicate its implementation.

Interfacial Solar Evaporator

An interfacial solar evaporator is a small power station or advanced system that can capture the often-wasted sunlight to evaporate water or any other liquid. Customarily made from low-density materials such as carbon-based

Table 2 Advantages and disadvantages of solar steam generator photothermal

Sl.	Description	Advantages	Limitations	Refs.
1	Plasmonic heating	Strong absorption Rapidly increase the surface temperature Beneficial to reduce heat loss Relatively high efficiency Scalable and adaptable	Possesses high cost. Tend to degrade over time. Limitations of economic viability Difficult to implement on a large scale	[87]
2	Electron excitation	Broad spectral absorption Low cost Ease of preparation Better chemical stability	Required to endure the stress of repeated excitation. Difficult to optimize Limited integration of materials	[88]
3	Thermal vibration	Potential energy conversion Functions on a microscopic level Require less time for heating	Limitations of choosing materials High system calibration cost Requires manufacturing materials Require material optimization	[89]

aerogels or sponges, these devices can be used in a state where they are hovering above water or else located at the liquid–air boundary [82]. The outer structures are very selective for their large surface area and low thermal conductivity, thus facilitating the heating and absorption of the incoming radiation. This localized heating increases the rate of evaporation, which is much faster than distillation or similar processes. In Fig. 8**,** there are two main components of the interfacial solar evaporator: One is the photothermal layer, and the second one is the substrate materials.

Interfacial solar evaporators are used in a wide cross section of fields, some of which include desalination, water purification, and renewable energy technologies, for their need for quick and efficient evaporation. These, therefore, form an environmentally friendly alternative to other conventional evaporation technologies that rely on fossil fuels or electricity sources to heat boilers, which in turn evaporate water. Versatile for covering ranges from single household units to industrial-level systems, interfacial solar evaporators are promising to cover aspects of water scarcity and improve sustainable water management solutions.

Table 3 summarizes the role of substrate and coating materials in solar interfacial desalination. Selected photothermal materials for solar interfacial evaporators because of their capacity to absorb sunlight and transform it into heat. Such conventional materials are chosen depending on their transparency, heat conduction coefficients, wear resistance, and price. Organic compounds such as graphene and carbon nanotubes are widely used because of their high absorptivity in the sun's rays and good thermal characteristics. They get well heated up by sunlight, and after absorbing heat, the metal plate transfers that heat to the liquid interface. On the other hand, Substrate materials offer mechanical support and, in most cases, determine the efficiency of a given setup. Ideally, they should be light in weight and float on water and have low thermal conductance in order not to lose heat to the surroundings. Foam, sponges, and aerogels are preferred because of the large surface area on which a liquid can spread, and localized heating is desirable. These materials are normally chemically stable to resist the effects of water and sunlight for a given period, reducing the degradation of the efficiency of the interfacial evaporator system. In this regard, both photothermal and substrate materials are vital

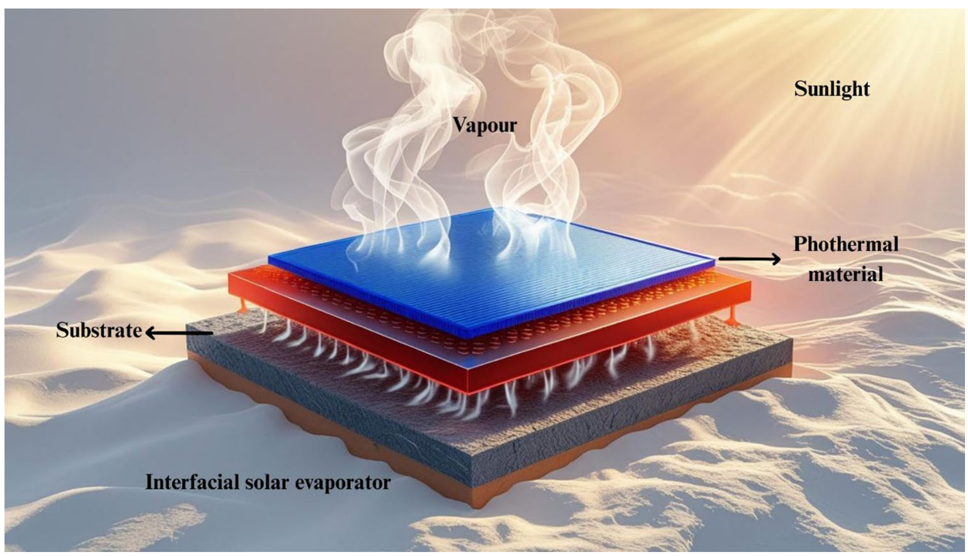

Fig. 8 Schematic illustration of the interfacial solar evaporator's components. Inspired by Ref. [83]. Copyright 2020, Wiley–VCH

Table 3 Summary of materials, their selection criteria, and scope of work

Sl	Description	The activity of the materials	Consideration for choosing the materials	Refs
1	Photothermal layer	Convert light into heat Transform water into steam Pass the heat to evaporate the water	High surface area High photothermal conversion efficiency High surface area High chemical stability Low cost	[84]
2	Substrate	Transport water for evaporation Make a barrier to transport heat into the bulk water body Resist the salt accumulation	Porous structure or able to make the porous structure Mechanical Stability High chemical stability UV-resistance Low cost	[85]

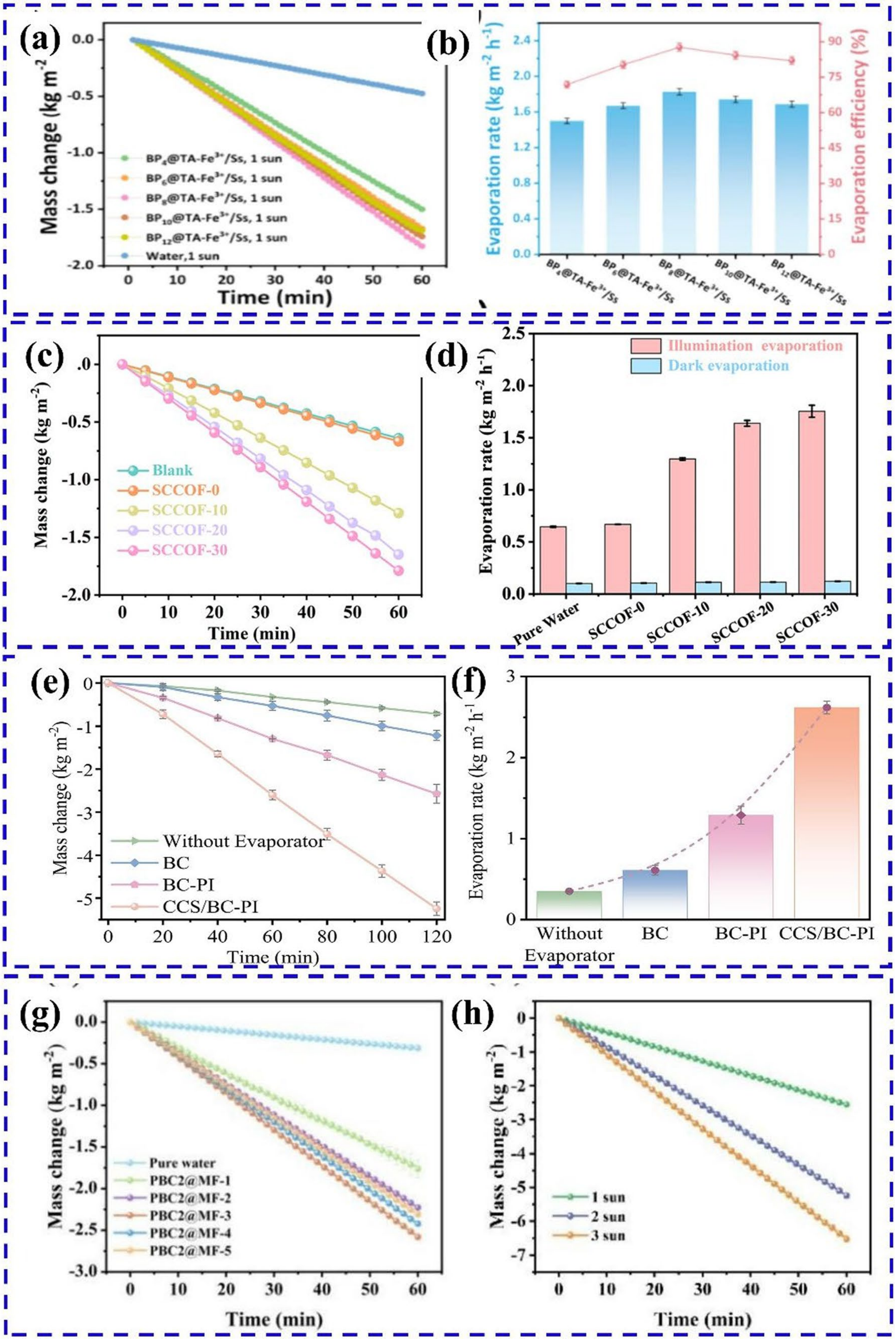
(a)
Mass change (kg m^{-2})
Time (min)
BP_4@TA-Fe^{3+}/Ss, 1 sun
BP_6@TA-Fe^{3+}/Ss, 1 sun
BP_8@TA-Fe^{3+}/Ss, 1 sun
BP_{10}@TA-Fe^{3+}/Ss, 1 sun
BP_{12}@TA-Fe^{3+}/Ss, 1 sun
Water,1 sun
(b)
Evaporation rate (kg m^{-2} h^{-1})
Evaporation efficiency (%)
(c)
Mass change (kg m^{-2})
Time (min)
Blank
SCCOF-0
SCCOF-10
SCCOF-20
SCCOF-30
(d)
Evaporation rate (kg m^{-2} h^{-1})
Illumination evaporation
Dark evaporation
Pure Water
(e)
Mass change (kg m^{-2})
Time (min)
Without Evaporator
BC
BC-PI
CCS/BC-PI
(f)
Evaporation rate (kg m^{-2} h^{-1})
Without Evaporator
(g)
Mass change (kg m^{-2})
Time (min)
Pure water
PBC2@MF-1
PBC2@MF-2
PBC2@MF-3
PBC2@MF-4
PBC2@MF-5
(h)
Mass change (kg m^{-2})
Time (min)
1 sun
2 sun
3 sun

Fig. 9 **a** Water mass change over time under one sun irradiation and **b** evaporation performance and efficiency for a solar interfacial evaporator at varying BP nanosheet concentrations. Reproduce with permission from Ref. [86]. Copyright 2025 Elsevier. **c** Time-based water mass change under sunlight, and **d** comparison of light and dark evaporation rates for SCCOF-0, SCCOF-10, SCCOF-20, SCCOF-30, and control seawater without an evaporator. Reproduce with permission from Ref. [88]. Copyright 2025 Elsevier. **e** Mass change trends and **f** evaporation rates for BC, BC-PI, and CCS/BC-PI aerogels, comparing no evaporator, under simulated seawater exposed to one sun. Reproduce with permission from Ref. [89]. Copyright 2025 Elsevier. **g** Water mass change using PBC2@MF at different heights over time under one sun exposure. **h** Water mass loss over time using PBC2@MF under different sunlight intensities. Reproduce with permission from Ref. [90]. Copyright 2025 Elsevier

in the design of solar interfacial evaporators and their functionality when it comes to the sustainable use of solar energy in water evaporation processes.

Photothermal Materials

Photothermal materials employed in solar thermal desalination systems play a crucial role in the conversion of solar energy to drive evaporation and purification of water. The materials chosen are receptors with high solar absorptance and low thermal emittance over a wide range of wavelengths. Selective absorber coatings of metal oxides or carbon-based materials that absorb heat in the visible and near-infrared part of the spectrum, where the solar radiation density is high, are other photothermal materials. A stable and efficient solar-driven interfacial evaporator is fabricated by using black phosphorus (BP) nanosheets coated with a tannic acid-Fe^{3+} complex to prevent oxidation and enhance photothermal performance. Integrated with sunflower straw and sodium alginate, the BP@TA–Fe^{3+}/Ss evaporator achieves a high evaporation rate of 1.826 kg/(m^2·h) and 87.6% efficiency under 1 sun (Fig. 9a, b). It demonstrates long-term stability, salt resistance, and effective purification of seawater and contaminated water, meeting WHO standards and offering a promising solution for sustainable water treatment [86]. Desalination technology employs carbon nanotubes and graphene with their thermal conductivity and ability to absorb light to improve the process of heat transfer and to bear high heat as is necessary during desalination [87]. With a flexible kind of structure, tunable optical features, and selectivity of light absorption, MOFs and plasmonic nanomaterials like metal nanoparticles can increase the energy conversion efficiency in the solar desalination process. An innovative solar evaporator using ionic covalent organic frameworks (i-COFs), synthesized via a Schiff base reaction, for efficient seawater desalination. i-COFs exhibit excellent solar light absorption, hydrophilicity, and low vaporization enthalpy (1819 J/g), enhancing interfacial water evaporation. When integrated into a sodium alginate-cotton fabric composite (SCCOF-30), the evaporator achieves an evaporation rate of 1.79 kg/(m^2·h) and 84.28% solar-to-vapor conversion efficiency under 1 kW/m^2 irradiation (Fig. 9c, d). It also removes up to 99.7% of ions, meeting WHO drinking water standards. This work highlights the potential of i-COFs in addressing global water scarcity through advanced photothermal materials [88]. These materials not only enhance the use of solar energy in thermal conversion but also propagate sustainable water treatment technology by cutting the dependence on fossil fuels and environmental pollution. Some of the recent study introduces a high-performance aerogel evaporator for solar-driven seawater desalination, combining bacterial cellulose and polyimide as the structural matrix with $CuCo_2S_4$ as the photothermal component. The system features tunable pores, efficient moisture transport, strong thermal insulation, and excellent light absorption. It achieves an impressive evaporation rate of 2.62 ± 0.08 kg/(m^2·h) and a high photothermal conversion efficiency of 97.7% under solar irradiation, offering a promising and competitive solution for sustainable freshwater production (Fig. 9e, f) [89]. Another study (Fig. 9g, h) presents a cost-effective solar-driven interfacial evaporator made by binding polydopamine-coated biochar to melamine foam (PBC_2@MF) via a simple one-step method. The optimized 3-cm PBC_2@MF costs only \$0.1508 and achieves a high cost-effectiveness of 54.74 g/(h·\$). It demonstrates excellent light absorption (96%), low water evaporation enthalpy (1844 J/g), and a high evaporation rate of 2.58 kg/(m^2·h) with 113% energy efficiency. Under enhanced convection and salinity, rates up to 6.80 kg/(m^2·h) were achieved, and 7.63 kg/(m^2·h) outdoors. Over 14 days of testing, daily evaporation exceeded 35 kg/m^2. With its low cost, high performance, and durability, PBC2@MF is a promising material for solar desalination [90].

Identification of suitable photothermal materials in solar thermal desalination systems is basic, and the criteria for selecting these materials should be a point of consideration to help achieve the best results with deterrence of the process. First, these materials must have high efficiency in absorption across the solar spectrum, predominantly in the regions of the spectrum with high solar flux density. Thermal stability is crucial for withstanding the high temperatures used in desalination and maintaining integrity without deterioration over time [91]. High thermal conductivity is desirable for efficient heat transfer within the system, which is required for the evaporation and condensation of water. Another aspect is also the costs and possible economies of scale, as well as material compatibility with already available production methods [10]. Furthermore, location and environmental issues are critical, which means that the materials must be non-hazardous, green, and possibly reusable. Durability and non-stick or non-corrosive attributes guarantee optimum implementation for the entire length of that system. Incorporating these criteria, the researchers' goal is to establish photothermal materials with high conversion efficiencies, low utilization costs, and high utilization for solar thermal desalination, which is beneficial for guaranteeing global water safety.

Photothermal materials provide significant advantages for solar thermal desalination systems by efficiently converting sunlight into thermal energy. Table 4 represents the advantages and disadvantages of different photothermal materials. Their high absorption efficiency across the solar spectrum ensures effective utilization of solar radiation, particularly in regions with abundant sunlight [109]. This capability not only enhances the overall energy conversion efficiency but also reduces reliance on fossil fuels and grid electricity, thereby promoting energy sustainability and lowering operational costs over time. Photothermal materials are versatile and can be integrated into various types of solar collectors and absorbers, accommodating diverse geographical and environmental conditions. This scalability makes them suitable for both small-scale applications, such as household water purification, and large-scale industrial desalination plants [110]. Additionally, using photothermal materials helps mitigate environmental impact by minimizing carbon emissions and reducing freshwater consumption through the conversion of seawater or brackish water into potable water.

Substrate Materials

Materials of the substrate in solar thermal desalination systems act as components that provide a structural framework and enhance the efficiency of the photothermal component, which is useful in converting solar irradiance into thermal energy. Figure 10a–e presents an environmentally friendly anisotropic porous cellulose (APC) hydrogel evaporator, inspired by natural wood and fabricated via a freeze-casting method. Its vertically aligned

Table 4 Comparison of photothermal materials, highlighting their pros and cons

Sl	Composite type	Advantage	Disadvantage	Refs
1	CNT's nanocomposite	Better conductivity Higher absorption capacity Possible added benefits of corrosion resistance Longer-lasting facilities	High cost of production Difficulties in fabricating Unpredicted stability	[92, 93]
2	Graphene nanocomposite	High thermal conduction Large surface area Superb mechanical strength Lightweight properties	Costs of production are high Large-scale production proves to be a challenge Stability and compatibility issues	[94]
3	Zeolites based	Enhanced adsorption of water Heat stability	Low coefficient of thermal conductivity Degradation problems in high-temperature and high-saline concentrations	[95, 96]
4	MXenes nanocomposite	Good thermal conductivity Moderate stability in corrosive environments Lightweight and flexible manner High photothermal conversion efficiency	Scalability issues	[20, 97, 98]
5	Nanofibers composite	Higher surface area Better heat transfer efficiencies Lightweight and has high pliability Relatively low costs	High production costs Complex and elongated manufacturing process Scalability for large-scale applications Degradations in durability under long-term exposure	[99]
6	Bimetallic nano composite	Light absorption due to the presence of surface plasmon resonance Better solar thermal conversion Permit optimum heat focusing and transmission Low heat dissipation	Expensive processing costs Instabilities and degradation in direct solar radiation	[100–102]
7	Magnetic nanocomposite	Ability to absorb light at various wavelengths Durable heat transfer Potentially lower fabrication costs	Poor spectral selectivity compared to plasmonic materials Can oxidize and lose their properties in corrosive environments	[103–105]
8	Janus particles nanocomposite	Enhance light absorption and heat-trapping Control over the outermost surface characteristics	Synthesis complications Controlling the orientation in arrangements Challenges in scaling Challenge of achieving uniform distribution	[106–108]

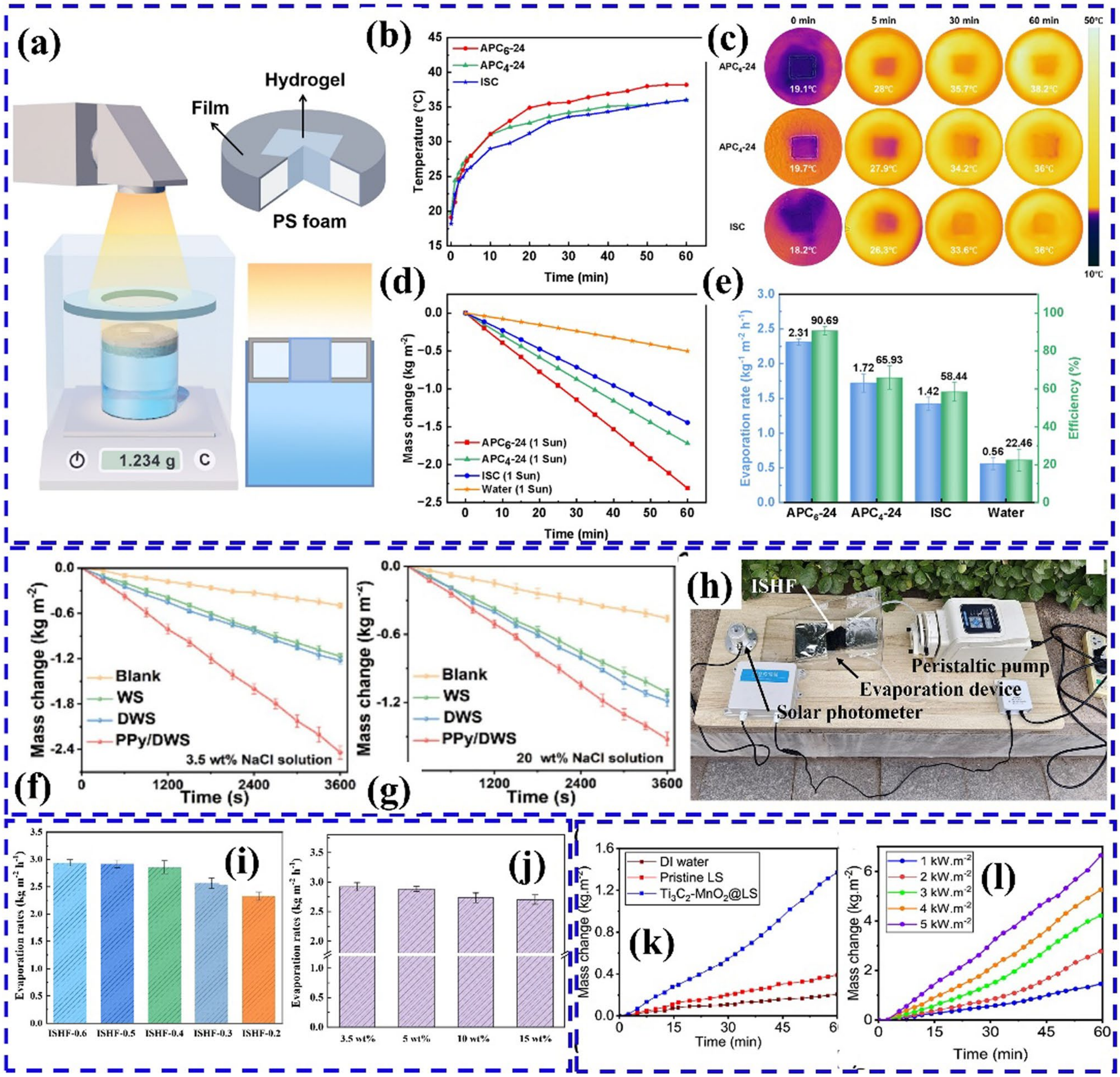

Fig. 10 **a** Diagram of the custom-built solar evaporation setup made of anisotropic porous cellulose (APC) hydrogel evaporator. **b** Surface temperature changes of the APC evaporators under one sun irradiation. **c** Infrared thermal images showing surface temperature distribution of APC evaporators under one sun. **d** Water mass loss and **e** corresponding evaporation rate and efficiency of the APC evaporators. Reproduce with permission from Ref. [112]. Copyright 2025 Elsevier. Time-based water mass change of the fabricated PPy/DWS evaporator in **f** 3.5 wt% and **g** 20 wt% NaCl solutions under solar illumination, respectively. **h** A customized ISHF evaporator. Reproduce with permission from Ref. [111]. Copyright 2025 Elsevier. **i** Evaporation rates of the ISHF system at varying HMFO loadings in 3.5 wt% brine. **j** Photothermal evaporation rates of the ISHF evaporator tested in different saline concentrations under 1 kW/m^2 light intensity. Reproduce with permission from Ref. [116]. Copyright 2025 Elsevier. **k** Time-dependent water mass loss for water alone, untreated LS, and Ti_3C_2-MnO_2@LS under one sun for a solar steam generation using the Ti_3C_2-MnO_2@LS system. **l** Evaporation efficiency of the Ti_3C_2-MnO_2@LS system under varying solar intensity levels. Reproduce with permission from Ref. [98]. Copyright 2023 Elsevier

porous structure enables efficient water transport, strong mechanical properties, and excellent salt resistance. With a low evaporation enthalpy (1657 J/g) and high photothermal performance, it achieves an evaporation rate of 2.31 kg/(m^2·h) and 90.69% efficiency under 1 sun. The APC evaporator offers a sustainable, high-performance solution for seawater desalination and water purification [111]. They are primarily employed in evacuated tube collectors or any form of high-efficiency solar thermal system. A sustainable, self-cleaning solar evaporator using polypyrrole-coated delignified wood spheres (PPy/DWS) to eliminate microplastic pollution risks from plastic-based systems has been studied. The eco-friendly, self-rotating design prevents salt accumulation, ensuring consistent performance. Under 1 sun, it achieves an evaporation rate of 2.43 kg/(m^2·h) in 3.5 wt.% saline and maintains 1.52 kg/(m^2·h) in 20 wt.% salinity for over 8 h (Fig. 10f, g). This system offers a stable, efficient, and environmentally safe solution for seawater desalination and clean water production [112]. Most metal substrates, such as aluminum, stainless steel, and copper, are preferred because of their high thermal conductivity, which enables enhanced heat transfer from the photothermal layer to the working fluid of the desalination process [113]. These substrates are also very hard wearing and ideal for the manufacturing of both flat-plate collectors and CSP systems. Due to their higher thermal stability and larger mechanical strength, alumina, and silicon carbide ceramic substrates are preferred when the product is expected to work under high temperatures and environmental stress [114]. The use of polymer substrates enhances flexibility and lowers weight, making them suitable for portable or flexible solar collectors and membrane-based desalination systems [115]. A novel solar-powered ion-selective hydrogel@fabric (ISHF) evaporator incorporates $H_{1.5}MnFe_2O_4$ (HMFO), a material with high photothermal efficiency and strong lithium selectivity. The ISHF system achieves simultaneous freshwater production and lithium extraction from seawater, with an evaporation rate of 2.93 kg/(m^2·h) and a Li^+ adsorption capacity of 879.4 mg/m^2 under 1 kW/m^2 solar irradiation (Fig. 10h–j). Featuring excellent salt resistance and a Janus structure generating 176.4 mV, this work offers a dual-solution strategy for water scarcity and lithium resource recovery [116]. For photothermal coating, glass substrates are desirable due to their transparency and resistance to weather, which keeps the coatings safe as well as provides for the correct transmittance of light in flat-plate collectors and solar stills. For every material used as the substrate, thermal characteristics, durability, and the compatibility with the photothermal materials are decided, which in turn enables solar thermal desalination technologies to produce freshwater sustainably out of seawater or brackish water [117]. One of the recent studies (Fig. 10k, l) introduces a biodegradable solar evaporator made from a luffa sponge coated with a Ti_3C_2-MnO_2 (MXene/MnO_2) nanocomposite. The coating enhances solar absorption, hydrophilicity, and stability, while the sponge's porous, insulating structure supports efficient water transport and heat localization. The Ti_3C_2-MnO_2@LS evaporator achieves a high evaporation rate of 1.36 kg/(m^2·h) and 85.28% solar-to-steam efficiency under one sun. It also shows excellent salt rejection and wastewater purification, highlighting the promise of combining 2D materials with natural biomass for sustainable desalination [98].

Thus, the requirements for the selection of substrate materials in STDS are as follows: First, thermal conductivity is the parameter of interest because a substrate should be able to drain heat from the photothermal layer to the working fluid of the desalination process, such as seawater or brine [118]. Such substances as metals (aluminum, stainless steel, and copper) will be used because of their good conduction of heat, thus enhancing the conversion of energy. Secondly, mechanical stability is necessary to cope with severe mechanical stresses, for example, when used in solar thermal processes without bending or corroding. Ceramic materials such as alumina and silicon carbide are preferred in design for solar steel desalination system because of their superior thermal stability and structural integrity. Their high thermal stability and exceptional mechanical strength are essential for components directly or indirectly exposed to intense solar radiation and severe environmental conditions, ensuring reliable long-term operation [119].

Another selection criterion involves toughness, as substrates must endure mechanical loads, corrosion from seawater, and weather conditions in the course of their service delivery lifetime. Also, compatibility with photothermal materials and manufacturing processes guarantees the right depositing and functioning of the adherend, ultimately improving the efficiency of the overall system. Finally, cost factors, weight issues, and the impact on the environment determine the kind of material that will be used in the implementation of solar thermal desalination technologies in a way that meets all the necessary performance criteria in the most efficient manner and at the same time does not pose any problems in the process of implementation [120].

The applicable use of substrates or support materials in the system of solar thermal desalination has benefits that are also vital to increasing effectiveness and performance stability. Table 5 represents the advantages and disadvantages of different substrate materials. First, the substrate supports and thermally isolates photothermal coatings and their conversion from solar irradiance to the desalination process. High heat transfer coefficient materials (e.g., metal, particularly aluminum, and copper) are desirable for electrical and thermal components, respectively, to aid heat distribution and control encountered in converting the energy in electrical systems [137]. Secondly, substrates such as ceramics (e.g., alumina, silicon carbide) improve the system's durability because of their high thermal shock, chemical stability, and mechanical stability, thus increasing the lifetime of the solar collection and absorption in aggressive environments [138]. Further, the substrates can be designed in many ways to suit the required specifications, for instance, flexible polymer substrates for portable or modular devices or transparent glass substrates for improved light transmission in flat-plate

Table 5 A comparison of the advantages and disadvantages of different substrate materials

Sl	Substrate type	Advantage	Disadvantage	Ref
1	Metal-based substrate	High thermal conductivity High mechanical strength Strong endurance when exposed to heat Recyclable	Corrosion from saline solutions Adding cost Layering complexity Heat loss when not controlled	[121, 122]
2	Non-metal based substrate	Corrosion-resistant Lightweight Easier to maintain and easier to transport	Lower thermal conductivity Vulnerable to mechanical deterioration	[123, 124]
3	Ceramics-based substrate	High thermal stability Chemical non-reactivity and durability Desirable mechanical properties of high strength and durability	More costly	[125, 126]
4	Bio-based substrate	Sustainable materials Lightweight Inexpensive Bio-degradable	Low crack-resistant Less life Need further processing or a protective layer to enhance their durability	[127, 128]
5	Polymer-based substrate	Low cost They are light, can be made very flexible Polymer substrates are less prone to corrosion	Require additional treatment or need a protection layer to increase their useful life	[129, 130]
6	Aerogel-based substrate	Extremely low density Highly porous and, best of all, exhibit thermal insulation They reduce heat transfer losses	Mechanically delicate and prone to damage during handling and installation Expensive to produce compared to conventional substrates	[131, 132]
7	Carbon-based substrate	High thermal conductivity High mechanical strength Chemical inertness	Comparatively higher cost It can also be susceptible to oxidation or degradation in some environmental conditions	[133, 134]
8	Waste Based	Relatively cheap Derived from recycled waste Better uptake of energy and can even be tailored Minimizing carbon emission impacts	Non-uniform and quite unpredictable	[135, 136]

collectors [139]. In conclusion, the right combination and incorporation of substrate materials in solar thermal desalination are critical to enhancing the efficiency, durability, and sustainability of the system to produce freshwater at a low cost and in an environmentally friendly way from seawater or brackish water.

Composites for Solar Interfacial Desalination

A variety of research has been published to enhance the performance of solar interfacial desalination, with varying outcomes due to differences in material characteristics. Some materials demonstrate high stability but show lower efficiency, often because their photothermal conversion efficiency is limited [140]. A novel bilayer anisotropic hydrogel (DPGCH) composed of graphene oxide, cellulose nanofibers, and polyvinyl alcohol, is designed to enhance solar-driven interfacial evaporation (SDIE) for desalination. Leveraging the Hofmeister effect and a directional structure, DPGCH achieves high evaporation rates and stability, even in high-salinity seawater, as evidenced in Fig. 11a–d. It demonstrates excellent efficiency-up to 92.9% in pure water and 77.0% in 20 wt% saline, making it a scalable and efficient solution for addressing global freshwater scarcity [141]. These materials may have longer lifespans but struggle to convert sunlight into heat effectively, thus reducing overall desalination performance [142, 143]. On the other hand, some materials excel at photothermal conversion, generating significant heat from sunlight, but tend to suffer from lower stability over time. A fabric-interleaved aerogel (FIA), combining a 3D chitosan/carbon-black aerogel with a 2D cotton fabric developed to enhance solar-driven seawater desalination. FIA achieves high solar absorption (96.78%) and an impressive evaporation rate of 2.67 kg/(m^2·h) under 1 sun (Fig. 11e–g). Its flexible and multilayered design ensures efficient water transfer and salt separation, offering a scalable and effective solution for solar-powered desalination [144]. These materials might initially perform well but degrade faster, affecting long-term efficiency and reliability [145]. Table 6 provides an overview of various studies, illustrating how different materials behave in solar interfacial desalination. It highlights the trade-off between photothermal efficiency and material stability, showing how researchers are working to find a balance [146]. In many cases, materials with high photothermal efficiency are being optimized for better stability, while stable materials are

Fig. 11 The solar evaporation performance of DPGCH hydrogels at various salt concentrations (0–20 wt%) in **a** rate of mass variation, **b** evaporation rates and energy efficiency, **c** DPGCH morphology before and after 8 h of desalination (3.5 wt% saline), and **d** DPGCH evaporation rate and efficiency over repeated 8-h desalination cycles (3.5 wt% brine). Reproduce with permission from Ref. [141]. Copyright 2025 Elsevier. A fabric-interleaved aerogel (FIA) evaporator with its achieved e mass variation of NaCl solution, CF, CFCS, and FIA-15 under solar illumination, f water mass change for FIA-0, 5, 10, 15, and 20 under one sun, and g FIA-15 mass change under different evaporation configurations (60 min, 1 sun). Reproduce with permission from Ref. [144]. Copyright 2025 Elsevier. h The experimental setup for solar evaporation and salt crystallization using a porous Janus CNF-MXene composite and its i rate of water mass loss during solar evaporation test. Reproduce with permission from Ref. [148]. Copyright 2025 Elsevier. Performance of a 3D Ag@rGO interfacial evaporator: j long-term outdoor desalination of 72 h with 3.5 wt% saline and k average evaporation rates [141, 144, 148, 149] Reproduce with permission from Ref. [149]. Copyright 2024 Springer Nature

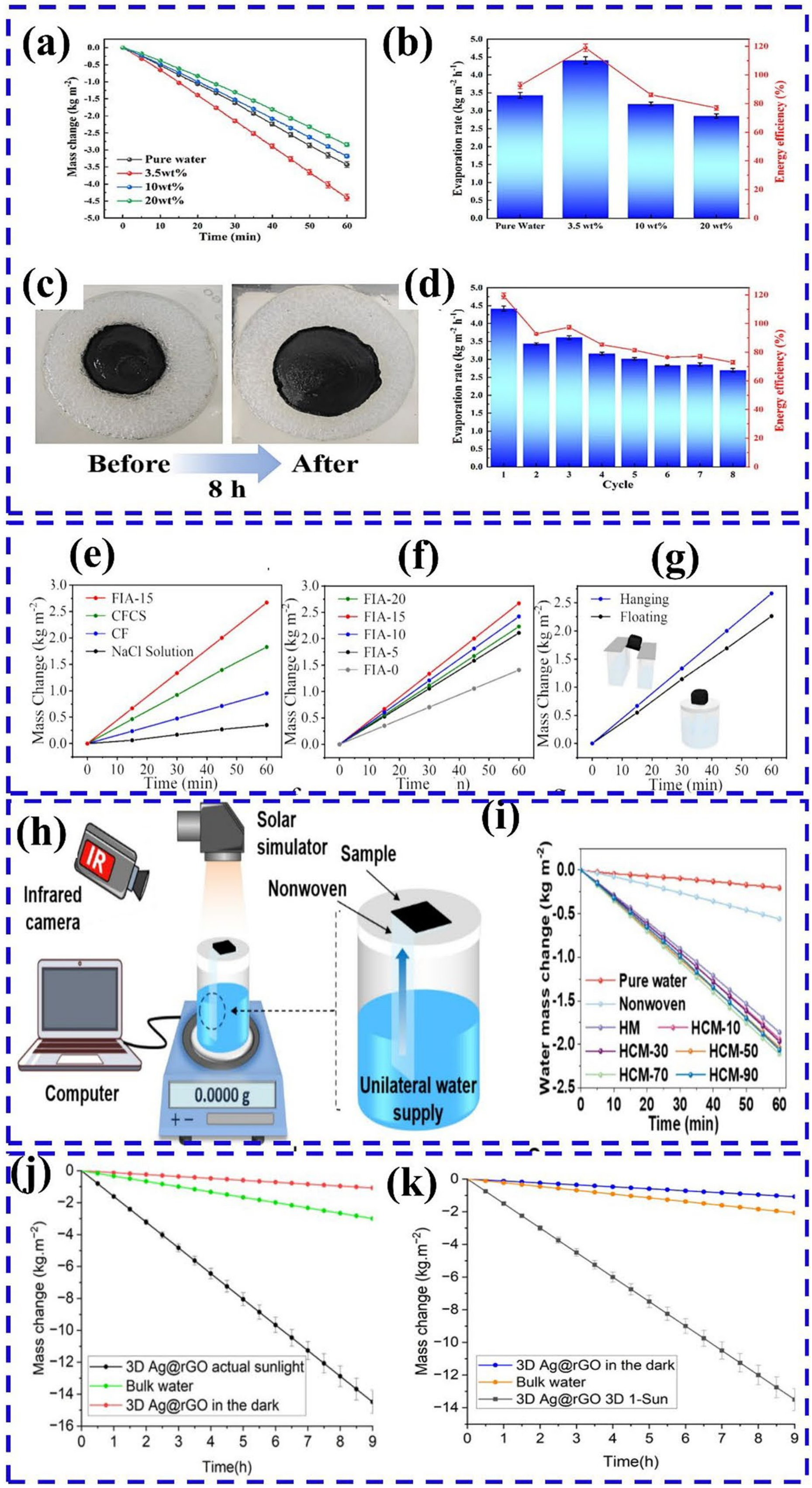

Table 6 A summary of the performance of different composite materials for solar interfacial desalination

Materials description	Coating materials	Substrate materials	Solar irradiation (kW/m^2)	Evaporation rate (kg/(m^2·h))	Efficiency (%)	Ref
TiO_x-SS mesh	TiO_x	SS mesh	1	0.8	50.3	[150]
CuS/PE	CuS	PE	1	1.0	63.9	[151]
CuS/SCM	CuS	SCM	1	1.0	68.6	[152]
Biochar-based	Biochar	–	1	1.2	80	[153]
rGO-MWCNT/PVDF	rGO & MWCNT	PVDF	1	1.2	80.4	[154]
CuS/MCE	CuS	MCE	1	1.1	80	[155]
CNT silica	CNT silica	–	1	1.3	82	[156]
Copper nanodot/N-doped graphene	Graphene	–	1	0.6	82	[157]
Au- NP/PBONF	Au- NP	PBONF	1	1.4	83	[158]
N-doped graphene	Graphene	–	1	1.5	80	[159]
PHT foam	–	PHT foam	1	1.1	80.5	[160]
Carbonized melamine foam	–	Melamine foam	1	1.2	87.3	[161]
Carbon sponge	–	Carbon sponge	1	1.3	90	[162]
N-doped graphene/carbon hybrid aerogel	Graphene	Carbon hybrid aerogel	1	1.5	90	[163]
Fe_3O_4@C film	Fe_3O_4	C film	1	1.0	67	[164]
CNT/tree stump	CNT	Tree stump	1	1.2	67.8	[165]
C-wood	–	Wood	1	1.0	68	[166]
C-paper	–	Paper	1	0.9	70	[167]
Pencil-drawn/paper	Lead	Paper	1	1.0	70	[168]
Activated carbon fiber felt	Activated carbon	Carbon fiber felt	1	1.2	79.4	[169]
GO-PS	Graphene oxide	PS	1	1.4	80	[170]
Graphite/wood block	Graphite	Wood block	1	1.2	80	[171]
$PMoS_2$-CC/PS	$PMoS_2$	PS	1	1.3	80.5	[172]
PPY cotton	–	Cotton	1	1.2	82.4	[173]
Ink stained paper/MTS	Ink	Paper	1	1.2	85.5	[174]
Carbonized wood/MTS	–	Wood	1	1.4	91.3	[175]
p-PEGDA-PANi	p-PEGDA	PANi	1	1.4	91.5	[176]
TiO_2-PDA/PPY/cotton	TiO_2-PDA	PPY/cotton	1	1.5	98	[177]
Cu_2ZnSnS_4/PU	Cu_2ZnSnS_4	PU	1	1.4	84.5	[178]
VPPyNWs-fabric (3D cone)	VPPyNWs	Fabric	1	2.3	98.5	[179]
MXene-TiO_x (3D inverted cone)	MXene & TiO_x	–	1	2.0	92	[180]
Carbon foam	–	Carbon foam	1	1.5	86	[181]
rGO-silk fabrics	rGO	Silk fabrics	1	1.4	81	[182]
PDA c fiber	PDA	Carbon fiber	1	1.8	103.7	[183]
$LaNiO_3$ (3D cone)	$LaNiO_3$	–	1	1.3	95	[184]
$LaCoO_3$ (3D cone)	$LaCoO_3$	–	1	1.4	83	[184]
Zn doping 1 T-MoS_2 (3D flower)	Zn doping 1 T-MoS_2	3D flower	1	3.4	-	[185]
Carbonized Cattail	–	Cattail	1	4.1	105.8	[186]
PAN/CNT's (3D pyramid)	PAN/CNT's	–	1	2.6	-	[187]
Hydrophobic ASA (3D cone)	–	Hydrophobic ASA	1	1.7	107.8	[188]
LMTE nanodroplets	LMTE nanodroplets	–	1	2.9	96.9	[189]
Tannic acid and iron (III) (3D cone)	Tannic acid & iron (III)	3D cone	1	1.9	94.4	[190]
Bionic	–	Bionic	1	4.1	92.1	[191]
Dopamine coated hydrogel-based carbon	Dopamine	Hydrogel	1	1.0	-	[192]
Biomass-based carbon particle	–	Biomass	1	1.6	93.4	[193]
Bilayer polymer foam	–	Polymer foam	1	1.4	90	[194]

Table 6 (continued)

Materials description	Coating materials	Substrate materials	Solar irradiation (kW/m^2)	Evaporation rate (kg/(m^2·h))	Efficiency (%)	Ref
MnO_2 nanowire reduced graphene oxide	rGO	MnO_2 nanowire	1	1.5	90.4	[195]
MXene/AC@Luffa	MXene & activated carbon	Luffa	1	1.8	89.8	[20]
MXene/MnO_2@Luffa	MXene & MnO_2	Luffa	1	1.3	85.2	[98]
CLS	–	Luffa	1	3.7	-	[196]
3D hydrogel evaporator	Hydrogel	–	1	4	93	[197]
HNG/PVA/PPy	HNG	PVA/PPy	1	3.2	94	[198]
Carbonized farm waste		Firm waste	1	2.8	98	[199]
rGO/$TiTe_2$	rGO & $TiTe_2$	–	1	2.0	87.7	[200]
Bio-hydrogel	–	Hydrogel	1	2.8	91.1	[201]

being modified to improve their photothermal conversion capabilities [147]. Another past study (Fig. 11h, i) presents a novel solar evaporation-based salt crystallization system for zero liquid discharge (ZLD), using a composite of cellulose nanofibrils (CNF) and MXene with a porous Janus structure. The design separates the salt crystallization and solar absorption surfaces, enabling efficient water transport and minimizing salt buildup. Capillary-driven vertical flow and lateral water pathways create salt gradients, enhancing performance. The system achieves an evaporation rate of 2.14 kg/(m^2·h) and salt collection rate of 0.23 kg/(m^2·h) with 96.9% salt separation efficiency under 1 sun. This work offers a promising, low-cost, low-carbon solution for scalable solar-powered ZLD applications [148]. Understanding the behavior of these materials is crucial in developing more effective and durable solutions for solar desalination. This ongoing research aims to optimize both the performance and longevity of materials used in solar interfacial desalination systems. A novel 3D interconnected Ag-doped reduced graphene oxide (rGO) network also has been developed for efficient solar-driven interfacial desalination (Fig. 11j, k). The material, developed via controlled hydrothermal reduction, offers high photothermal conversion efficiency (~97.54%), excellent water evaporation rates (1.40–1.50 kg/(m^2·h)), and strong salt rejection. Its porous, hydrophilic structure ensures effective heat localization and water transport, while outdoor tests confirm real-world applicability without salt accumulation over 54 h. This work highlights the material's potential for sustainable, high-performance saline water desalination [149].

One of these studies explores the use of MXene@GF (GF-Graphite) for enhancing thermal desalination while promoting sustainability. The MXene composites achieved a solar evaporation rate of 3.0 kg/(m^2·h) and a high solar steam conversion efficiency of 96.03%. Extensive characterization, including SEM, FESEM, EDX, XRD, and BET analysis, confirmed the materials' mechanical robustness, thermal stability, and resistance to acidic, alkaline, and saline environments. This research highlights the potential of MXene composites as a sustainable, energy-efficient solution for water desalination, offering both ecological and economic benefits. The findings underscore the importance of using renewable materials in developing environmentally friendly desalination technologies [19]. Another research presents a novel solar evaporator made from $Ti_3C_2T_x$ MXene coated over carbon-enhanced cellulose fibers (CCF), called $Ti_3C_2T_x$ MXene@CCF composite, for solar water desalination. Under 1 sun exposure, the composite achieves an impressive evaporation rate of 3.8 kg/(m^2·h), demonstrating its efficiency. Furthermore, it maintains water purity, meeting World Health Organization (WHO) standards. This sustainable approach reduces reliance on fossil fuels and lowers environmental impacts, offering a promising solution for energy-efficient, cost-effective desalination [202]. In another study a novel $Ti_3C_2T_x$ MXene-decorated polypropylene fiber (PPF) composite as a photothermal absorber for solar desalination. The composite demonstrates a high evaporation rate of 4.63 kg/(m^2·h) and an impressive solar evaporation efficiency of 93.48% under 1 sun exposure. The $Ti_3C_2T_x$ MXene@PPF absorber excels in system stability, maintaining performance despite temperature fluctuations, pH variations, and mechanical stresses. It also shows excellent mechanical stability, chemical resistance (including in acidic and alkaline conditions), and strong salt tolerance, ensuring consistent evaporation over extended periods. Beyond desalination, its salt-preserving and filtration properties make it a promising candidate for wastewater treatment. This scalable and cost-effective material offers high efficiency and versatility, presenting a sustainable solution for solar water purification and wastewater treatment across various water contaminants. The study highlights the potential of this composite for both desalination and environmental cleanup applications [18].

Future Direction

To sum up, great potential remains for coating materials in solar interfacial desalination, driven by advancements in several key areas. First, current research consistently investigates more sophisticated hydrophilic layers. These layers would intensify water spreading and evaporation rates, boosting the overall effectiveness of desalination processes. Beyond enhancing heat transfer, these coatings mitigate salt buildup and biofouling, which in turn extends the desalination systems' operational lifetime. Furthermore, materials used in anti-fouling coatings are being improved to optimally counter organic and inorganic fouling agents for extended periods. Additionally, there is an increasing market demand for self-cleaning coatings that help minimize maintenance by preventing contaminant and salt accumulation. These coatings enable the use of new materials and surface designs that mimic phenomena like the lotus effect, giving them the capability of repelling water and contaminants. Moreover, functional nanoparticles have been incorporated into coating materials to improve their durability, thermal stability, and corrosion resistance. On the other hand, manufacturing technologies that are cheap and efficient in the making of these coatings should be pursued for the enhancement of the practicality of solar interfacial desalination applications. Further, spray coating, chemical vapor deposition, and electrospinning are some of the approaches that are being sought to obtain uniform thickness and area coverage of the coating layer over different substrates. However, the incorporation of these coatings on the other parts of solar desalination systems, including the photovoltaic panels and the thermal collectors, is critical in determining the efficiency of the energy system and the reliability of the entire system. The authors believe that further advancements in the R&D of coating materials, specifically regarding their performance, sturdiness, and cost-efficiency within the framework of solar desalination, will usher in even better and improved solutions for generating sustainable sources of freshwater worldwide. Figure 12a, b outlines strategies and design principles to enhance SDID performance, focusing on improving stability, water output, and exploring future applications and challenges for industrial-scale implementation.

The technological prospects of substrate materials in solar interfacial desalination are set to further enhance improvements and enhancements via the implementation of nanotechnology, flexible composites, and advanced coatings of the related composites. Nanotechnology possibilities consist of nanocomposites and nanostructured surfaces for light absorption, which increases efficiency. These may include features that are hydrophilic and endowed with strategies that reduce fouling in this part. Scalable and cheap flexible polymers and composites are actively investigated, similarly to thermal management systems like phase-change materials. To derive inspiration for improvement in substrate performance, concepts like lotus effect surfaces and aquaporin membranes are known to have been developed from bio-inspired materials. Combining these materials with photovoltaics for energy harvesting and the use of manufacturing technologies such as 3D printing is essential to attaining highly reliable and effective substrate systems. In future, as more research is carried out, it will be crucial to develop more sustainable materials while achieving more cost-efficient results and applying solar interfacial desalination to harsh environments.

Conclusion

In summary, the work identifies the global challenge of the availability of freshwater due to population expansion and climate change effects on sources of water. It mentions the solution through desalination, especially through the appropriate use of solar thermal technology that is considered efficient in terms of energy usage. A strong focus is given to the fine-tuning of photothermal absorbers, with the main emphasis on the great importance of materials allowing for any sort of substrate materials, which were still not given much attention in prior research. From such a standpoint, the review pays attention to the state-of-the-art advancement in solar evaporator technology while emphasizing the need for research on suitable substrates to optimize the performance of solar thermal desalination systems for real-world, large-scale applications. The paper suggests directions for further research to address present limitations and contribute to the development of these technologies in various fields.

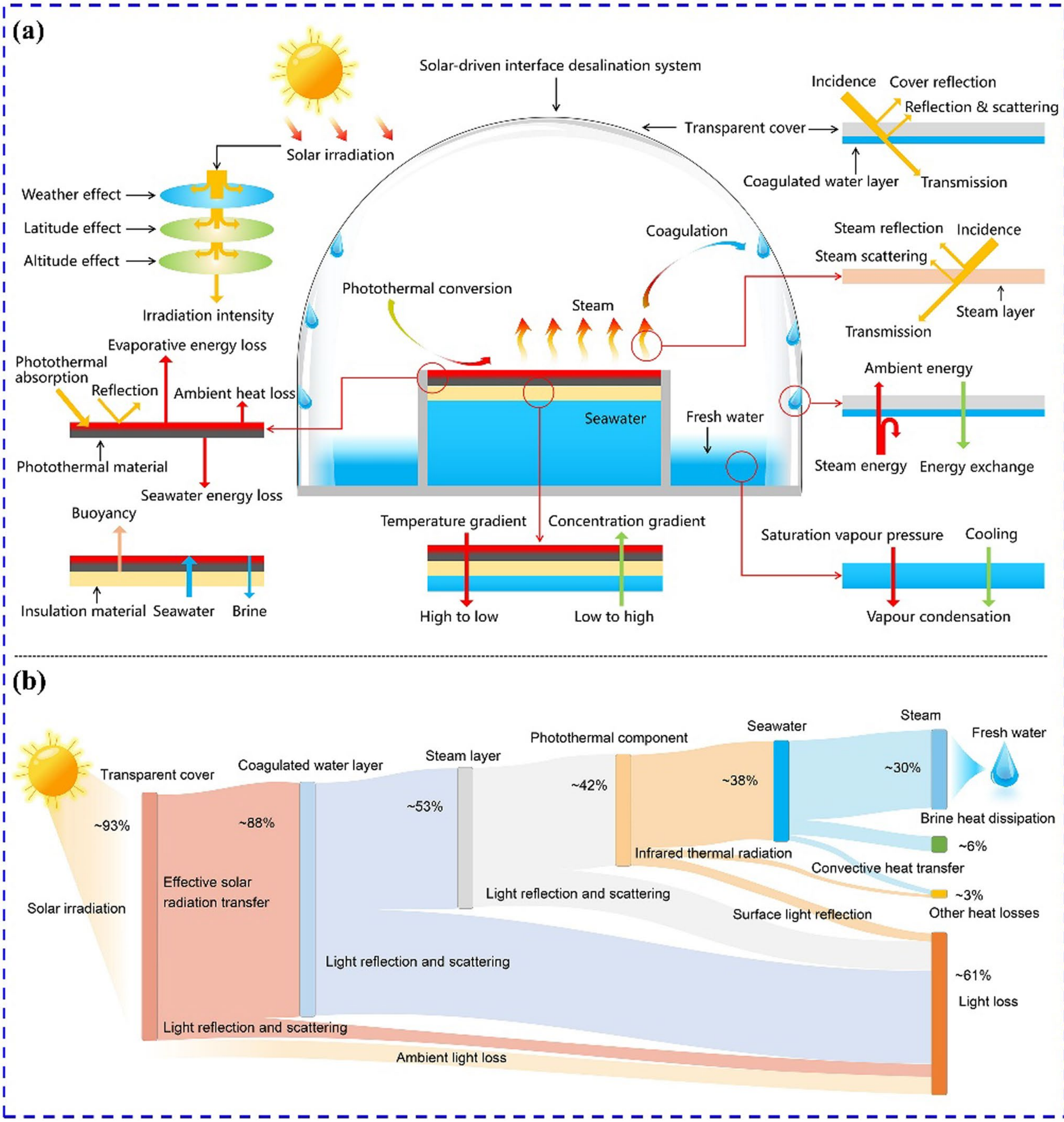

Fig. 12 Basic principle and energy flow in an SDID system. **a** Structure and working mechanism of a typical solar-driven interfacial desalination system, showing photothermal conversion and vapor generation. **b** Energy transfer and loss pathways, including light loss through cover materials and water mist, and energy loss in brine at 20 wt.% salinity. Reproduce with permission from Ref. [71]. Copyright 2024 Elsevier

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Declarations

Competing interest All authors declare that there is no competing interest.

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