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Recent advances and challenges of emerging solar-driven steam and the contribution of photocatalytic effect

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Abstract

In recent years, solar-driven steam materials and systems for water desalination and decontamination have received increasing attention from the scientific community. Notwithstanding the fundamental scientific achievements reached on this topic, numerous technological concerns still remain to be addressed, including heat loss, radiation reflection, low degree of purification of condensed water, biofouling, and salt accumulation on the surface. In this report, we critically reviewed the most recent advances in the engineering of solar-driven steam materials and the main technology challenges which may limit their large-scale application. First, different classes of materials, e.g., inorganic semiconductors, carbonaceous materials, polymers, and surface plasmon resonance metals, are compared in terms of the mechanistic pathways to generate steam vapor and condensed to freshwater on their surface. Then, the main approaches to tackle the technology shortcomings of solar-driven steam systems are discussed in depth. For instance, in terms of salt accumulation, several strategies were proposed such as solar-driven surfaces with ion exchange or/and salt dissolving, an inversion system to remove the salt from the active surface, and salt rejection surfaces. To enhance the photothermal process and limit the reflection of light, thermal insulators, reflective layers, and 3D/pyramidal photoabsorbers were proved to be excellent strategies. The review addresses as well the recent research regarding hybrid systems by incorporating photocatalysis effect in solar-driven water evaporators. Photocatalyst addition endows the surface of evaporators with unique properties, such as the radical oxidation of organic pollutants and microbial inactivation, resulting in reduced fast biofouling and condensed waters with higher purity. Finally, the remaining challenges and prospects for future developments are critically discussed.

Keywords: Solar-driven steam, Photothermal, Photocatalysis, Desalination, Environmental remediation.

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1. Introduction

Freshwater scarcity has become a serious threat due to the ever-increasing population and social development [1]. Currently, 1.6 billion people, mostly living in remote areas, have no access to clean potable water, and this situation will grow worse in the coming decades [2, 3]. To date, the most common methods to generate pure freshwater include reverse osmosis (RO) and thermal desalination processes [4-6]. However, these technologies are vulnerable due to some drawbacks such as high energy consumption (5-8 kW/m^3) and the required extensive infrastructure, which dramatically limit their application particularly in remote areas [7]. Consequently, it is imperative to develop suitable alternatives to overcome this trade-off between energy consumption and water desalination. From a practical point of view, next-generation pure water production technologies are expected to be characterized by low energy consumption, low cost, facile fabrication and implementation, durability, portability, scalability, accessibility, and sustainability. In this regard, the scientific community has been motivated to exploit solar energy for photothermal evaporation as a potential alternative to existing technologies [8].

The concept of photothermal evaporation is similar, in most steps, to the natural hydrologic cycle, wherein the solar light evaporates the seawater/surface water to vapor, and then the vapor is transformed into clean water in the form of rain [9]. In a solar-driven steam system, the evaporation of water is accelerated several times by the use of photothermal absorbers. Solar photothermal desalination is further classified into two groups based on the energy supply i.e., passive and active solar photothermal evaporators [10]. Passive solar still desalination is the conventional approach that utilizes solar energy as the only source of thermal energy. Conversely, active solar still desalination systems rely on extra thermal energy to enhance the evaporation rate. This extra energy can be acquired from a solar collector or any other accessible waste thermal energy, e.g. from power plants. To evaluate the efficiency of solar photothermal desalination, the specific water productivity (SWP) metric can be used [2, 11-15]: SWP shows the produced water volume per solar radiation area at a given time. In other words, SWP estimates how effectively solar light energy is converted into heat to desalinate water. Such a calculation involves numerous factors (as reported in **Figure 1)**, including the solar radiation intensity (E), the ability of the photothermal material to absorb solar light (α) and convert it into heat, the efficiency of generated heat used for water evaporation (η_t), and the gained output ratio which represents how effectively the vapor is converted into water (GOR).

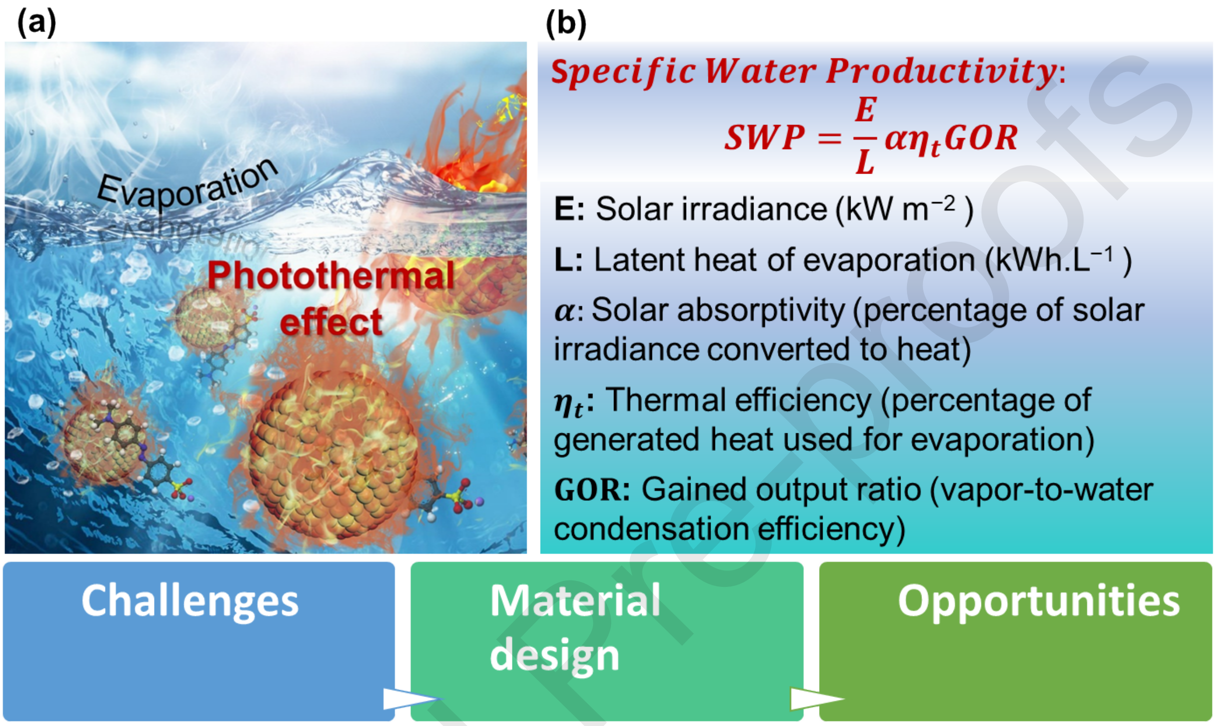

Figure 1. a) Scheme of solar photothermal conversion for water desalination, with permission from ref [9] and b) SWP metric, which evaluate the efficiency of the production of clean water by solar steam technology.

As it can be figured out from the SWP metric, the photothermal material plays the main role at a given solar irradiance. The sunlight-to-heat conversion and vapor generation steps crucially depend on the material engineering in terms of light absorption percentage, heat generation/management, and water pumping from bulk water to the top surface for evaporation. In recent years, numerous research studies have reported innovative solar absorbers based on different materials, to maximize the utilization and conversion of solar light [16-20]. In parallel, for better heat generation and water evaporation, insulator materials have received a lot of attention from the scientific community to improve the functioning of absorber materials by minimizing the heat loss in bulk water and concentrating the heat on the top surface of the solar absorber.

To counter technology issues of solar-driven steam systems, a great deal of research has been devoted to the development of smart multifunctional materials and systems [21-26]. Photocatalytic oxidation technologies have recently been combined with solar photothermal absorbers: in such a combination, cooperative and synergistic effects have been observed in the same platform [27-29]. The photoproduction of reactive oxygen species on the top surface of the photoabsorber brings up a self-cleaning option and the possibility to use simultaneously the solar photoabsorber system for wastewater purification.

In this review, we address the state-of-the-art research on the development of solar photothermal materials for enhanced solar-to-heat conversion. The main reported strategies to address common technology issues, i.e., salt accumulation, biofouling, evaporation, and condensation of volatile organic contaminants (VOCs) along with water, heat loss, and light refection, are critically discussed. Additionally, we have emphasized the recent development and advancement of engineering of combined photocatalytic-photothermal solar evaporators towards water desalination and purification. The contributions of photocatalytic action to fight some common issues in classical evaporators were stressed point by point. Eventually, the future opportunities and difficulties for developing high-performance solar absorbers in both basic research and industrial-scale applications are taken into account.

2. Floating solar-to-heat materials

The concept of solar photothermal water evaporators is based on the accelerated heating of the air-water interface (excluding bulk water) using floating materials that can convert effectively the solar light into heat. In this approach, the engineering of materials and systems are key determinants for enhanced photothermal conversion and water evaporation under daily solar light [30, 31]. Recently, the scientific community has devoted a lot of effort to enhancing water evaporation rates, and overcoming some technical issues facing this solar technology [21]. Many factors should be controlled to fabricate effective water evaporators that meet the requirements for the transfer of this technology to the real world, such as, in terms of materials engineering, broad solar light absorption, high wettability, good transport velocity of water, structural durability, and lower thermal conductivity of the bottom layer to heat loss into bulk water [32-34].

In general, two solar evaporator modes are recognized: direct contact and indirect contact modes. In the direct contact mode system, the process of evaporation occurs at the original air-water interface, implying that the height of the evaporating interface and water surface is at the same level. In such a case, the photoabsorber is in direct contact with the bulk water (**Figure 2a**), or it could be supported on porous floating materials to keep it on top of the water (**Figure 2b**). In the indirect contact mode, the photoabsorber is supported on a thermal insulator to avoid heat transfer and promote the heat localization at the evaporative surface (**Figure 2c**). Unlike contact mode, the heat loss can be limited in indirect contact mode, wherein the top evaporative surface is separated from bulk water using an insulator [35, 36]. This system involves a water pumping process and hydrophilic solar light-absorbing materials (photothermal material). In the evaporation process, bulk water is lifted to the evaporative surface through capillary action or hydrophilic fibers, and the pumped water is efficiently evaporated (**Figure 2d**).

Photothermal materials, as a primary constituent of light to heat converter, play a vital role in solar energy harvesting. Other desired properties of photothermal materials include broadband and robust light absorption, secure and scalable manufacturing methods, and affordable cost. Solar absorber materials can be classified into different classes. In the next sections, the working principles and main characteristics of each class of absorber materials will be reviewed.

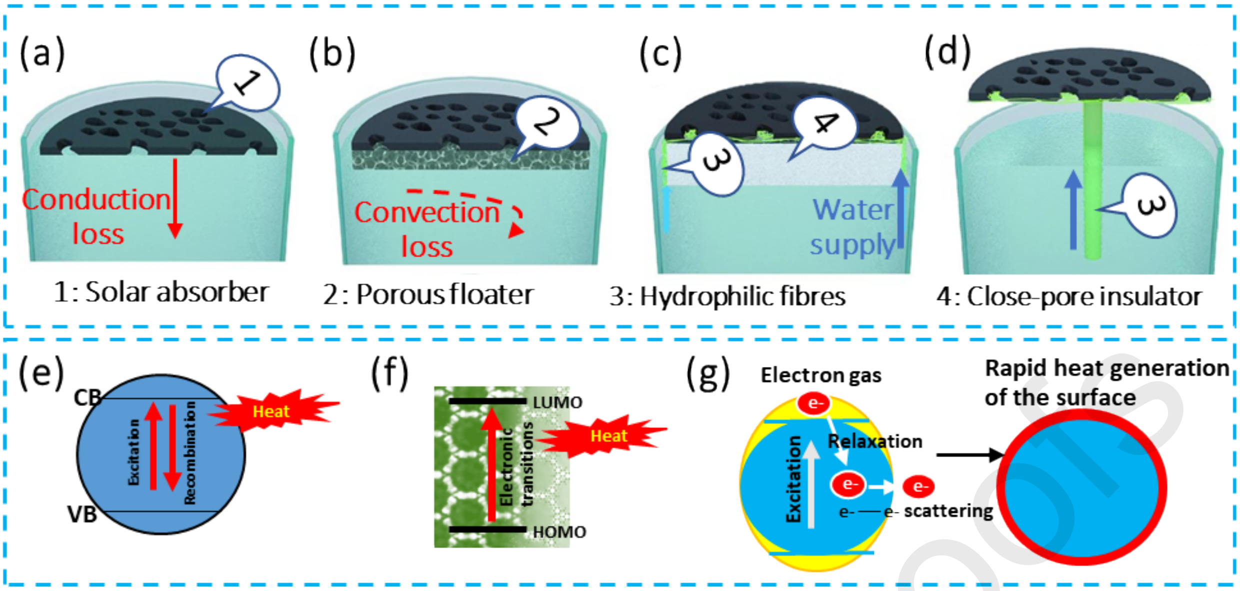

Figure 2. (a,d) Classification of the current photothermal evaporators: (a, b) Direct contact mode, (c,d) indirect contact mode with hydrophobic fibers, reproduced with permission from ref [37]. (e-g) Light-to-heat generation in different material systems: (e) photothermal excitation of narrow band gap semiconductors, (f) photothermal excitation of nanostructured carbon conjugated system-based materials, (g) photothermal heat generation in plasmonic NPs (e.g., Au).

2.1. Inorganic semiconductor-based absorbers

Semiconductors having narrow bandgap and intrinsic thermalization could be excited via photothermal process to generate heat on the surface, as shown in **Figure 2e**. In such a process, narrow gap semiconductors absorb high amounts of light with energy higher than their band gap, causing the excitation of electrons from the valence band to the conduction band, to create electron/hole pairs, followed by recombination. As a result of non-radiative recombination, heat is generated on the surface of the semiconductor [38]. The main issue of heat generation in semiconductor systems is heat emission which decreases the surface-localized heat. For enhanced surface heat generation, doping and surface modification of semiconductors have been reported to improve the process efficiency [39]. $Cu_{2-x}S$ $(0 < x < 1)$ semiconductors have received much attention as solar water evaporators due to their high solar absorption, low cost and rapid light-to-heat conversion [40-43].

For enhanced performance, the construction of $Cu_{2-x}S$ based catalysts in different structures and shapes was the subject of many studies [41]. Many other semiconductor-based materials showed excellent water evaporation efficiencies under 1 sun such as Bi_2S_3/Pd (97%) [44], 2D/2D Ti_3C_2/MoS_2 (87.2%) [45], MoO_{3-x} (62.1%) [46], MoS_2/LaF_3/PDMS (91%) [47], MoS_2@sponge (85%) [30], MoS_2/expandable polyethylene (80%) [48], MoS_2 nanosheets (~76% under 0.76 kW/m^2) [49], Fe_3O_4/PVA/Wood (73%) [50]. PVDF/WS_2 (94.2% under 3 sun) [51], MnO_2-Deposited Wood (81.4%) [52].

2.2. Carbonaceous materials

Carbonaceous materials, including activated carbon, graphene, monolithic carbon sponges, carbon dots (CDs), hollow carbon, and carbon nanotubes (CNTs), are very effective and largely applied as water evaporators due to their superior solar light absorption, excellent light-to-heat conversion, high porosity, and physical and thermal stability [31, 53-61]. Since bare carbon materials exhibit low emissivity, different structures/morphologies were investigated. The generation of heat on the surface of carbon materials is due to the electronic transitions within the carbon conjugated units under light (**Figure 2.f**). Hence, constructing a carbon platform with a long conjugation system could enhance the solar light absorption response [31]. Qin et al. [62] fabricated a multifunctional bilayer structure aerogel composed of hydrophilic ultralong hydroxyapatite nanowire on the top and hydrophobic carbon nanotubes as photo-absorber (**Figure 3a**). This floatable bilayer aerogel exhibits a water evaporation rate of 1.34 kg·m^{-2}·h^{-1} under 1 kW·m^{-2} solar light irradiation. Its photothermal activity is high and the process showed efficiency in the removal of five major ions from real seawater samples (Huanghai Sea) and as well as the oxidation of rhodamine B (RhB). Zhu and co-workers [57] developed a floatable self-contained monolithic carbon sponge that can condensate water in outdoor conditions.

Some studies showed that carbon-based water evaporators could also produce electricity [57, 63-66]. For instance, Xue et al. [67] showed that carbon-based materials can generate a sustained voltage during the water evaporation process, which was comparable to that of a standard AA battery. It was reported that the interface interaction of H_2O on the porous carbon surface and the evaporation mechanism is the major keys behind the generation of electricity. Dao et al. [68] has recently reported that electricity can be generated using an evaporator based on multi-walled carbon nanotubes in the dark and under 1 sun. It was found that the highest P_{max} levels using Zn wire electrodes were 94 and 174 $\mu W \cdot m^{-2}$ in the dark and under 1 sun, respectively.

2.3. Organic polymers

Polymers with an extended π-conjugated system of sp^2-hybridized carbon can be excited by a low energy input, similarly to carbon-based materials. The more extended the π-conjugated system is, the longer is the wavelength of light absorption and photoexcitation [69, 70]. The light-to-heat conversion is realized through the energy transfer from the photogenerated electron to vibrational modes over the atomic lattices [71, 72]. In practice, polymers can play many roles in solar photothermal evaporators: from light absorbers to immobilization and floating aids, to insulators.

Meng et al. [73] fabricated controlled porous poly(ethylene-co-octene) elastomers (pPOE); the polymer-based evaporator showed excellent thermal localized heating, along with high porosity, leading to excellent seawater desalination. Polypyrrole (PPy) is a conducting polymer that has been widely used as a solar evaporator due to its extended solar absorption and high evaporation efficiency [74-81]. Wu et al. [33] reported that doping of polypyrrole by butanetetracarboxylic acid (BTA) improves the efficiency in terms of water evaporation. BTA-doped polypyrrole hydrogel showed an evaporation rate 1.55 times higher than that of bare polypyrrole. The differential scanning calorimeter patterns showed that the glassy transitions started at 71.6 and 80.5 °C for bare polypyrrole and doped polypyrrole, respectively. The electrodeposition of nickel-modified polypyrrole as salt-resistant solar absorber was recently reported by Wang et al. [80]; a conversion efficiency of 82.18% under 1 sun was reported. In a water evaporator system consisting of porous carbon and polyaniline, Wang et al. [82] found a water evaporation rate of 1.496 $kg \cdot m^{-2} \cdot h^{-1}$ and solar-to-steam efficiency of 87% under one sun without the use of a thermal insulator layer. Han et al. [83] fabricated a water evaporator system composed of PEDOT:PSS/nanofibrillated cellulose (acting as a light-to-heat converter) and expanded polyethylene (EPE) foam (as a thermal insulator). Poly(3,4-ethylene dioxythiophene) polystyrene sulfonate (PEDOT:PSS) was largely used as a solar absorber due to its excellent solar light absorption up to the NIR region. This evaporator showed excellent thermal localization and superior water evaporation around 1.6 $kg \cdot m^{-2} \cdot h^{-1}$ under 1 sun. The effect of water content on the water evaporation rate was studied and optimized water content was obtained. This floatable gel showed a great potential to desalinate artificial and real seawaters.

Polymers can also be used to enhance the immobilization of solar absorbers due to their ability to support powder materials and to improve their affinity with different supports. Song et al. [50] reported the coating of wood with Fe_3O_4/polyvinyl alcohol as a water evaporator to be used for water desalination.

Polymers are commonly used to fabricate hydrogel-based materials as solar water evaporators. The topic of hydrogel for water evaporation was reviewed recently by Guo et al. [84, 85]. Gels offer key advantages for the optimization of water evaporation and heat management of floating material. In this respect, Zhao et al. [86] fabricated a hierarchically nanostructured gel as a water evaporator composed of polyvinyl alcohol and polypyrrole for solar water evaporation and remediation (**Figure 3.b**). They found that the structure of this floating gel induced a regulated water distribution and high-water absorption.

Gas-foaming technology is a widely used technique to fabricate water evaporators (2D/3D foams) with excellent porosity and mass transfer effectiveness [85, 87, 88]. As shown in **Figure 3c**, closed-cell polymer foam using bisphenol A (BPA) and polyacrylonitrile (PAN) was fabricated by electrospinning followed by gas foaming [32].

2.3. Surface plasmon resonance metals

Metals with localized surface plasmon resonance (LSPR) can absorb the solar light and convert it into heat as a result of the transition of electrons from Fermi level to higher energy levels and electron-phonon scattering processes [9, 89-91]. **Figure 2g** shows the mechanism of heat generation in plasmonic metals. LSPR metals are mostly used to modify other solar absorbers for enhanced water evaporation. Cui et al. [92] coated carbonized organosilica with a trace amount of Au nanoparticles (NPs) for solar water purification. Very effective water evaporation was found with a conversion efficiency of up to 94.6% under one sun. Au NPs supported carbonized organosilica was tested to desalinate simulated seawater and towards the oxidation of dyes and recovery of heavy metals. Guo et al. [93] fabricated a solar absorber based on silica gel modified with gold nanoflowers. The surface area of the gel was 809 $m^2 \cdot g^{-1}$, while the pore size was around 3.5 nm. This combination allows using lower Au amounts and boosts the water evaporation due to the heat confinement through gel pores. Ag immobilized on the surface of carbonized melamine foam was reported by Shi et al. [69], which showed a very high evaporation rate of 2.39 $kg \cdot m^{-2} \cdot h^{-1}$ along with a conversion efficiency of 119.46% under 1 $kW \cdot m^{-2}$ due to the excellent light-to-heat generation and enhanced water absorption. Chen et al. [94] reported plasmonic $Cu_{2-x}Te$ nanowires (bp$Cu_{2-x}Te$), which exhibited an evaporation rate of 4.3 $kg \cdot m^{-2} \cdot h^{-1}$ under 3 suns (**Figure 3d**).

Table 1 summarizes selected recent studies on the fabrication of solar evaporator floating materials for water evaporation and/or water decontamination. It can be seen that the material plays an important role in enhanced evaporation and water purification. Comparing results in Table 1, carbon materials show high evaporation rates. Polymers also have good performance, e.g., polymeric hierarchical gel showed an evaporation rate of 3.8 $kg \cdot m^{-2} \cdot h^{-1}$ under one sun. On top of that, hybrids containing metals/metal oxides with carbon and/or polymer materials have great potential for solar conversion due to synergistic effects.

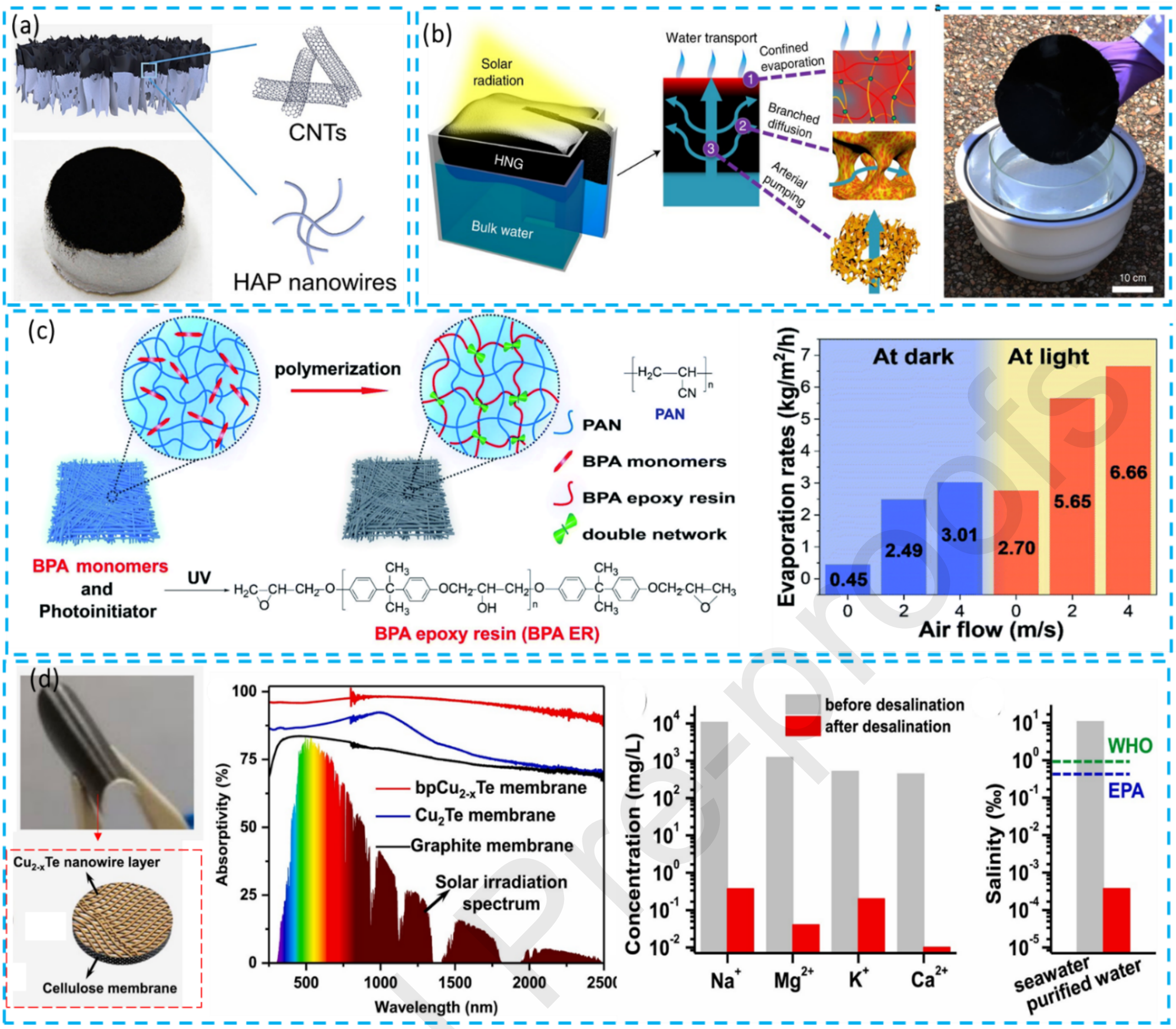

Figure 3. (a) Multifunctional bilayer structure aerogel composed of hydrophilic ultralong hydroxyapatite nanowire on the top and hydrophobic carbon nanotubes as photo-absorber for the removal of heavy metals and dyes from water under solar light, reproduced with permission from reference [62] (). (b) Hierarchically nanostructured gel as a water evaporator composed of polyvinyl alcohol and polypyrrole for solar water evaporator, reproduced with permission from [86]. (c) Synthesis of closed-cell polymer foam using bisphenol A (BPA) and PAN polymer for water evaporation, reproduced with permission from [32]. (d) Plasmon $Cu_{2-x}Te$ nanowires supported on cellulose membrane, reproduced with permission from [94].

Table 1. Recently reported solar evaporator floating materials for water purification and desalination.

System	Sunlight (kW·m^{-2})	Evaporation efficiency	Evaporation rate (kg·m^{-2}·h^{-1})	Application	Ref
CNTs coated on ultralong hydroxyapatite nanowires	1	89.4%	1.34	Water desalination Recovery of heavy metals Oxidation of dyes	[62]
Cotton-Cs_xWO_3 fabrics	1	86.8%	1.56	NaCl removal from water	[95]
Carbon foams with interconnected microchannels	1	80.1%	/	Water desalination	[96]
CNTs supported on macroporous silica	1	82%	1.31	Water desalination Oxidation of dyes	[54]
Polymeric hierarchical gel	1	94%	3.2	Water desalination	[86]
Graphene/rice-straw-fibers	1	88.9%	2.25	Water desalination	[97]
Black phosphorous	1	64.63%	0.94	Seawater desalination Oxidation of MB dye	[98]
BPA/PAN foam	1	/	2.7 6.66	Water desalination Bacteria inactivation	[32]
Au NPs/paper	1	77.8%	/	Seawater desalination	[99]
Hierarchical Cu_xS	1	94.5%	1.96	Oil-water treatment Iron rejection Bacteria inactivation Dye oxidation	[43]
$Cu_{2-x}Se-TiO_2$	2.5	83.06%		Water desalination Dye oxidation	[100]
$Cu_7S_4-MoS_2$-Au on polydimethylsiloxane (PDMS)	2.5	96.6%	3.82	Water desalination	[87]
MoS/expandable polyethylene	1	80%	1.27	Water evaporation Oxidation of organic pollutants (nitrobenzene, carbamazepine, and naproxen).	[48]
Phenolic aldehyde foam	1	87.86%	1.49	Seawater desalination	[101]
BTA polyacid doped polypyrrole	1	89%	1.90	Seawater desalination Dye oxidation	[33]
Ni_1Co_3 doped polydopamine	1	109%	2.42	Seawater desalination	[102]
MnO_2 nanowires/chitosan	1	90.6%	1.78	Evaporation of industrial wastewater and oil-emulsified water	[103]
Ag/polypyrrole	1	92.6%	1.55	Water desalination Bacteria inactivation	[104]
Sea urchin-like carbon obtained from Ni-MOFs.	1	91.5%	2.07	Seawater desalination	[105]

[illegible]

3. Technology challenges in solar water evaporators

The transfer of solar water evaporators to real-world applications still faces several technology issues [21, 106-108]. In this section, the most investigated strategies to overcome common issues of solar-driven steam will be reviewed.

3.1. Salt accumulation and rejection

During the water evaporation process, the deposition of salts on the evaporator surface is considered as one of the main issues to be solved for the large-scale use of solar water evaporators. Saline deposition blocks the active surface and therefore cuts the light-to-heat operation. Several recent studies have proposed smart materials or/and systems that can dissolve or reject continuously the solid salt from the active surface [2, 109-119]. The fabrication of photoabsorbers with a morphology able to dissolve or exchange the salt ions has been suggested to limit/reduce the salt accumulation of the top surface (**Figure 4a**). Xiao et al. [120] designed a floatable water evaporator that prevents the accumulation of salt on the top surface. The floating evaporator is composed of carbon black as a solar evaporator, and a super hydrophilic melamine-formaldehyde foam as a salt ions exchanger, wherein the deposited salt on the top surface can move down through the channel of foam to seawater. The authors studied comparatively the water evaporation efficiency with and without ions exchanger foam and it was found that the salt can be accumulated on the surface of carbon black in the system without foam. The water evaporation rate was found to be 3.2 times higher in the salt-rejecting floating system than that of the pristine system. In addition, the reflecting water evaporation system showed the same efficiency after 20 days. For fast salt dissolving on the surface of the photo-evaporator, Wang et al. [80] fabricated a bilayer photothermal evaporator with a top layer made by electrodeposition of polypyrrole on nickel foam and polyurethane sponge as a lower layer. It was found that such a morphology can dissolve quickly the accumulated salt compared to common solar water evaporators. Inversion strategy was used to reject the salt accumulated on the surface of the evaporator. Liu et al. [95] designed a floatable system to clean seawater, based on high sunlight absorbing Cotton-Cs_xWO_3 (**Figure 4b)**. In this study, surface deactivation due to the high deposition of NaCl salt was tackled by surface inversion strategy, wherein, the active surface can be inverted periodically for further cycles. Wang and coworkers developed rational expandable polyethylene to discharge salt from the evaporator [121]. In this study, the authors reported that this salt-rejecting system improved the evaporation efficiency by 3.74 times compared to the pristine system, providing enhanced reusability. Chen et al. [122] fabricated a Janus-structured organic evaporator system, which includes a hydrophobic top and a hydrophilic bottom to fight the deactivation of the photoactive surface of the evaporator as a result of salt deposition. Xia et al. [123] developed a novel smart seawater evaporator disc able to continuously isolate and crystallize the salt (**Figure 4c**). The top evaporating surface of the disc is based on CNTs. Seawater can be moved to the top surface of the disc through a cotton thread, then the salt is formed by solar evaporation. The falling off of salt crystallites from the top surface to the salt collector is driven by gravity. An evaporator with a lily-inspired hierarchical structure for long-term use was reported by Xu et al. [124]; in this system, the generated salt is continuality excreted by water passing from the top surface to bottom surface.

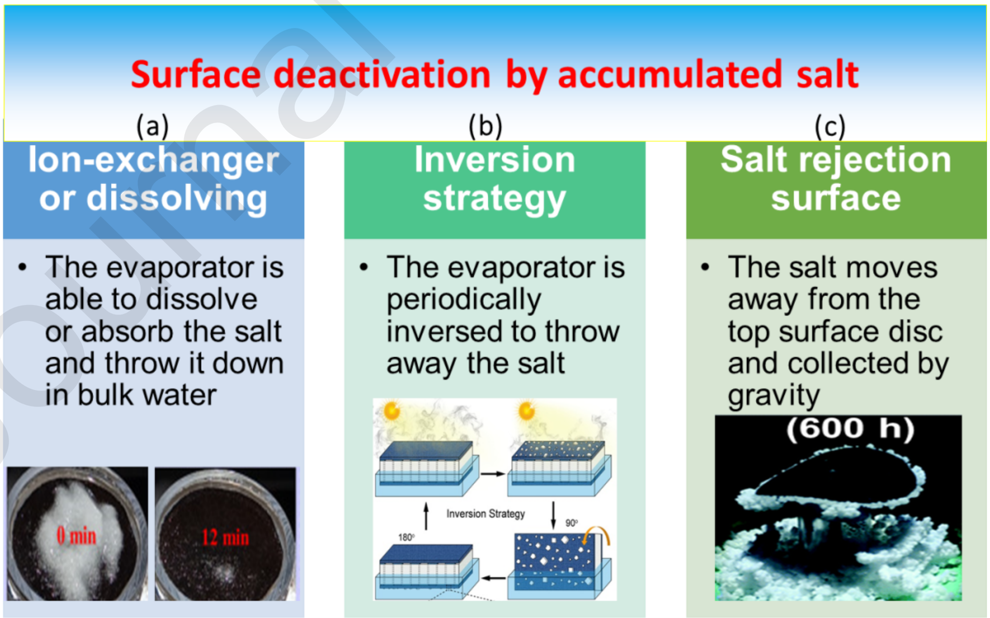

Figure 4. Most reported approaches to solve the deactivation of photoabsorber top surface by accumulated salt: (a) Salt rejection on the surface of polypyrrole-coated nickel foam-based

evaporator; the morphology of this evaporator allows a fast salt dissolution; the image was reproduced with permission from [80]. (b) Self-cleaning evaporator based on floating cotton-Cs_xWO_3; the system can clean itself via inversion to remove the accumulated salt for further processing; the image was reproduced with permission from [95]. (c) Spatially isolating salt crystallization over a novel water evaporator design which allows a continuous steam generation for 600 h; reproduced with permission from [123].

3.2. Heat and energy management

Several materials are very effective in solar-to-heat conversion. However, the generated heat could be lost via its transfer to bulk water or emitted in the air due to reflection, thus limiting the water evaporation. In general, surfaces with lower heat loss are able to promote higher water evaporation rates [30, 125, 126]. Many research groups have spent a lot of effort to limit the heat loss via the construction of materials able to localize and manage the generated heat in their active surface for maximum use [127-130]. Herein, the nature of the insulating material is determinant to protect the heat transfer to bulk water. Insulators with extremely low thermal conductivity are mostly used to avoid the diffusion of heat from the top active surface to unheated bulk water. On top of that, the wettability of the bottom insulators is a limiting factor in this system, wherein, the continuous transfer of bulk water to the upper active evaporator surface is an important parameter to be controlled during the fabrication of evaporating systems. Xu et al. [131] fabricated an integrated three-layer evaporator. The top surface is based on polypyrrole particles with high thermal conductivity. The medium and bottom layers exhibit a lower thermal conductivity to avoid the transfer of heat to bulk water, and excellent hydrophilicity that enables the pumping of bulk water to the top surface of the evaporator (**Figure 5a**). This system showed superior water evaporation rates, up to 2.41 $kg \cdot m^{-2} \cdot h^{-1}$.

To limit the diffusion of solar energy, Fan et al. [132] suggested the use of a light-reflective layer (**Figure 5b**) to concentrate the energy and heat, and therefore, the light-reflection system showed high-water evaporation of 87.5% under one sun, which was 12% superior to conventional evaporators. 3D systems are able to manage the heat and light energy for enhanced water evaporation as they can reduce the emission of heat energy. Shi et al. [133] designed a 3D cylindrical cup evaporator, which ensures solar energy efficiency around 100% under one sun. The top active surface was composed of 20 metal oxides as solar absorbers. The improvement of energy efficiency and heat generation in this system is due to the recovery of diffused energy and heat by the cup wall (**Figure 5c**). On top of that, unlike conventional open-air 2D systems, the reflection of energy and heat on the cup wall led to a further increase in the heat generation and water evaporation rate (2.04 $kg \cdot m^{-2} \cdot h^{-1}$). Yang et al. [134] compared the efficiency of flat and pyramid polyurethane sponges for water evaporation (**Figure 5d**); they found that the pyramid-shaped evaporator exhibits an evaporation efficiency of 85.27% under one sun, which was 9.23% higher than that of the conventional flat system due to the strong energy recovery and heat generation. The combination of solar absorbers may also enhance heat generation and management. A recent study [135] reported that the addition of carbon black to the top surface of an absorber composed of reduced graphene oxide and polystyrene microspheres leads to improve evaporation rate from 1.06 to 1.86 $kg \cdot m^{-2} \cdot h^{-1}$, while the efficiency was increased from 69.58% to 124.14% under one sun.

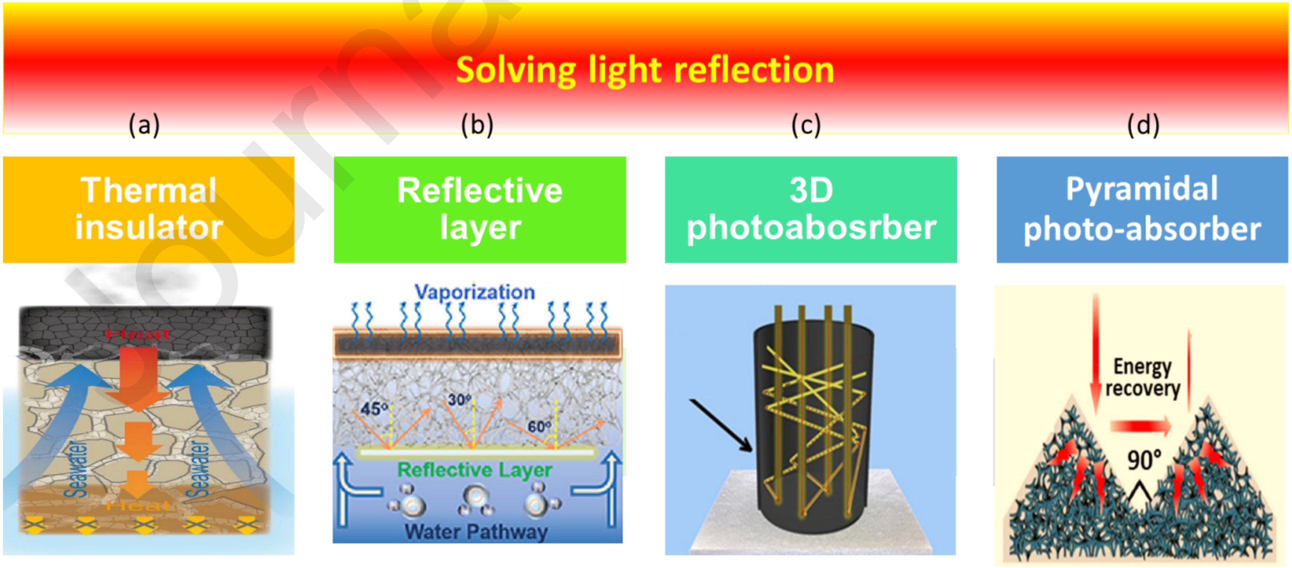

Figure 5. Some of the strategies reported to overcome the issue of heat loss and light reflection: (a) Three-layered evaporators including an active top surface, a middle layer for salt management and

bacteria inactivation, and the third layer with excellent hydrophilicity and low thermal conductivity; reproduced with permission from [131]. (b) Enhanced heat generation by using a light-reflecting evaporator, reproduced with permission from [132]. (c) Energy and heat diffusion and management in 3D evaporator systems reproduced with permission from [133]. (d) Energy recovery in pyramid sponge-based evaporators reproduced with permission from [134].

3.3. Biofouling and bacteria inactivation

In real-life applications, biofouling of evaporators is expected due to the growth of seawater microorganisms. Biofouling can screen the surface of evaporators and block their active sites. Many studies reported strategies to deal with the biofouling issue [131, 136-138]. One of the well-reported approaches to fight biofouling of the top surface of evaporators is based on incorporating hydrophilic polymers, which can limit the growth of microorganisms [124]. Qiao et al. [32] reported that the incorporation of bisphenol A (BPA) epoxy resins on polyacrylonitrile (PAN) based evaporator reduced the population of bacterial cells on the top surface by 3.7 fold compared to bare PAN. The incorporation of MXene in cellulose-based solar evaporators leads to stress and damage of the bacteria membranes, inhibiting the growth of bacteria and biofilm formation. Ag NPs have also been used to prevent bacterial growth in polypyrrole-based evaporators [104]. A promising approach to solve this issue is represented by the combination of photocatalytic materials in photothermal evaporators, as will be discussed in the next Section.

4. Contribution of photocatalysis in floating photothermal evaporators

Multifunctional materials/systems often exhibit beneficial synergistic effects that can speed up the whole process and solve common issues found in single systems. Recently, many research groups have been interested in the fabrication of multifunctional floating materials involving both the thermal catalytic and photocatalytic activities for scalable and sustainable water remediation/desalination. In general, most of the properties required to fabricate photothermal catalysts fit with the requirements of solar floating photocatalytic materials, which helps the combination of these two solar technologies. Visible light-responsive catalysts can initiate thermal activity on the surface of floating materials for water evaporation. Similarly, visible light absorption is an important factor in solar photocatalytic materials to generate effective reactive oxygen species (ROS). Therefore, the combination of both processes on the same floating materials is very promising. In addition, the thermal effect can boost positively the photocatalytic activity through the enhancement of mass transfer and adsorption on the surface of the catalyst during the photocatalytic action. The engineering of materials able to initiate simultaneously photothermal and photocatalytic performances could be obtained through the use of compounds able to convert light-to-heat/ROS at once or the immobilization of photocatalytic semiconductors on solar absorbers. In this section, the major advantages obtained from the combination of photocatalysis and photothermal processes towards water desalination and/or purification will be discussed, emphasizing radical oxidation of pollutants and the inactivation of microbial species.

4.1. Radical oxidative inactivation of microbial species on water evaporators

Biofouling of water evaporator systems due to the ubiquitous presence of microbial species in seawater or contaminated waters is a major barrier to the transfer of water evaporator technology to real applications. As discussed in Section 3.3, some approaches have been suggested including the coating of evaporators with antibacterial agents, *i.e.*, Ag, or the tuning of the hydrophobicity of the top active surface of evaporators. The radical oxidative inactivation of microbial species is a very interesting alternative approach, based on the high efficiency of photoproduced ROS to damage the nearby bacterial species. Xu et al. [139] studied the antibacterial activity of water evaporators based on CuO mesh, PPy membrane, and carbon-spray paper by testing domestic sewage containing multiple bacterial strains. The carbon-sprayed paper was notably degraded in the presence of microbial species because of the high biocompatibility of cellulose. A biofilm layer was observed in the PPy-based evaporator due to the attachment of bacterial species, which may limit water evaporation in real conditions. However, CuO mesh-based evaporators showed a great antibacterial activity which is due to the photocatalytic bacteria inactivation on the surface of CuO. Noureen et al. [140] reported that the incorporation of Ag_3PO_4 into rGO coated textile water evaporator could help to solve the issue of biofouling and simultaneously this evaporator showed great potential for the oxidation of dyes within the source water, as will be discussed in Section 4.2.

4.2. Photocatalytic oxidation of organic pollutants in water evaporator systems

Unlike conventional evaporators, those having a photocatalytic ability can lead to the fast oxidation of organic pollutants by the photoproduced ROS on the top surface, and as a result, these systems can purify the contaminated water and produce cleaner water at once. During the evaporation of water in photothermal systems, volatile organic compounds (VOCs) and odours can be evaporated and condensed along with water, resulting in collected waters of low quality [48]. Many research groups have reported several approaches to address the issue posed by VOCs and other organic pollutants. Solar absorbers with a high surface area could be used to adsorb organic pollutants and generate cleaner waters [141, 142], but the saturation or release of VOCs may limit the efficiency of this approach. Zuo et al. [143] reported that a CuO/CN-based solar evaporator can limit the transfer of VOCs along with the condensed water, due to the photocatalytic radical oxidation of VOCs on the surface of the evaporator.

In addition, in conventional evaporator systems, the over-deposition of water pollutants can block the active sites of evaporators, requiring continuous regeneration/cleaning of the system. Currently, numerous research groups are investigating strategies to endow water evaporators with photocatalytic self-cleaning properties to fight organic pollution as a crucial approach to expand the application of this technology. Liu et al. [141] reported that the incorporation of TiO_2 on the surface of Au NPs/membrane-based evaporators led to producing highly pure freshwater due to the photocatalytic oxidation at the surface of the evaporator. Zhang and co-workers [144] reported that the coating of bi-layered bacterial cellulose (BC) biofoam with CuS resulted in simultaneous enhanced photothermal water conversion and effective photocatalytic dye oxidation. The incorporation of CuS in BC biofoam enhanced the light absorption from 4.7%-74.6% to 97.9-100%. In addition, under light, the evaporator showed excellent methylene blue oxidation due to the photocatalytic activity of CuS. Zhang et al. [145] fabricated Bi_2S_3@Ag_2S/carbon fiber cloth combining water evaporation and photocatalytic activity under solar light. The authors reported effective oxidation of tetracycline, while a localized heat of 51.9 °C was recorded at low temperature. Photoproduced superoxide radicals $^{\bullet -}O_2$ were the main oxidizing species in this system. The photoproduced heat on the surface of evaporators can further promote the oxidation of tetracycline, highlighting possible synergisms. Among the different photocatalysts, CuO nanowires are particularly promising [139]. CuO nanowires display superhydrophilicity and high solar light absorption (93%), which yield water evaporation of 84.4% under one sun. CuO can initiate also the photocatalytic oxidation of organic pollutants by photogenerated redox species. In addition, the catalytic activation of peroxymonosulfate (PMS) was recorded in dark and light conditions. Zhu et al. [146] have used also used CuO/dopamine/Prussian blue as a photothermal-photocatalytic system, and they reported that material exhibits a superhydrophilic top surface and can produce continuous water vapor under the solar spectrum (300-2500 nm). It was found that the hydrophilicity of the evaporator has a significant effect on the evaporation rate compared to the hydrophobic evaporator. This solar evaporator has been used for the purification of dyeing, oily, and saline waters. The photogeneration of $^{\bullet}O_2^{-}$, $SO_4^{\bullet -}$ and $^{\bullet}OH$ for oxidation of organic pollutants on the surface of the evaporator was confirmed by EPR. The combination of photothermal with photocatalysis enhances as well the photocatalytic ability due to interfacial heat/charge management, Li et al. [147] reported that the photothermal excited carbon spheres can transfer electrons to TiO_2 which results in a high yield of separated charges to activate dissolved oxygen in the water. Similarly, Noureen et al. [148] reported that rGO synergistically promotes the photocatalytic activity of $BiVO_4$ via the transfer of photothermal produced electrons to $BiVO_4$. Shi and co-workers [149] reported that in (TiO_2/Au-CNT)-coated SiC ceramic plate system, that CNTs play the role of electron mediator to improve the generation of a high yield of separated charges in the Z-scheme system. The photocatalytic oxidation of RhB and photoreduction of Cr(VI) simultaneously were studied on the surface of this floating material.

To conclude, the introduction of photocatalysis to solar-driven stream systems can help to solve several issues. The main cooperative effects as listed below and simplified in **Figure 6**.

- The lifetime of the evaporator can be enhanced due to the self-cleaning effect as a result of the continuous photogeneration of ROS, which are able to oxidize the deposited organic pollutants and prevent the formation of microbial films.

- Many semiconductors with excellent solar absorption may act simultaneously as photocatalytic materials and water evaporators, therefore, their presence on the surface of the evaporator can contribute directly to converting light into heat for water evaporation through the photo-excitation-recombination process.

- In the case of water evaporation from contaminated waters, VOCs could be evaporated and condensed along with water vapor, lowering the quality of the obtained purified water; the photogenerated ROS on the surface of the evaporator can oxidize organics and generate better-purified water.

- The heat produced on the surface of the evaporator can boost the photocatalytic activity by increasing the mass transfer between the photocatalytic NPs and pollutants. The mass transfer and slow photocatalytic reaction are known as technical issues in photocatalytic systems [150, 151]. Interestingly, the literature has proved an enhanced photocatalytic ability on the surface of floating photocatalytic-photothermal evaporators as a result of the contribution of solar absorber materials [152].

- Effective solar absorbers can enhance the photoexcitation of photocatalytic NPs because of the promoted light harvesting. Li et al. [147] reported that the enhanced photocatalytic performance in carbon-TiO_2 yolk-shell is due to the positive combination of photothermal excitation and photocatalytic activity. The heat accumulation on the surface of the catalyst as a result of the photothermal excitation can initiate the activation of oxygen species in water. At the interface of photocatalytic NPs and water evaporator, this latter may act both as electron emitter or receiver which enhances the separation of charges and ROS yield generation.

- In general, the deposition of photocatalytic NPs on highly adsorbing materials leads to improve photooxidation of pollutants due to the adsorption and pollutant-shuttle process [153], wherein the sorbing domain enhances the concentration of pollutants for further ROS oxidative degradation by the photoactive domain. In photocatalytic-photothermal systems, photothermal absorbers, e.g., carbon materials or polymers, can improve the adsorption of pollutants for further oxidation via the so-called "adsorb & shuttle" process.

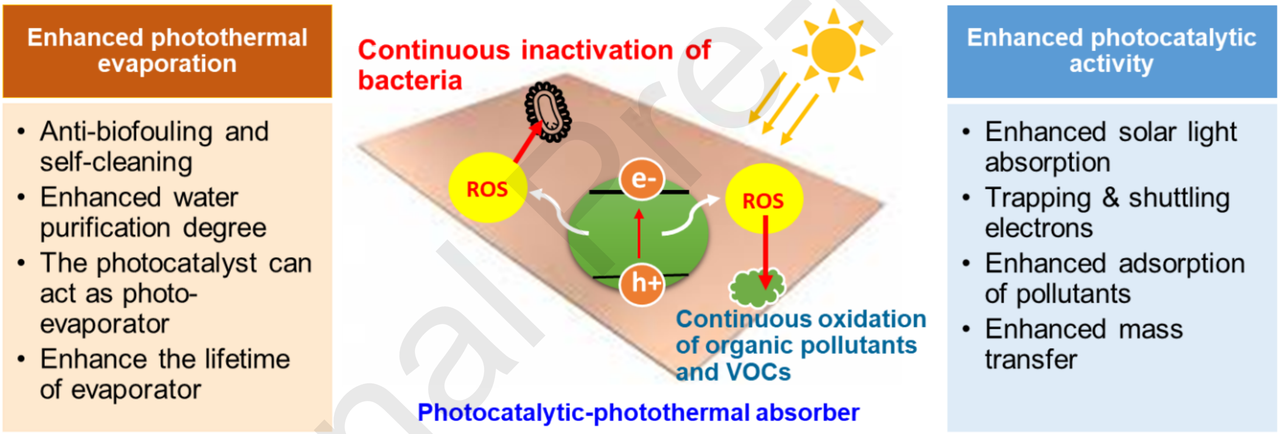

Figure 6. Synergistic effects in photocatalytic-photothermal absorbers.

5. Conclusions and perspectives

In this review, most advances in solar-driven stream systems were discussed from materials engineering to the main approaches to tackle the shortcomings of this technology. The contribution of photocatalysis to enhance and overcome some technical issues were addressed as well. In photoabsorber engineering, the construction of systems with indirect contact mode has proved to be more effective compared to direct mode. In this approach, the evaporating top surface is isolated from the bulk water using a convenient insulating layer. Designing such insulators to prevent the transfer of heat from the top surface to bulk water and allowing the pumping of water from the bulk to the top evaporating surface has recently been a hot research topic.

In the field of solar-driven steam generation materials, numerous light absorbers have been suggested in the literature with varying evaporation rates. While it is hard to assume which type of materials could be used successfully at a large scale, carbon-based materials could be considered as one of the best solar evaporators due to their high solar absorption and reasonable stability in harsh conditions for large-scale application. Aerogels and polymers have proved to be very effective, however, the low-long term stability may limit their large-scale use. Hybrid-based photoabsorbers, i.e., metal oxides or plasmonic metals with carbon materials or polymers, ensure very high evaporation rates due to the synergistic photonic effects. It is important to point out that the insulator characteristics have a direct impact on the evaporation rates, as they act directly to enhance the heat localization on the top surface of the evaporator. Therefore, obtaining a good combination between photo-absorber and a thermal insulator is a key factor to fabricate an efficient solar-driven steam system.

Many strategies have been put into solving widespread technology issues in solar-driven steam systems by designing smart materials and systems. Slat accumulation can be solved by the use of (i) periodically surface inversion strategy, (ii) surface with ion exchanging ability, and (iii) salt-rejecting disc which can remove the salt from the active top. For better heat generation and management, recent solutions were suggested including the use of 3D system, pyramid surface, and a light-reflective layer. The coating of evaporators with antibacterial agents, i.e., Ag or hydrophilic polymers, was suggested to inhibit/decrease the growth/accumulation of microorganisms.

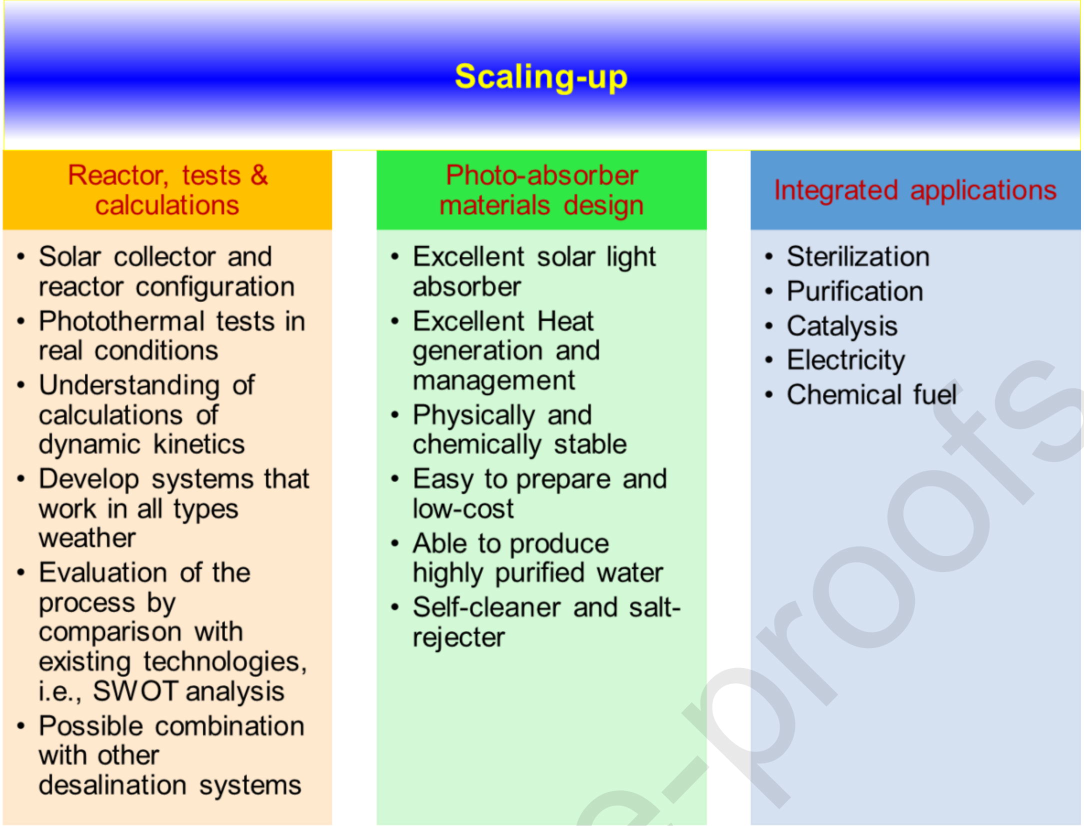

Figure 7. Main parameters to control for better scale-up opportunities for solar water evaporation and integrated applications.

The integration of photocatalysis with solar-driven steam can lead to an interesting combination that deserves more attention from the scientific community. This integration solves several common problems such as biofouling, VOCs contamination, organic pollutant accumulation, etc. In addition, synergistic effects in terms of light absorption and heat production can take place. The photocatalytic-photothermal solar-driven steam strategy may open new doors for further larger applications such as simultaneous wastewater purification and evaporation in real conditions. Usually, classical materials for photothermal solar-driven steam could face very fast surface deactivation in real wastewater due to the presence of organic pollutants and microorganisms. Furthermore, to clearly elucidate the photothermal mechanism of various processes as photocatalysis and solar to steam, both experimental and computational should be conducted. Further advancements in the integration of photocatalysis with solar-driven steam not only demand the synthesis of low-cost, well-controlled nanostructure but also those that are endowed with hybrid photonic, thermionic, and electronic functionalities that can be spatially modulated.

From a practical point of view, following recent achievements of high conversion efficiencies of photocatalytic-aided solar-driven steam process in laboratory studies, the evaluation of solar-driven steam process should be carried under outdoor natural conditions with natural sunlight. Identifying the main strength and weaknesses of the system may lead to better understanding and technology transfer as an alternative to existing technologies. More effort is needed to further enhance the efficiency of solar-driven steam applications through innovative process design and integration to interlink water purification/desalination and energy generation in an eco-friendly and synergistic approach (**Figure 7**). It is also recommended to investigate future systems that can operate efficiently under natural conditions in a continuous mode daily.

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CRediT authorship contribution statement

Ridha Djellabi: Conceptualization, Visualization, Organization, Writing, Review and editing. Laila Noureen: Writing, Organization, Review and editing. Van-Duong Dao: Writing, Visualization, Review and editing. Daniela Meroni: Review, editing and suggestion. Ermelinda Falletta: Review. Dionysios D. Dionysiou: Review, editing and suggestion. Claudia L. Bianchi: Review, editing and suggestion.

References

[1] P.J. Alvarez, C.K. Chan, M. Elimelech, N.J. Halas, D. Villagrán, Emerging opportunities for nanotechnology to enhance water security, Nat. Nanotechnol. 13(8) (2018) 634-641.

[2] G. Ni, S.H. Zandavi, S.M. Javid, S.V. Boriskina, T.A. Cooper, G. Chen, A salt-rejecting floating solar still for low-cost desalination, Energy Environ. Sci. 11(6) (2018) 1510-1519.

[3] L. Zhu, C. Fu Tan, M. Gao, G.W. Ho, Design of a Metal Oxide–Organic Framework (MoOF) foam microreactor: solar-induced direct pollutant degradation and hydrogen generation, Adv. Mater. 27(47) (2015) 7713-7719.

[4] R. Verbeke, V. Gomez, I.F. Vankelecom, Chlorine-resistance of reverse osmosis (RO) polyamide membranes, Prog. Polym. Sci. 72 (2017) 1-15.

[5] M. Elimelech, W.A. Phillip, The future of seawater desalination: energy, technology, and the environment, Science 333(6043) (2011) 712-717.

[6] M. Al-Sahali, H. Ettouney, Developments in thermal desalination processes: Design, energy, and costing aspects, Desalination 214(1-3) (2007) 227-240.

[7] A.D. Khawaji, I.K. Kutubkhanah, J.-M. Wie, Advances in seawater desalination technologies, Desalination 221(1-3) (2008) 47-69.

[8] M. Chandrashekara, A. Yadav, Water desalination system using solar heat: A review, Renew. Sust. Energy Rev. 67 (2017) 1308-1330.

[9] L. Zhu, M. Gao, C.K.N. Peh, G.W. Ho, Solar-driven photothermal nanostructured materials designs and prerequisites for evaporation and catalysis applications, Mater. Horizons 5(3) (2018) 323-343.

[10] H. Panchal, M.I. Patel, B. Patel, R. Goswami, M. Doshi, A comparative analysis of single slope solar still coupled with flat plate collector and passive solar still, Int. J. Res. Rev. Appl. Sci. 7(2) (2011) 111-116.

[11] Z. Wang, T. Horseman, A.P. Straub, N.Y. Yip, D. Li, M. Elimelech, S. Lin, Pathways and challenges for efficient solar-thermal desalination, Sci. Adv. 5(7) (2019) eaax0763.

[12] L. Zhou, Y. Tan, J. Wang, W. Xu, Y. Yuan, W. Cai, S. Zhu, J. Zhu, 3D self-assembly of aluminium nanoparticles for plasmon-enhanced solar desalination, Nat. Photonics 10(6) (2016) 393-398.

[13] L. Zhou, Y. Tan, D. Ji, B. Zhu, P. Zhang, J. Xu, Q. Gan, Z. Yu, J. Zhu, Self-assembly of highly efficient, broadband plasmonic absorbers for solar steam generation, Sci. Adv. 2(4) (2016) e1501227.

[14] M. Zhu, Y. Li, F. Chen, X. Zhu, J. Dai, Y. Li, Z. Yang, X. Yan, J. Song, Y. Wang, Plasmonic wood for high-efficiency solar steam generation, Adv. Energy Mater. 8(4) (2018) 1701028.

[15] L. Zhang, B. Tang, J. Wu, R. Li, P. Wang, Hydrophobic light-to-heat conversion membranes with self-healing ability for interfacial solar heating, Adv. Mater. 27(33) (2015) 4889-4894.

[16] H.N. Panchal, P.K. Shah, Improvement of solar still productivity by energy absorbing plates, Renew. Energy Environ. 1(1) (2014) 1-7.

[17] H.N. Panchal, P. Shah, Effect of varying glass cover thickness on performance of solar still: in a winter climate conditions, Int. J. Renew. Energy Res. 1(4) (2012) 212-223.

[18] L. Zhu, M. Gao, C.K.N. Peh, G.W. Ho, Recent progress in solar-driven interfacial water evaporation: advanced designs and applications, Nano Energy 57 (2019) 507-518.

[19] T. Yang, H. Lin, K.-T. Lin, B. Jia, Carbon-based absorbers for solar evaporation: Steam generation and beyond, Sustain. Mater. Technol. 25 (2020) e00182.

[20] S. Cao, Q. Jiang, X. Wu, D. Ghim, H.G. Derami, P.-I. Chou, Y.-S. Jun, S. Singamaneni, Advances in solar evaporator materials for freshwater generation, J. Mater. Chem. A 7(42) (2019) 24092-24123.

[21] V.-D. Dao, N.H. Vu, S. Yun, Recent advances and challenges for solar-driven water evaporation system toward applications, Nano Energy 68 (2020) 104324.

[22] K. Xu, C. Wang, Z. Li, S. Wu, J. Wang, Salt mitigation strategies of solar-driven interfacial desalination, Adv. Funct. Mater. 31(8) (2021) 2007855.

[23] J. Li, X. Zhou, J. Zhang, C. Liu, F. Wang, Y. Zhao, H. Sun, Z. Zhu, W. Liang, A. Li, Migration crystallization device based on biomass photothermal materials for efficient salt-rejection solar steam generation, ACS Appl. Energy Mater. 3(3) (2020) 3024-3032.

[24] Z. Deng, J. Zhou, L. Miao, C. Liu, Y. Peng, L. Sun, S. Tanemura, The emergence of solar thermal utilization: solar-driven steam generation, J. Mater. Chem. A 5(17) (2017) 7691-7709.

[25] M.S. Irshad, X. Wang, A. Abbas, F. Yu, J. Li, J. Wang, T. Mei, J. Qian, S. Wu, M.Q. Javed, Salt-resistant carbon dots modified solar steam system enhanced by chemical advection, Carbon 176 (2021) 313-326.

[26] Z.-B. Fang, T.-T. Liu, J. Liu, S. Jin, X.-P. Wu, X.-Q. Gong, K. Wang, Q. Yin, T.-F. Liu, R. Cao, Boosting interfacial charge-transfer kinetics for efficient overall co_2 photoreduction via rational design of coordination spheres on Metal–Organic Frameworks, J. Am. Chem. Soc. 142(28) (2020) 12515-12523.

[27] D. Fan, Y. Lu, H. Zhang, H. Xu, C. Lu, Y. Tang, X. Yang, Synergy of photocatalysis and photothermal effect in integrated 0D perovskite oxide/2D MXene heterostructures for simultaneous water purification and solar steam generation, Appl. Cat. B: Environ. 295 (2021) 120285.

[28] J. Ni, D. Liu, W. Wang, A. Wang, J. Jia, J. Tian, Z. Xing, Hierarchical defect-rich flower-like BiOBr/Ag nanoparticles/ultrathin g-C_3N_4 with transfer channels plasmonic Z-scheme heterojunction photocatalyst for accelerated visible-light-driven photothermal-photocatalytic oxytetracycline degradation, Chem. Eng. J. 419 (2021) 129969.

[29] P. Qiu, N. Xue, Z. Cheng, X. Kai, Y. Zeng, M. Xu, S. Zhang, C. Xu, F. Liu, Z. Guo, The cooperation of photothermal conversion, photocatalysis and sulfate radical-based advanced oxidation process on few-layered graphite modified graphitic carbon nitride, Chem. Eng. J. 417 (2021) 127993.

[30] Q. Wang, F. Jia, A. Huang, Y. Qin, S. Song, Y. Li, M.A.C. Arroyo, MoS_2@ sponge with double layer structure for high-efficiency solar desalination, Desalination 481 (2020) 114359.

[31] F. Zhao, Y. Guo, X. Zhou, W. Shi, G. Yu, Materials for solar-powered water evaporation, Nat. Rev. Mater. 5(5) (2020) 388-401.

[32] L. Qiao, N. Li, L. Luo, J. He, Y. Lin, J. Li, L. Yu, C. Guo, P. Murto, X. Xu, Design of monolithic closed-cell polymer foams via controlled gas-foaming for high-performance solar-driven interfacial evaporation, J. Mater. Chem. A 9(15) (2021) 9692-9705.

[33] Y. Wu, L. Shen, C. Zhang, H. Gao, J. Chen, L. Jin, P. Lin, H. Zhang, Y. Xia, Polyacid doping-enabled efficient solar evaporation of polypyrrole hydrogel, Desalination 505 (2021) 114766.

[34] F. Liu, W. Liang, C. Wang, J. He, C. Xiao, Z. Zhu, H. Sun, A. Li, Superwetting monolithic hypercrosslinked polymers nanotubes with high salt-resistance for efficient solar steam generation, Sol. Energy Mater. Sol. Cells 221 (2021) 110913.

[35] L. Gong, C. Li, N. Wei, J. Li, J. Shen, R. Xu, Q. Li, J. Tian, H. Cui, Highly efficient solar evaporator based on graphene/moo3-x coated porous nickel for water purification, Sep. Purif. Technol. (2021) 119139.

[36] J. Yan, W. Xiao, L. Chen, Z. Wu, J. Gao, H. Xue, Superhydrophilic carbon nanofiber membrane with a hierarchically macro/meso porous structure for high performance solar steam generators, Desalination 516 (2021) 115224.

[37] L. Zhou, , X. Li, , Ni, W. G., S. Zhu, , J. Zhu, (2019). The revival of thermal utilization from the Sun: interfacial solar vapor generation. Natl. Sci. Rev., 6(3), 562-578.

[38] M. Umlauff, J. Hoffmann, H. Kalt, W. Langbein, J.M. Hvam, M. Scholl, J. Söllner, M. Heuken, B. Jobst, D. Hommel, Direct observation of free-exciton thermalization in quantum-well structures, Phys. Rev. B Condens. Matter 57(3) (1998) 1390.

[39] N. Yu, Y. Hu, X. Wang, G. Liu, Z. Wang, Z. Liu, Q. Tian, M. Zhu, X. Shi, Z. Chen, Dynamically tuning near-infrared-induced photothermal performances of TiO_2 nanocrystals by Nb doping for imaging-guided photothermal therapy of tumors, Nanoscale 9(26) (2017) 9148-9159.

[40] P. Roy, S.K. Srivastava, Nanostructured copper sulfides: synthesis, properties and applications, CrystEngComm 17(41) (2015) 7801-7815.

[41] S. Sun, P. Li, S. Liang, Z. Yang, Diversified copper sulfide (Cu_2− x S) micro-/nanostructures: a comprehensive review on synthesis, modifications and applications, Nanoscale 9(32) (2017) 11357-11404.

[42] Z. Guo, X. Ming, G. Wang, B. Hou, X. Liu, T. Mei, J. Li, J. Wang, X. Wang, Super-hydrophilic copper sulfide films as light absorbers for efficient solar steam generation under one sun illumination, Semicond. Sci. Technol. 33(2) (2018) 025008.

[43] W. Huang, P. Su, Y. Cao, C. Li, D. Chen, X. Tian, Y. Su, B. Qiao, J. Tu, X. Wang, Three-dimensional hierarchical CuxS-based evaporator for high-efficiency multifunctional solar distillation, Nano Energy 69 (2020) 104465.

[44] X. Geng, D. Zhang, Z. Zheng, G. Ye, S. Li, H. Tu, Y. Wan, P. Yang, Integrated multifunctional device based on Bi_2S_3/Pd: Localized heat channeling for efficient photothermic vaporization and real-time health monitoring, Nano Energy 82 (2021) 105700.

[45] R. Xu, N. Wei, Z. Li, X. Song, Q. Li, K. Sun, E. Yang, L. Gong, Y. Sui, J. Tian, Construction of hierarchical 2D/2D Ti_3C_2/MoS2 nanocomposites for high-efficiency solar steam generation, J. Colloid Interface Sci. 584 (2021) 125-133.

[46] X. Li, D. Wang, Y. Zhang, L. Liu, W. Wang, Surface-ligand protected reduction on plasmonic tuning of one-dimensional MoO_3−x nanobelts for solar steam generation, Nano Res. 13(11) (2020) 3025-3032.

[47] H. Jiang, H. Fang, D. Wang, J. Sun, Spray-coated commercial PtFe membrane from mos2/laf3/pdms ink as solar absorber for efficient solar steam generation, Solar RRL 4(6) (2020) 2000126.

[48] R. Chen, X. Wang, Q. Gan, T. Zhang, K. Zhu, M. Ye, A bifunctional MoS_2-based solar evaporator for both efficient water evaporation and clean freshwater collection, J. Mater. Chem. A 7(18) (2019) 11177-11185.

[49] D. Ghim, Q. Jiang, S. Cao, S. Singamaneni, Y.-S. Jun, Mechanically interlocked 1T/2H phases of MoS2 nanosheets for solar thermal water purification, Nano Energy 53 (2018) 949-957.

[50] L. Song, X.-F. Zhang, Z. Wang, T. Zheng, J. Yao, Fe_3O_4/polyvinyl alcohol decorated delignified wood evaporator for continuous solar steam generation, Desalination 507 (2021) 115024.

[51] N. Wei, Z. Li, Q. Li, E. Yang, R. Xu, X. Song, J. Sun, C. Dou, J. Tian, H. Cui, Scalable and low-cost fabrication of hydrophobic PVDF/WS_2 porous membrane for highly efficient solar steam generation, J. Colloid Interface Sci. 588 (2021) 369-377.

[52] D. Li, D. Han, C. Guo, C. Huang, Facile preparation of MnO_2-deposited wood for high-efficiency solar steam generation, ACS Appl. Energy Mater. 4(2) (2021) 1752-1762.

[53] Y. Zeng, K. Wang, J. Yao, H. Wang, Hollow carbon beads for significant water evaporation enhancement, Chem. Eng. Sci. 116 (2014) 704-709.

[54] Y. Wang, L. Zhang, P. Wang, Self-floating carbon nanotube membrane on macroporous silica substrate for highly efficient solar-driven interfacial water evaporation, ACS Sustain. Chem. Eng. 4(3) (2016) 1223-1230.

[55] G. Liu, J. Xu, K. Wang, Solar water evaporation by black photothermal sheets, Nano Energy 41 (2017) 269-284.

[56] Q. Hou, C. Xue, N. Li, H. Wang, Q. Chang, H. Liu, J. Yang, S. Hu, Self-assembly carbon dots for powerful solar water evaporation, Carbon 149 (2019) 556-563.

[57] L. Zhu, M. Gao, C.K.N. Peh, X. Wang, G.W. Ho, Self-contained monolithic carbon sponges for solar-driven interfacial water evaporation distillation and electricity generation, Adv. Energy Mater. 8(16) (2018) 1702149.

[58] H. Yin, H. Xie, J. Liu, X. Zou, J. Liu, Graphene tube shaped photothermal layer for efficient solar-driven interfacial evaporation, Desalination 511 (2021) 115116.

[59] H. Jian, Q. Qi, W. Wang, D. Yu, A Janus porous carbon nanotubes/poly (vinyl alcohol) composite evaporator for efficient solar-driven interfacial water evaporation, Sep. Purif. Technol. 264 (2021) 118459.

[60] V.D. Dao, H.S. Choi, Carbon-based sunlight absorbers in solar-driven steam generation devices, Global Chall. 2(2) (2018) 1700094.

[61] H. Li, X. Li, H. Lei, G. Zhou, W. Zhang, R. Cao, Convenient immobilization of cobalt corroles on carbon nanotubes through covalent bonds for electrocatalytic hydrogen and oxygen evolution reactions, ChemSusChem 12(4) (2019) 801-806.

[62] D.-D. Qin, Y.-J. Zhu, F.-F. Chen, R.-L. Yang, Z.-C. Xiong, Self-floating aerogel composed of carbon nanotubes and ultralong hydroxyapatite nanowires for highly efficient solar energy-assisted water purification, Carbon 150 (2019) 233-243.

[63] B. Hou, Z. Cui, X. Zhu, X. Liu, G. Wang, J. Wang, T. Mei, J. Li, X. Wang, Functionalized carbon materials for efficient solar steam and electricity generation, Mater. Chem. Phys. 222 (2019) 159-164.

[64] D. Wu, J. Liang, D. Zhang, C. Zhang, H. Zhu, Solar evaporation and electricity generation of porous carbonaceous membrane prepared by electrospinning and carbonization, Sol. Energy Mater. Sol. Cells 215 (2020) 110591.

[65] V.-D. Dao, N.H. Vu, H.-S. Choi, All day Limnobium laevigatum inspired nanogenerator self-driven via water evaporation, J. Power Sources 448 (2020) 227388.

[66] J. Liu, J. Gui, W. Zhou, X. Tian, Z. Liu, J. Wang, L. Yang, P. Zhang, W. Huang, J. Tu, Self-regulating and asymmetric evaporator for efficient solar water-electricity generation, Nano Energy 86 (2021) 106112.

[67] G. Xue, Y. Xu, T. Ding, J. Li, J. Yin, W. Fei, Y. Cao, J. Yu, L. Yuan, L. Gong, Water-evaporation-induced electricity with nanostructured carbon materials, Nat. Nanotechnol. 12(4) (2017) 317-321.

[68] V.-D. Dao, An experimental exploration of generating electricity from nature-inspired hierarchical evaporator: The role of electrode materials, Sci. Total Environ. 759 (2021) 143490.

[69] Y. Shi, C. Zhang, Y. Wang, Y. Cui, Q. Wang, G. Liu, S. Gao, Y. Yuan, Plasmonic silver nanoparticles embedded in flexible three-dimensional carbonized melamine foam with enhanced solar-driven water evaporation, Desalination 507 (2021) 115038.

[70] Q. Hao, G. Jia, W. Wei, A. Vinu, Y. Wang, H. Arandiyan, B.-J. Ni, Graphitic carbon nitride with different dimensionalities for energy and environmental applications, Nano Res. 13(1) (2020) 18-37.

[71] J.R. Vélez-Cordero, J. Hernandez-Cordero, Heat generation and conduction in PDMS-carbon nanoparticle membranes irradiated with optical fibers, Int. J. Therm. Sci. 96 (2015) 12-22.

[72] L. Xie, J. Tian, Y. Ouyang, X. Guo, W. Zhang, U.P. Apfel, W. Zhang, R. Cao, Water-soluble polymers with appending porphyrins as bioinspired catalysts for the hydrogen evolution reaction, Angew. Chem. 132(37) (2020) 15978-15982.

[73] S. Meng, T. Gong, X. Zhao, C.-Y. Tang, P. Yu, R.-Y. Bao, K. Ke, Z.-Y. Liu, M.-B. Yang, W. Yang, Boosting solar steam generation in dynamically tunable polymer porous architectures, J. Polym. (2021) 123811.

[74] P. Mu, W. Bai, Y. Fan, Z. Zhang, H. Sun, Z. Zhu, W. Liang, A. Li, Conductive hollow kapok fiber-PPy monolithic aerogels with excellent mechanical robustness for efficient solar steam generation, J. Mater. Chem. A 7(16) (2019) 9673-9679.

[75] W. Huang, G. Hu, C. Tian, X. Wang, J. Tu, Y. Cao, K. Zhang, Nature-inspired salt resistant polypyrrole–wood for highly efficient solar steam generation, Sustain. Energy Fuels 3(11) (2019) 3000-3008.

[76] C. Wang, Y. Wang, X. Song, M. Huang, H. Jiang, A facile and general strategy to deposit polypyrrole on various substrates for efficient solar-driven evaporation, Adv. Sustain. Syst. 3(1) (2019) 1800108.

[77] X. Wang, Q. Liu, S. Wu, B. Xu, H. Xu, Multilayer polypyrrole nanosheets with self-organized surface structures for flexible and efficient solar–thermal energy conversion, Adv. Mater. 31(19) (2019) 1807716.

[78] C. Xiao, W. Liang, Q.-M. Hasi, L. Chen, J. He, F. Liu, C. Wang, H. Sun, Z. Zhu, A. Li, Ag/polypyrrole co-modified poly (ionic liquid) s hydrogels as efficient solar generators for desalination, Mater. Today Energy 16 (2020) 100417.

[79] Y. Xu, J. Wang, F. Yu, Z. Guo, H. Cheng, J. Yin, L. Yan, X. Wang, Flexible and efficient solar thermal generators based on polypyrrole coated natural latex foam for multimedia purification, ACS Sustain. Chem. Eng. 8(32) (2020) 12053-12062.

[80] S. Wang, Y. Fan, F. Wang, Y. Su, X. Zhou, Z. Zhu, H. Sun, W. Liang, A. Li, Potentially scalable fabrication of salt-rejection evaporator based on electrogenerated polypyrrole-coated nickel foam for efficient solar steam generation, Desalination 505 (2021) 114982.

[81] B. Wen, X. Zhang, Y. Yan, Y. Huang, S. Lin, Y. Zhu, Z. Wang, B. Zhou, S. Yang, J. Liu, Tailoring polypyrrole-based Janus aerogel for efficient and stable solar steam generation, Desalination 516 (2021) 115228.

[82] K. Wang, Z. Cheng, P. Li, Y. Zheng, Z. Liu, L. Cui, J. Xu, J. Liu, Three-dimensional self-floating foam composite impregnated with porous carbon and polyaniline for solar steam generation, J. Colloid Interface Sci. 581 (2021) 504-513.

[83] S. Fabiano, S. Braun, X. Liu, E. Weverberghs, P. Gerbaux, M. Fahlman, M. Berggren, X. Crispin, Poly (ethylene imine) impurities induce n-doping reaction in organic (semi) conductors, Adv. Mater. 26(34) (2014) 6000-6006.

[84] Y. Guo, G. Yu, Engineering hydrogels for efficient solar desalination and water purification, Acc. Mater. Res. (2021).

[85] Y. Guo, J. Bae, Z. Fang, P. Li, F. Zhao, G. Yu, Hydrogels and hydrogel-derived materials for energy and water sustainability, Chem. Rev. 120(15) (2020) 7642-7707.

[86] F. Zhao, X. Zhou, Y. Shi, X. Qian, M. Alexander, X. Zhao, S. Mendez, R. Yang, L. Qu, G. Yu, Highly efficient solar vapour generation via hierarchically nanostructured gels, Nat. Nanotechnol. 13(6) (2018) 489-495.

[87] H. Wang, R. Zhang, D. Yuan, S. Xu, L. Wang, Gas foaming guided fabrication of 3D porous plasmonic nanoplatform with broadband absorption, tunable shape, excellent stability, and high photothermal efficiency for solar water purification, Adv. Funct. Mater. 30(46) (2020) 2003995.

[88] W. Fang, L. Zhao, H. Chen, X. He, W. Li, X. Du, Z. Sun, T. Zhang, Y. Shen, Graphene oxide foam fabricated with surfactant foaming method for efficient solar vapor generation, J. Mater. Sci. 54(19) (2019) 12782-12793.

[89] A. Lalisse, G. Tessier, J. Plain, G. Baffou, Quantifying the efficiency of plasmonic materials for near-field enhancement and photothermal conversion, J. Phys. Chem. C 119(45) (2015) 25518-25528.

[90] M. Gao, P.K.N. Connor, G.W. Ho, Plasmonic photothermic directed broadband sunlight harnessing for seawater catalysis and desalination, Energy Environ. Sci. 9(10) (2016) 3151-3160.

[91] L. Zhang, J. Xing, X. Wen, J. Chai, S. Wang, Q. Xiong, Plasmonic heating from indium nanoparticles on a floating microporous membrane for enhanced solar seawater desalination, Nanoscale 9(35) (2017) 12843-12849.

[92] R. Cui, J. Wei, C. Du, S. Sun, C. Zhou, H. Xue, S. Yang, Engineering trace AuNPs on monodispersed carbonized organosilica microspheres drives highly efficient and low-cost solar water purification, J. Mater. Chem. A 8(26) (2020) 13311-13319.

[93] M. Gao, C.K. Peh, H.T. Phan, L. Zhu, G.W. Ho, Solar absorber gel: localized macro-nano heat channeling for efficient plasmonic Au nanoflowers photothermic vaporization and triboelectric generation, Adv. Energy Mater. 8(25) (2018) 1800711.

[94] C. Chen, H. Liu, H. Wang, Y. Zhao, M. Li, A scalable broadband plasmonic cuprous telluride nanowire-based hybrid photothermal membrane for efficient solar vapor generation, Nano Energy 84 (2021) 105868.

[95] Z. Liu, Q. Zhong, N. Wu, H. Zhou, L. Wang, L. Zhu, N. Jiang, B. Zhu, Z. Chen, M. Zhu, Vertically symmetrical evaporator based on photothermal fabrics for efficient continuous desalination through inversion strategy, Desalination 509 (2021) 115072.

[96] P. Qiu, F. Liu, C. Xu, H. Chen, F. Jiang, Y. Li, Z. Guo, Porous three-dimensional carbon foams with interconnected microchannels for high-efficiency solar-to-vapor conversion and desalination, J. Mater. Chem. A 7(21) (2019) 13036-13042.

[97] D.P. Storer, J.L. Phelps, X. Wu, G. Owens, N.I. Khan, H. Xu, Graphene and rice-straw-fiber-based 3D photothermal aerogels for highly efficient solar evaporation, ACS Appl. Mater. Interfaces 12(13) (2020) 15279-15287.

[98] Z. Li, W. Cai, X. Wang, Y. Hu, Z. Gui, Self-floating black phosphorous nanosheets as a carry-on solar vapor generator, J. Colloid Interface Sci. 582 (2021) 496-505.

[99] Y. Liu, S. Yu, R. Feng, A. Bernard, Y. Liu, Y. Zhang, H. Duan, W. Shang, P. Tao, C. Song, A bioinspired, reusable, paper-based system for high-performance large-scale evaporation, Adv. Mater. 27(17) (2015) 2768-2774.

[100] P. Ren, X. Yang, Bifunctional Cu_2-xSe-decorated hierarchical TiO_2 nanotube mesh with solar water evaporation and photodegradation effects for clean water generation, Water Supply 19(7) (2019) 2001-2008.

[101] F. Liu, W. Liang, C. Wang, C. Xiao, J. He, G. Zhao, Z. Zhu, H. Sun, A. Li, Superhydrophilic and mechanically robust phenolic resin as double layered photothermal materials for efficient solar steam generation, Mater. Today Energy 16 (2020) 100375.

[102] B. Shao, Y. Wang, X. Wu, Y. Lu, X. Yang, G.Y. Chen, G. Owens, H. Xu, Stackable nickel–cobalt@ polydopamine nanosheet based photothermal sponges for highly efficient solar steam generation, J. Mater. Chem. A 8(23) (2020) 11665-11673.

[103] M.S. Irshad, X. Wang, M.S. Abbasi, N. Arshad, Z. Chen, Z. Guo, L. Yu, J. Qian, J. You, T. Mei, Semiconductive, Flexible MnO_2 NWs/Chitosan hydrogels for efficient solar steam generation, ACS Sustain. Chem. Eng. 9(10) (2021) 3887-3900.

[104] Y. Xu, J. Ma, Y. Han, H. Xu, Y. Wang, D. Qi, W. Wang, A simple and universal strategy to deposit Ag/polypyrrole on various substrates for enhanced interfacial solar evaporation and antibacterial activity, Chem. Eng. J. 384 (2020) 123379.

[105] P. He, L. Hao, N. Liu, H. Bai, R. Niu, J. Gong, Controllable synthesis of sea urchin-like carbon from metal-organic frameworks for advanced solar vapor generators, Chem. Eng. J. (2021) 130268.

[106] P. Wang, Emerging investigator series: the rise of nano-enabled photothermal materials for water evaporation and clean water production by sunlight, Environ. Sci.: Nano 5(5) (2018) 1078-1089.

[107] V.-D. Dao, N.H. Vu, H.-L.T. Dang, S. Yun, Recent advances and challenges for water evaporation-induced electricity toward applications, Nano Energy (2021) 105979.

[108] C. Chen, Y. Kuang, L. Hu, Challenges and opportunities for solar evaporation, Joule 3(3) (2019) 683-718.

[109] Y. Pang, J. Zhang, R. Ma, Z. Qu, E. Lee, T. Luo, Solar–thermal water evaporation: a review, ACS Energy Lett. 5(2) (2020) 437-456.

[110] L. Song, P. Mu, L. Geng, Q. Wang, J. Li, A novel salt-rejecting linen fabric-based solar evaporator for stable and efficient water desalination under highly saline water, ACS Sustain. Chem. Eng. 8(31) (2020) 11845-11852.

[111] Q. Huang, C. Du, C. Guo, C. Huang, X. Wang, A high-efficiency salt-rejecting solar evaporator with optimized porous structure for continuous solar desalination, Appl. Therm. Eng. 187 (2021) 116515.

[112] D. Li, X. Zhang, S. Zhang, D. Wang, Z. Wang, Y. Liu, X. Yu, Q. Zhao, B. Xing, A flexible and salt-rejecting electrospun film-based solar evaporator for economic, stable and efficient solar desalination and wastewater treatment, Chemosphere 267 (2021) 128916.

[113] Z. Liu, B. Wu, B. Zhu, Z. Chen, M. Zhu, X. Liu, Continuously producing watersteam and concentrated brine from seawater by hanging photothermal fabrics under sunlight, Adv. Funct. Mater. 29(43) (2019) 1905485.

[114] Y. Yang, H. Zhao, Z. Yin, J. Zhao, X. Yin, N. Li, D. Yin, Y. Li, B. Lei, Y. Du, A general salt-resistant hydrophilic/hydrophobic nanoporous double layer design for efficient and stable solar water evaporation distillation, Mater. Horizons 5(6) (2018) 1143-1150.

[115] S. He, C. Chen, Y. Kuang, R. Mi, Y. Liu, Y. Pei, W. Kong, W. Gan, H. Xie, E. Hitz, Nature-inspired salt resistant bimodal porous solar evaporator for efficient and stable water desalination, Energy Environ. Sci. 12(5) (2019) 1558-1567.

[116] W. Xu, X. Hu, S. Zhuang, Y. Wang, X. Li, L. Zhou, S. Zhu, J. Zhu, Flexible and salt resistant Janus absorbers by electrospinning for stable and efficient solar desalination, Adv. Energy Mater. 8(14) (2018) 1702884.

[117] Q. Zhang, H. Yang, X. Xiao, H. Wang, L. Yan, Z. Shi, Y. Chen, W. Xu, X. Wang, A new self-desalting solar evaporation system based on a vertically oriented porous polyacrylonitrile foam, J. Mater. Chem. A 7(24) (2019) 14620-14628.

[118] L. Wu, Z. Dong, Z. Cai, T. Ganapathy, N.X. Fang, C. Li, C. Yu, Y. Zhang, Y. Song, Highly efficient three-dimensional solar evaporator for high salinity desalination by localized crystallization, Nat. Commun. 11(1) (2020) 1-12.

[119] Y. Li, X.-l. Shi, L.-j. Sun, M. Zhao, T. Jiang, W. Jiang, M. Deng, S. Yang, Y. Wang, Composite hydrogel-based photothermal self-pumping system with salt and bacteria resistance for super-efficient solar-powered water evaporation, Desalination 515 (2021) 115192.

[120] Y. Xiao, X. Wang, C. Li, H. Peng, T. Zhang, M. Ye, A salt-rejecting solar evaporator for continuous steam generation, J. Environ. Chem. Eng. 9(1) (2021) 105010.

[121] X. Wang, Q. Gan, R. Chen, H. Peng, T. Zhang, M. Ye, Water delivery channel design in solar evaporator for efficient and durable water evaporation with salt rejection, ACS Sustain. Chem. Eng. 8(21) (2020) 7753-7761.

[122] J. Chen, J.L. Yin, B. Li, Z. Ye, D. Liu, D. Ding, F. Qian, N.V. Myung, Q. Zhang, Y. Yin, Janus evaporators with self-recovering hydrophobicity for salt-rejecting interfacial solar desalination, ACS Nano 14(12) (2020) 17419-17427.

[123] Y. Xia, Q. Hou, H. Jubaer, Y. Li, Y. Kang, S. Yuan, H. Liu, M.W. Woo, L. Zhang, L. Gao, Spatially isolating salt crystallisation from water evaporation for continuous solar steam generation and salt harvesting, Energy Environ. Sci. 12(6) (2019) 1840-1847.

[124] N. Xu, J. Li, Y. Wang, C. Fang, X. Li, Y. Wang, L. Zhou, B. Zhu, Z. Wu, S. Zhu, A water lily–inspired hierarchical design for stable and efficient solar evaporation of high-salinity brine, Sci. Adv. 5(7) (2019) eaaw7013.

[125] X. Wang, G. Ou, N. Wang, H. Wu, Graphene-based recyclable photo-absorbers for high-efficiency seawater desalination, ACS Appl. Mater. Interfaces 8(14) (2016) 9194-9199.

[126] Y. Wang, X. Wu, B. Shao, X. Yang, G. Owens, H. Xu, Boosting solar steam generation by structure enhanced energy management, Sci. Bull. 65(16) (2020) 1380-1388.

[127] S.-L. Wu, H. Chen, H.-L. Wang, X. Chen, H.-C. Yang, S.B. Darling, Solar-driven evaporators for water treatment: challenges and opportunities, Environmental Science: Water Res. Technol.7(1) (2021) 24-39.

[128] F. Peng, J. Xu, X. Bai, G. Feng, X. Zeng, M.R.I. Raihan, H. Bao, A janus solar evaporator with 2D water path for highly efficient salt-resisting solar steam generation, Sol. Energy Mater. Sol. Cells 221 (2021) 110910.

[129] X. Wu, Z. Wu, Y. Wang, T. Gao, Q. Li, H. Xu, All-Cold Evaporation under one sun with zero energy loss by using a heatsink inspired solar evaporator, Adv. Sci. 8(7) (2021) 2002501.

[130] S. Zhou, S. Huang, Y. Ming, Y. Long, H. Liang, S. Ruan, Y.-J. Zeng, H. Cui, A scalable, eco-friendly, and ultrafast solar steam generator fabricated using evolutional 3D printing, J. Mater. Chem. A 9(15) (2021) 9909-9917.

[131] T. Xu, Y. Xu, J. Wang, H. Lu, W. Liu, J. Wang, Sustainable self-cleaning evaporator for long-term solar desalination using gradient structure tailored hydrogel, Chem. Eng. J. 415 (2021) 128893.

[132] Y. Fan, Z. Tian, F. Wang, J. He, X. Ye, Z. Zhu, H. Sun, W. Liang, A. Li, Enhanced solar-to-heat efficiency of photothermal materials containing an additional light-reflection layer for solar-driven interfacial water evaporation, ACS Appl. Energy Mater. 4(3) (2021) 2932-2943.

[133] Y. Shi, R. Li, Y. Jin, S. Zhuo, L. Shi, J. Chang, S. Hong, K.-C. Ng, P. Wang, A 3D photothermal structure toward improved energy efficiency in solar steam generation, Joule 2(6) (2018) 1171-1186.

[134] Q. Yang, C. Xu, F. Wang, Z. Ling, Z. Zhang, X. Fang, A high-efficiency and low-cost interfacial evaporation system based on graphene-loaded pyramid polyurethane sponge for wastewater and seawater treatments, ACS Appl. Energy Mater. 2(10) (2019) 7223-7232.

[135] H. Fan, A. Gao, G. Zhang, S. Zhao, J. Cui, Y. Yan, A design of bifunctional photothermal layer on polysulfone membrane with enclosed cellular-like structure for efficient solar steam generation, Chem. Eng. J. 415 (2021) 128798.

[136] X. Zhou, F. Zhao, Y. Guo, Y. Zhang, G. Yu, A hydrogel-based antifouling solar evaporator for highly efficient water desalination, Energy Environ. Sci. 11(8) (2018) 1985-1992.

[137] Y. Yang, W. Que, J. Zhao, Y. Han, M. Ju, X. Yin, Membrane assembled from anti-fouling copper-zinc-tin-selenide nanocarambolas for solar-driven interfacial water evaporation, Chem. Eng. J. 373 (2019) 955-962.

[138] X.-Y. Wang, J. Xue, C. Ma, T. He, H. Qian, B. Wang, J. Liu, Y. Lu, Anti-biofouling double-layered unidirectional scaffold for long-term solar-driven water evaporation, J. Mater. Chem. A 7(28) (2019) 16696-16703.

[139] Y. Xu, J. Ma, Y. Han, J. Zhang, F. Cui, Y. Zhao, X. Li, W. Wang, Multifunctional CuO nanowire mesh for highly efficient solar evaporation and water purification, ACS Sustain. Chem. Eng. 7(5) (2019) 5476-5485.

[140] L. Noureen, Z. Xie, Y. Gao, M. Li, M. Hussain, K. Wang, L. Zhang, J. Zhu, Multifunctional Ag_3PO_4-rGO-coated textiles for clean water production by solar-driven evaporation, photocatalysis, and disinfection, ACS Appl. Mater. Interfaces 12(5) (2020) 6343-6350.

[141] Y. Liu, J. Lou, M. Ni, C. Song, J. Wu, N.P. Dasgupta, P. Tao, W. Shang, T. Deng, Bioinspired bifunctional membrane for efficient clean water generation, ACS Appl. Mater. Interfaces 8(1) (2016) 772-779.

[142] X. Wang, J. Ding, S. Yao, X. Wu, Q. Feng, Z. Wang, B. Geng, High supercapacitor and adsorption behaviors of flower-like MoS_2 nanostructures, J. Mater. Chem. A 2(38) (2014) 15958-15963.

[143] S. Zuo, D. Xia, Z. Guan, F. Yang, S. Cheng, H. Xu, R. Wan, D. Li, M. Liu, Dual-functional CuO/CN for highly efficient solar evaporation and water purification, Sep. Purif. Technol. 254 (2021) 117611.

[144] D. Zhang, M. Zhang, S. Chen, Q. Liang, N. Sheng, Z. Han, Y. Cai, H. Wang, Scalable, self-cleaning and self-floating bi-layered bacterial cellulose biofoam for efficient solar evaporator with photocatalytic purification, Desalination 500 (2021) 114899.

[145] Z. Zhang, Z. Xing, K. Wang, T. Cheng, Z. Li, W. Zhou, Bi_2S_3@ Ag2S nano-heterojunction decorated self-floating carbon fiber cloth and enhanced solar-driven photothermal-photocatalytic performance, Chemosphere 271 (2021) 129500.

[146] R. Zhu, M. Liu, Y. Hou, D. Wang, L. Zhang, D. Wang, S. Fu, Mussel-inspired photothermal synergetic system for clean water production using full-spectrum solar energy, Chem. Eng. J. 423 (2021) 129099.

[147] Y. Li, Q. Shen, R. Guan, J. Xue, X. Liu, H. Jia, B. Xu, Y. Wu, AC@ TiO_2 yolk–shell heterostructure for synchronous photothermal–photocatalytic degradation of organic pollutants, J. Mater. Chem. C 8(3) (2020) 1025-1040.

[148] L. Noureen, Z. Xie, M. Hussain, M. Li, Q. Lyu, K. Wang, L. Zhang, J. Zhu, $BiVO_4$ and reduced graphene oxide composite hydrogels for solar-driven steam generation and decontamination of polluted water, Sol. Energy Mater. Sol. Cells 222 (2021) 110952.

[149] L. Shi, Y. Shi, C. Zhang, S. Zhuo, W. Wang, R. Li, P. Wang, An integrated photocatalytic and photothermal process for solar-driven efficient purification of complex contaminated water, Energy Technol. 8(9) (2020) 2000456.

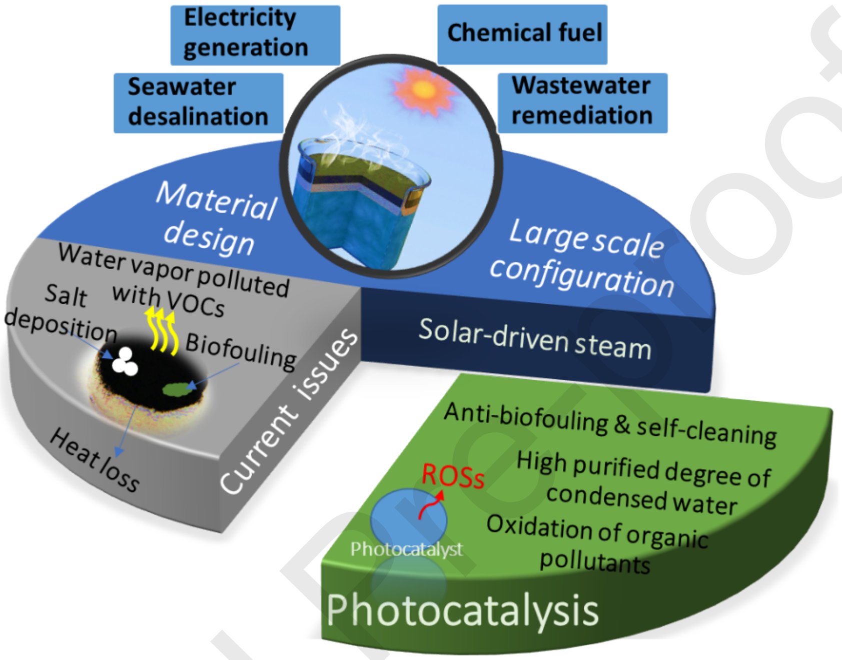
[150] R. Djellabi, R. Giannantonio, E. Falletta, C.L. Bianchi, SWOT analysis of photocatalytic materials towards large scale environmental remediation, Curr. Opin. Chem. Eng. 33 (2021) 100696.

[151] M.G. Alalm, R. Djellabi, D. Meroni, C. Pirola, C.L. Bianchi, D.C. Boffito, Toward scaling-up photocatalytic process for multiphase environmental applications, Catalysts 11(5) (2021) 562.

[152] Z. Gan, X. Wu, M. Meng, X. Zhu, L. Yang, P.K. Chu, Photothermal contribution to enhanced photocatalytic performance of graphene-based nanocomposites, ACS Nano 8(9) (2014) 9304-9310.

[153] R. Djellabi, M.F. Ghorab, A. Smara, C.L. Bianchi, G. Cerrato, X. Zhao, B. Yang, Titania–Montmorillonite for the photocatalytic removal of contaminants from water: adsorb & shuttle process, Green materials for wastewater treatment, Springer 2020, pp. 291-319.

Graphical abstract



Highlights

- Advances in emerging solar-driven steam materials towards water desalination
- Main technology issues and challenges facing photothermal water desalination
- Reported strategies to overcome technology issues and enhance the desalination efficiency
- Contribution of photocatalysis in photothermal materials to solve some technology issues
- Photocatalytic-photothermal synergism towards water desalination and purification