



Review

Recent advances in conducting polymers for hybrid solar-driven evaporation systems: Fundamentals, innovations, and applications

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ABSTRACT

Solar-driven interfacial evaporation (SDIE) has emerged as a sustainable solution for addressing global water scarcity and energy challenges. This review comprehensively examines the integration of conducting polymers (CPs) into hybrid solar-driven evaporation systems, synergizing them with complementary energy resources to enhance efficiency and multifunctionality. First, we systematically classify key CPs such as polypyrrole (PPy), polyaniline (PANI), poly(3,4-ethylenedioxythiophene) (PEDOT), Poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT: PSS), and poly(3-hexylthiophene) (P3HT), detailing their synthesis methods, structural properties, and inherent challenges such as stability and scalability. Then, the focus shifted toward the design and fabrication of CP-based photothermal evaporators (foam, wood, hydrogel, aerogel, membrane, and plant-based systems), which are critically analyzed, alongside vapor generation mechanisms under varying solar irradiance. Recent advancements in optimizing evaporator performance through material engineering and hybrid energy inputs are highlighted, offering pathways to improve evaporation rates and energy utilization. Beyond water production, the applications of CP-based photothermal materials (PTMs) are explored in desalination, water purification, and solar-driven photocatalysis, underscoring their versatility. Challenges, including long-term durability, environmental impact, and cost-effectiveness, are addressed, with proposed strategies for scalable manufacturing and integration with smart technologies. By contextualizing this review against existing literature, we emphasize its unique focus on CP-driven hybrid systems and their multifunctional applications. This work provides a roadmap for advancing SDIE technologies toward practical implementation, advocating interdisciplinary approaches to overcome current limitations and harness CPs' full potential in sustainable energy-water nexus solutions.

1. Introduction

According to the United Nations World Water Development Report

2020, global water consumption has surged sixfold over the past century and continues to rise by approximately 1 % annually. This steady growth is attributed to the expanding population, economic expansion, and

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changing deployment patterns. By 2050, an estimated 3.9 billion people (exceeding 40 % of the global population) are expected to experience acute water scarcity, affecting nearly the whole populations of the Middle East and South Asia, as well as substantial regions in China and North Africa [1,2]. Global warming, rapid industrialization, population growth, and urbanization are significantly disrupting the balance between the demand and availability of vital resources [3,4]. Currently, between 1.8 and 2.9 billion people worldwide experience acute freshwater shortages for not less than 4 months each year, while fossil fuel reserves continue to deplete rapidly [5–7]. These intertwined water and energy crises have intensified the need for sustainable, low-cost technologies capable of addressing both challenges simultaneously.

Conventional desalination approaches, such as reverse osmosis [8], multi-stage flash evaporation, and multi-effect distillation, are highly effective but energy-intensive and costly, which limits their use in resource-constrained regions. For instance, forward osmosis suffers from internal concentration polarization and fouling, whereas large-scale desalination plants remain energy-intensive and raise environmental concerns [9]. SDIE has therefore emerged as a sustainable alternative, utilizing solar energy for water purification with minimal environmental impact [10,11]. Recent advances in photocatalysis enable efficient visible-near infrared (Vis-NIR) photon harvesting, hybrid photovoltaic (PV)-thermal systems improve energy utilization, and perovskite PVs remain dominant due to scalability. Nonetheless, solar energy faces challenges of intermittency and dispersed availability. Unlike bulk water heating, SDIE relies on PTMs that localize heat at the water-air interface, achieving high solar-to-vapor efficiency [12,13]. Representative PTMs include plasmonic Au nanoparticles (NPs) for localized heating [14], porous receivers and nanofluids with efficiencies up to 85 % [15], and plasmonic Al membranes achieving ~90 % desalination durability [16]. Traditional solar stills are simple but require modifications for higher productivity [17], while NP dispersions enable steam generation without bulk heating [18]. Nanofluid-based systems report ~69 % vapor efficiency [19], underscoring the importance of interfacial heating and advanced PTM integration [20], aligned with broader advances in sustainable materials [21,22]. While diverse PTMs such as plasmonic metals, carbon-based materials, and semiconductors have been explored [23,24], many face limitations, including high cost, brittleness, and complex processing [25]. In this context, CPs and their hybrids represent a particularly attractive class of PTMs for hybrid solar-driven evaporation. CPs such as PANI, PPy, PEDOT, and P3HT offer several advantages: broadband solar absorption, tunable conductivity, structural flexibility, low cost, and facile processing. Unlike inorganic absorbers, CPs can be spray-coated, printed, or electron-spun on a wide range of substrates, enabling scalable and adaptable device architectures. Furthermore, their porous and flexible structures enhance water transport, reduce heat loss, and resist salt accumulation, thereby improving long-term operation and stability in solar evaporation systems [16,26].

Beyond fresh water production, CP-based solar evaporators have demonstrated multifunctionality in oil-water separation, biomedical applications, and energy harvesting [27]. Key reviews emphasize strategies to boost solar-water efficiency and scalability, while also highlighting persistent challenges [23,28]. However, salt accumulation remains a major barrier to long-term stability, requiring innovative material and structural solutions [19]. Recent advances include integrated photothermal-thermogalvanic devices achieving 91.4 % efficiency with concurrent electricity generation [29], black titania nanocages reaching 70.9 % conversion efficiency [30], and low-cost aerogels from cotton/CuS yolk-shell nanocages achieving 94.9 % efficiency [31]. Hybrid designs that integrate CPs with carbonaceous materials such as graphene, carbon nanotubes (CNTs), MXenes, metal oxides, or plasmonic nanostructures provide synergistic benefits, including improved charge transport, heat localization, and structural stability [32]. These innovations have enabled CP-based systems to achieve high water evaporation rate (WER) and photothermal conversion efficiencies (PCE), while maintaining operational stability and

scalability.

This review aims to examine the most recent developments in CP-based materials and their emerging roles in environmental applications, with a special focus on wastewater treatment, desalination, SDIE, and photocatalysis. CPs, such as PEDOT: PSS, PANI, PPy, and P3HT, have demonstrated significant promise as PTMs due to their light absorption, stability, and tunable conductivity. These materials have been actively explored for solar-driven water purification processes where their unique physicochemical properties enable efficient photothermal conversion, improved water transport, and resistance to salt accumulation. We provide a summary of various engineering strategies for enhancing the performance of these materials, including methods of synthesis, surface functionalization, and composite formation. Recent advances in the application of these technologies for wastewater purification, desalination, photocatalysis, and the sustainable energy-water nexus are discussed. As depicted in Fig. 1, conducting scaffolds are either intrinsically conductive or functionalized with CPs or carbon-based nanomaterials such as graphene oxide and cellulose, and present challenges while designing these materials. These material systems collectively form a foundation for future sustainable technologies in water purification and clean energy applications.

As shown in Table 1, recent reviews on solar water evaporation have predominantly focused on specific technical domains. In this review, a comprehensive analysis of CPs is presented, emphasizing their use as PTMs, their structural morphologies conducive to capillary-driven water transport, optical properties, and various synthesis strategies. Relevant tables are provided to support a thorough analysis and to highlight potential directions for future research. Furthermore, this study explores the applications of CPs across the water-energy-health nexus, specifically categorizing their roles in water purification, SDIE technologies, and photocatalysis, aiming to aid the design of next-generation multifunctional SDIE evaporators. The influence of key physicochemical properties such as photostability, broadband light absorption, tunable conductivity, and efficient heat generation on the performance of CPs in environmental applications is also discussed. In addition, the multifunctionality of PTMs is examined with respect to pollutant degradation, photocatalysis, and solar-driven water purification. Finally, the review provides insights into current challenges and future directions, focusing on issues such as scalability, stability, selectivity, and field of applicability, through the integration of material design principles with practical environmental considerations. This work is intended to serve as a valuable resource for early-career researchers and established scientists working on SDIE technology, offering deep insights into the role of CPs as PTMs and their potential in sustainable water-energy systems.

2. Conducting polymers: synthesis, properties, and design

CPs are a distinctive class of organic materials that combine electrical conductivity with tunable optoelectronic properties. Their π -conjugated backbone facilitates charge transport, making them highly versatile for applications in energy storage, sensing, and photothermal processes such as solar vapor evaporation. In recent years, CPs have gained significant attention for SDIE systems due to their exceptional optical and electronic characteristics. Their strong light absorption, efficient photothermal conversion, and adjustable conductivity make them ideal candidates for SDIE. In comparison to other PTMs, CPs such as PANI, PPy, PEDOT, and other polythiophene (PTh) derivatives, *etc.*, offer notable advantages, including cost-effectiveness, chemical stability, and structural adaptability [30,31,41,42]. These polymers effectively capture solar energy and transform it into heat, enabling rapid water evaporation with minimal energy dissipation. By integrating CPs-based NCs with enhanced surface area and thermal insulation, researchers seek to advance water purification and desalination technologies, promoting greater energy efficiency and sustainability [43].

CPs such as PANI, PPy, PEDOT: PSS, and P3HT possess unique features that enhance their performance in solar-driven seawater

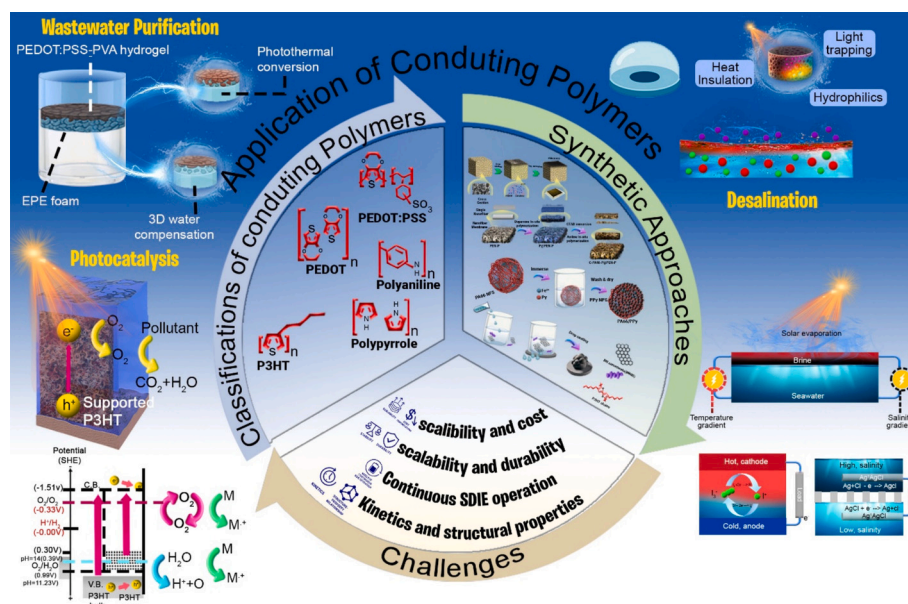


Fig. 1. Schematic roadmap illustrating the concept of CP-based PTMs for various applications and integration of material design, and challenges.

desalination. Their conjugated backbones and surface functional groups enable efficient solar absorption and interaction with ions in saline water, improving salt tolerance and evaporation efficiency. In PANI, protonated $-\text{NH}^+$ groups interact electrostatically with salt ions, reducing surface accumulation and enhancing long-term performance [32]. PPY exhibits strong light absorption and high conductivity, while its hydrophilic nature promotes water transport and surface wettability, improving stability under saline conditions [44]. PEDOT:PSS contains sulfonate ($-\text{SO}_3^-$) groups that stabilize the polymer in high-salinity environments and maintain photothermal efficiency [45]. P3HT offers strong solar absorption, and surface functionalization can impart salt-repellent behavior for stable evaporation [46]. Overall, these CPs combine intrinsic photothermal conversion, tunable electronic properties, and charged functional groups to enable efficient water transport, superior salt tolerance, and stable solar-vapor generation, making them highly effective for seawater desalination applications.

CPs have shown great promise as PTMs for solar water evaporation, wastewater treatment, and desalination due to their strong light absorption, efficient solar-to-heat conversion, and environmental stability. In particular, PEDOT:PSS combines excellent conductivity with biocompatibility, making it suitable for both clean water generation and biomedical applications like photothermal imaging and tissue scaffolds. These polymers are often fabricated into porous, biomimetic structures using techniques like electrospinning, freeze-drying, and oxidative polymerization, which enhance their photothermal performance and adaptability for device integration (Fig. 2). While P3HT is not commonly used for solar water evaporation, it is widely applied in thermal imaging, optoelectronic, PVs, and water-electricity co-generation devices due to its strong Vis-NIR absorption and high PCE. Advances in additive manufacturing now enable customized scaffold design, but challenges such as long-term stability, scalability, and cytocompatibility still need to be addressed for real-world applications.

2.1. Poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate)

PEDOT, a dark, conductive polymer with a rich π -conjugated structure, exhibits excellent stability, biocompatibility, and potential for photothermal conversion applications. When combined with PSS, it forms PEDOT:PSS, a water-dispersible complex that enhances processability, flexibility, and stability for applications in electronics, energy storage, medicinal chemistry, and photothermal conversion.

Xu et al. developed a bilayered wood-PEDOT:PSS hydrogel (PPH) interfacial evaporator utilizing a facile drop-casting and dry-annealing approach (Fig. 3a). The integration of nanofibrous PEDOT:PSS within the hydrogel matrix enabled excellent light absorption ($\sim 99.9\%$) and efficient photothermal conversion, while the inherent hydrophilicity and rapid water transport properties of wood facilitated efficient water supply to the evaporative interface via capillary action through porous structure presented in Fig. 3b. As a result, the bilayered wood-PPH evaporator achieved a high evaporation rate of approximately $1.47 \text{ kg m}^{-2} \text{ h}^{-1}$ and energy efficiency of $\sim 75.76\%$ under 1 kW m^{-2} solar irradiation. The PPH network successfully permeated and integrated within the wood matrix, enhancing chain entanglement (Fig. 3c). This process resulted in a PPH layer of defined thickness and established strong interfacial bonds within the wood's microstructure. Furthermore, practical evaluations demonstrated the evaporator's effectiveness in sewage purification and seawater desalination and exhibited remarkable long-term stability over a continuous 10-day operation in simulated seawater. Additionally, the system displayed an ultrahigh ion removal efficiency of 99.0% for metal ion-containing wastewater, highlighting its potential for sustainable steam generation applications (Fig. 3d) [47]. PEDOT:PSS-NFC aerogels were synthesized by freeze-drying a blend of PEDOT:PSS, carboxymethylated nano fibrillated cellulose (NFC), and 3-glycidoxypolytrimethoxysilane in liquid nitrogen, yielding a micron-sized porous structure as presented in Fig. 3e. When incoming light struck the aerogel, the top film absorbed a significant portion, while the unabsorbed energy was refracted and further absorbed within the material. This repeated absorption-refraction process maximized the solar energy capture. As given in Fig. 3f, a 2 mm thick PEDOT:PSS-NFC aerogel achieved over 99% sunlight absorption efficiency [48].

Zhao et al. prepared the novel hydrogel-based solar evaporator using a simple one-step cross-linking method. The functional layer, composed of sodium alginate and PEDOT:PSS composite hydrogels, enabled efficient photothermal conversion and *in situ* heating for SDIE. The evaporator demonstrated a high evaporation rate of $1.23 \text{ kg m}^{-2} \text{ h}^{-1}$ and achieved an exceptional ion removal efficiency of over 99.8% in simulated seawater, ensuring excellent application stability. Additionally, it effectively mitigated salt crystallization during the solar desalination process. This aims to provide valuable insight into the practical implementation of hydrogel-based solar evaporators in desalination applications [50]. To enhance the efficient utilization of sunlight, advanced PTMs are essential. Additionally, optimizing the evaporator's

Table 1

An overview of recent review articles on CPs and their applications in solar-driven water purification and evaporation systems.

Sr. No.	Summary	Year	Ref.
1.	This article presented the recent advancements in solar-assisted surface evaporation and explored the additional applications beyond desalination.	2023	[24]
2.	This review focuses on material selection and Janus membranes for photothermal applications while recommending hybrid photothermal polymers and identifying key opportunities for future research and practical implementation.	2023	[33]
3.	This review presents the mechanisms, advancements, and prospects of using organic polymer semiconductors as efficient and sustainable PTMs for wastewater purification.	2023	[34]
4.	This review explores the evaporation-driven hydrovoltaic effect as a promising technology for converting environmental thermal energy into electricity using nanomaterials, summarizes recent material advancements, discusses strategies for enhancing device performance, and highlights future applications and challenges.	2022	[35]
5.	This review article provided the electrospinning technique for producing PANI nanocomposites (NCs) and nanofibers, highlighting their potential for various multifunctional applications.	2021	[36]
6.	This review highlights the evolution, structure, and conduction mechanisms of key CPs and their derivatives for advanced energy storage applications and discusses their current challenges and prospects.	2021	[37]
7.	This review paper reviewed the strategies, applications, and challenges in enhancing the efficiency of SDIE systems.	2021	[38]
8.	This article reviews recent advancements in PTMs for efficient solar-to-steam generation, highlighting their light-to-heat conversion mechanisms, innovative evaporation configurations, and potential for sustainable clean-water production.	2019	[39]
9.	This review highlights the recent resurgence of CPs, emphasizing their versatile synthesis and surface deposition methods, and focuses on their key applications in energy storage, environmental remediation, and electrochemical sensing.	2018	[40]
10.	This mini-review discussed carbon-based materials to absorb sunlight and efficiently generate steam in SDIE systems.	2018	[29]
11.	This review highlights the significance of commercially available PEDOT: PSS and its derivatives, focusing on its properties, film-forming techniques, challenges in electrochemical applications under humid conditions, and recent advances in sensor technologies, concluding with prospects for PEDOT: PSS-based electrodes.	2017	[27]
12.	This review discusses the recent advancements in CP-based nanomaterials used in SDIE systems aimed at addressing global water purification and associated challenges and limitations.	2025	This work

structure can facilitate multiple light scattering while minimizing transmission and reflection. Further, Zhao et al. developed a PEDOT: PSS-PVA hydrogel by coordinating PEDOT: PSS nanofibers with poly (vinyl alcohol) (PVA) and glutaraldehyde. The resulting hydrogel exhibited a remarkable 99.7 % light absorption in the 250–2500 nm range [49]. Further, water evaporation tests revealed that this hydrogel exhibited an exceptionally high energy efficiency of approximately 98.0 %, along with a rapid evaporation rate of around $2.84 \text{ kg m}^{-2} \text{ h}^{-1}$ under one-sun irradiation. An important technological advantage is its outstanding long-term durability, as confirmed by a continuous 60-day operation in seawater, along with stable performance across several evaporation cycles (Fig. 3g–i) [48]. However, despite these promising outcomes, challenges such as the scalability of the aerogel synthesis, potential fabrication cost, and performance consistency under fluctuating environmental conditions remain unresolved. Future work should

focus on optimizing the aerogel's structural robustness, testing under outdoor/real-world scenarios, and extending applicability to different water sources beyond seawater. The PEDOT: PSS-PVA hydrogel represents a mechanically robust interfacial PTM designed via a microphase semi-separation network that combines PEDOT: PSS nanofibers with hydrophilic PVA through both chemical cross-linking and physical freeze-thawing. This structure enables excellent light absorption (~ 99.7 % across 250–2500 nm), efficient light-to-heat conversion, fast water transport, and high mechanical stretchability, making it highly suitable for solar-driven water purification (Fig. 3j) [49]. Optimized 43 wt% PEDOT: PSS-PVA hydrogel achieves an exceptional evaporation rate of $\sim 2.84 \text{ kg m}^{-2} \text{ h}^{-1}$ and energy efficiency of ~ 98 % under one-sun irradiation, maintaining stable performance over 60 days of continuous testing. Moreover, the large-scale fabrication of these hydrogels, including casting and molding methods, has been demonstrated, producing free-standing hydrogel films up to $500 \text{ mm} \times 500 \text{ mm} \times 5 \text{ mm}$, which can be integrated into solar evaporation devices to achieve effective desalination and removal of heavy metal ions and dyes, meeting drinking water standards. These results highlight the hydrogel's potential as a practical, durable, and high-performance material for sustainable water purification applications. Additionally, the *in situ* polymerization of porous PEDOT: PSS hydrogels (PPH) forms a homogeneous polymer network without the need for an external polymer backbone, further enhancing solar energy absorption and reducing the evaporation enthalpy. This structural design improves water transport and light-to-heat conversion efficiency, providing a robust strategy for long-term stability and high-performance wastewater purification [51].

2.2. Polyaniline

PANI is a metallic-luster powder and one of the most widely studied organic semiconductors due to its extensively conjugated π -electron system, which enables free-electron migration and transfer. Its excellent photothermal conversion properties have made it widely applicable in interfacial solar photothermal conversion [52]. Liu et al. [53] designed an innovative PANI-modified polyarylene ether nitrile (PEN) electrospun nanofibrous membrane (PANI@PEN) by incorporating polydopamine (PDA) and cetyltrimethylammonium bromide (CTAB). This strategy enhanced PANI polymerization and enabled precise morphological control through sequential *in situ* polymerization (Fig. 4a) to enhance the membrane's performance in SDIE. The membrane's unique architecture resulted in a maximum WER of $1.822 \text{ kg m}^{-2} \text{ h}^{-1}$ and an evaporation rate of $1.527 \text{ kg m}^{-2} \text{ h}^{-1}$ for a 3.5 wt% NaCl solution. Zou et al. [54] fabricated stretchable PANI@PVDF photothermal membranes by *in situ* polymerizing PANI directly onto hydrophilic polyvinylidene fluoride (PVDF) membranes, as shown in Fig. 4b. These membranes showed a high vaporization rate of $1.41 \text{ kg m}^{-2} \text{ h}^{-1}$ and an efficiency of 85.0 % under solar irradiation, maintaining performance over 40 vaporization cycles. The protonated PANI enhanced NIR absorption and photothermal conversion, while the composite's mechanical robustness (tensile strength 36.4 MPa, strain 17.4 %) and stability under sonication and hot water confirmed long-term durability. The device design, featuring a two-dimensional (2D) water path and floating silk-wrapped polystyrene (PS) foam, enabled efficient water supply, minimized heat loss, and reduced ion concentrations in the sweater below World Health Organization (WHO) and Environmental Protection Agency (EPA) limits. This study demonstrates PANI@PVDF's potential as a low-cost, flexible, and durable solar desalination material; however, its moderate evaporation rate compared to advanced hybrid systems and potential photodegradation suggest that future work should focus on enhancing NIR absorption, integrating multifunctional nanostructures, and optimizing scalable fabrication.

Furthermore, recent studies indicate that CTAB can significantly influence the morphology of PANI post-polymerization [55]. CTAB forms rod-like micelles that attract and concentrate aniline molecules around their surfaces. This promotes the electrostatic attraction of

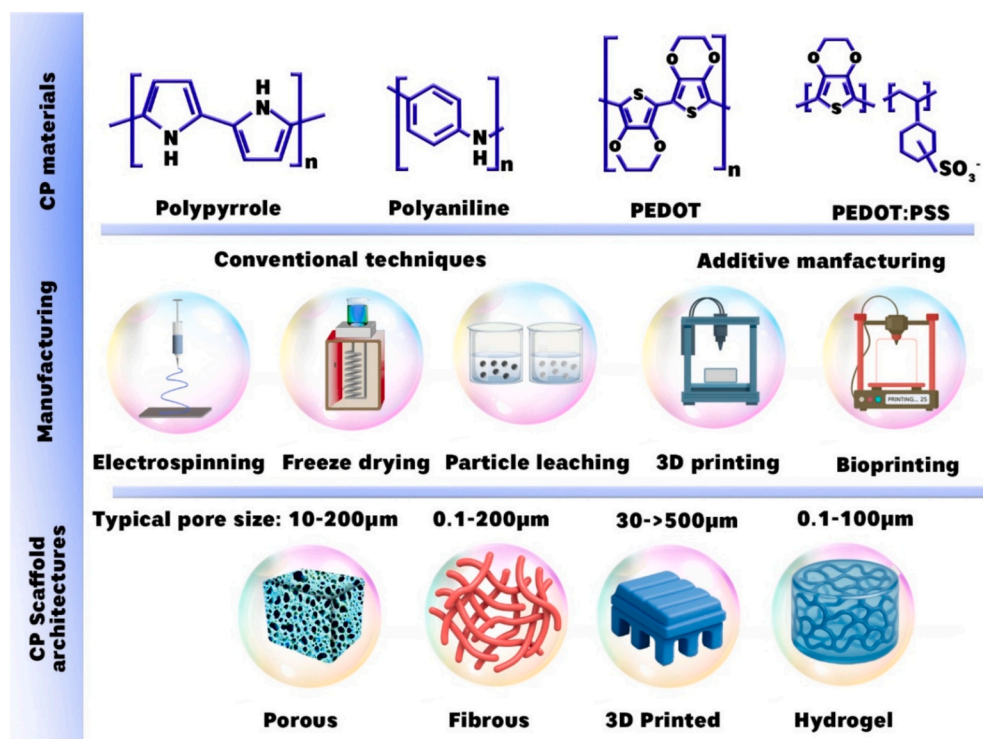


Fig. 2. CP materials and their chemical structures with different manufacturing processes and three-dimensional (3D) CP scaffold constructions.

persulfate ions to the micelle interface, initiating the oxidation of aniline and completing its *in situ* polymerization. This morphology control strategy for PANI shows great promise for enhancing photothermal absorption performance in SDIE applications. As shown in Fig. 4c, repeated experiments revealed no significant variation in the evaporation efficiency of all PANI@PENs, with an error margin within 4 %, demonstrating the excellent reproducibility and stability of PANI@PENs as photothermal membranes. Additionally, the PEN provided a strong framework, granted the PANI@PEN membranes corrosion resistance, and offered excellent mechanical properties for reusability [53].

Another significant contribution was from Ding et al., who synthesized $\text{Ti}_3\text{C}_2\text{T}_x$ MXene/PANI composite fibers by blending $\text{Ti}_3\text{C}_2\text{T}_x$ MXene with PANI via wet spinning, followed by drying superhydrophilic MXene/PANI composite fiber nonwoven fabrics (MPs). The combination with MXene significantly improved light absorption in the NIR region, resulting in the MPs (functioning as an acid absorber via the doping process) achieving exceptional light absorption across the whole spectral range, with an average absorption of 88.3 % [56]. More importantly, due to the unique reversible doping process of PANI, MPs exhibited excellent stability and reusability as an aqueous acid purifier after dedoping. Drawing inspiration from the hexagonal eyes of nocturnal moths, which are uniformly covered with conical bumps to enhance light absorption, Peng et al. engineered PANI nanolayers on the surface of PVDF through a vacuum self-assembly technique.

The pre-assembled PANI particles acted as nucleation sites, enabling the creation of PANI nanocone arrays on the membrane (PANI-m). These nanoscale conical projections created a refractive index gradient from air to PVDF, effectively reducing the light reflection with improved sunlight harvesting. As a result, this composite achieved a light absorption exceeding 95.0 % within the 250–800 nm wavelength range. Under sun irradiation, the evaporation rate of a 1.0 % NaCl solution reached $1.09 \text{ kg m}^{-2} \text{ h}^{-1}$, nearly double that of the evaporation rate from a directly *in situ* polymerized photothermal membrane, determining its high salt durability. During the 10-cycle solar-driven membrane distillation tests, PANI-m maintained a stable distillate flux, low distillate conductivity, and high salt rejection. This demonstrated that

fabricating PANI nanocone arrays is a promising technique to improve photothermal efficiency [57].

In another study, PANI nanoarrays were synthesized on polyethersulfone microfiltration membrane (PES-m). After interfacial polymerization, this resulted in the synthesis of a polyamide (PA) layer on PANI-m, leading to the preparation of PANI-PA membranes. The PANI-PA film demonstrated over 93.5 % light absorption in the 250–800 nm spectral range. In contrast, the light absorption in the NIR region (800–2500 nm) was 55.5 %, highlighting that PANI possessed excellent light absorption in the UV–Vis range but was less effective in absorbing sunlight in the NIR region [58]. In another study, Ding et al. [59] introduced a photothermal/catalytic micro-evaporator ($\text{g-C}_3\text{N}_4$ @PANI/PS), where PANI served as both a binder and a reinforcing agent to stabilize $\text{g-C}_3\text{N}_4$, simultaneously enhancing its light absorption. Furthermore, Wu et al. [60] developed a pliable photothermal fiber using the electrophoretic approach for micro- and nanoscale assembly. Further progress was achieved with a scalable arch-bridge photothermal fabric (ABPF), fabricated by weaving PANI/cotton fibers (CFs) with hydrophilic cotton pathways. The arch-bridge design enabled precise water–heat management, minimized interfacial heat loss, enlarged the evaporation area, and promoted efficient gas–liquid transport, enhancing solar light absorption and photothermal conversion. The ABPF achieved a solar evaporation rate of $2.31 \text{ kg m}^{-2} \text{ h}^{-1}$ with 99.9 % solar-vapor conversion efficiency under one-sun illumination, retaining high performance under saline conditions and multiple cycles, demonstrating scalability, recyclability, and long-term stability [63]. Ding et al. [61] synthesized an AS-g-PANI functionalized cotton fabric via covalent grafting, which produced a superhydrophilic, highly corrosion-resistant polyurethane (PU) nanofibrous membrane with enhanced mechanical strength and photothermal performance (Fig. 4d). Under one-sun irradiation, the evaporation rate of the nanofibrous membrane was found to be $1.61 \text{ kg m}^{-2} \text{ h}^{-1}$, demonstrating efficient SDIE for brine treatment. This work highlights the advantage of combining robust mechanical durability with stable evaporation performance in harsh saline conditions, although long-term fouling resistance and scalability remain areas for further research. Chen et al. [62] developed a

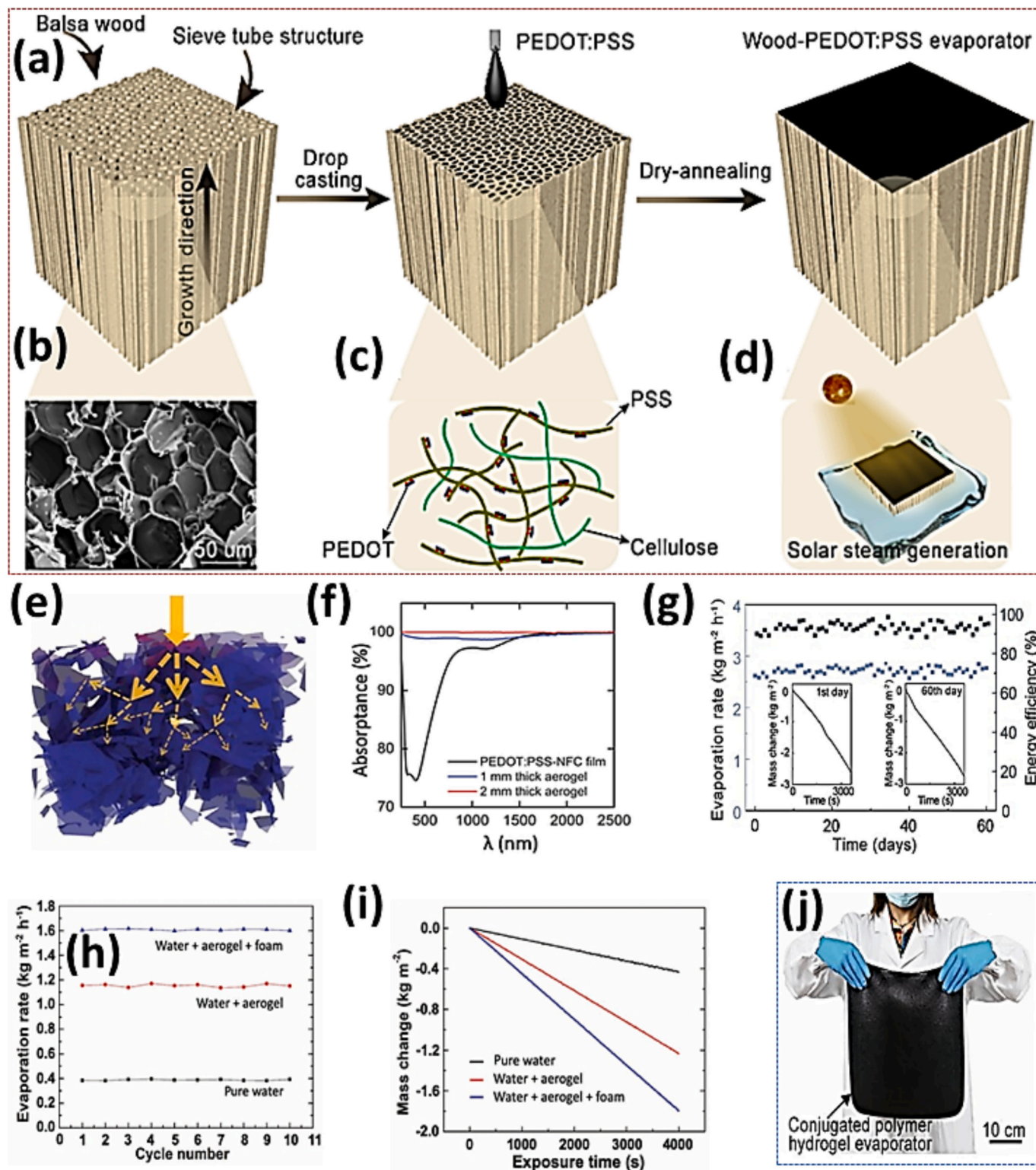


Fig. 3. (a) Illustrative scheme of the preparation process for the bilayered wood-PEDOT:PSS hydrogel evaporator. Reproduced under license from [47]. Copyright 2023, MDPI nanomaterials. (b) Scanning electron microscopy analysis of wood's natural porous architecture. Reproduced under license from [47]. Copyright 2023, MDPI nanomaterials. (c) Schematic overview of the PEDOT:PSS hydrogel network's interaction with the fiber network on the wood surface. Reproduced under license from [47]. Copyright 2023, MDPI nanomaterials. (d) The mechanism of steam generation in the wood-PEDOT:PSS hydrogel evaporator. Reproduced under license from [47]. Copyright 2023, MDPI nanomaterials. (e) Visual representation of light beam interaction with the aerogel. Reproduced under license from [48]. Copyright 2020, Wiley. (f) The absorbance values for the PEDOT:PSS-NFC film, the 1 mm aerogel, and the 2 mm aerogel [48]. Reproduced under license from [48]. Copyright 2020, Wiley. (g) Stability and reliability tests over 60 days on the evaporation rate and PCE of 43 wt% PEDOT:PSS-PVA hydrogel in a simulated seawater. Insets: mass change of seawater on the 1st and 60th days. Reproduced under license from [49]. Copyright 2022, Elsevier. (h) The evaporation rates for pure water, water with aerogel, and water with aerogel and foam under one-sun irradiation for 10 cycles are displayed in (i) [48]. Reproduced under license from [48]. Copyright 2020, Wiley. (j) A digital image of a 43 wt% PEDOT:PSS-PVA free-standing hydrogel, measuring 500 mm × 500 mm × 5 mm, designed for solar desalination [49]. Reproduced under license from [49]. Copyright 2022, Elsevier.

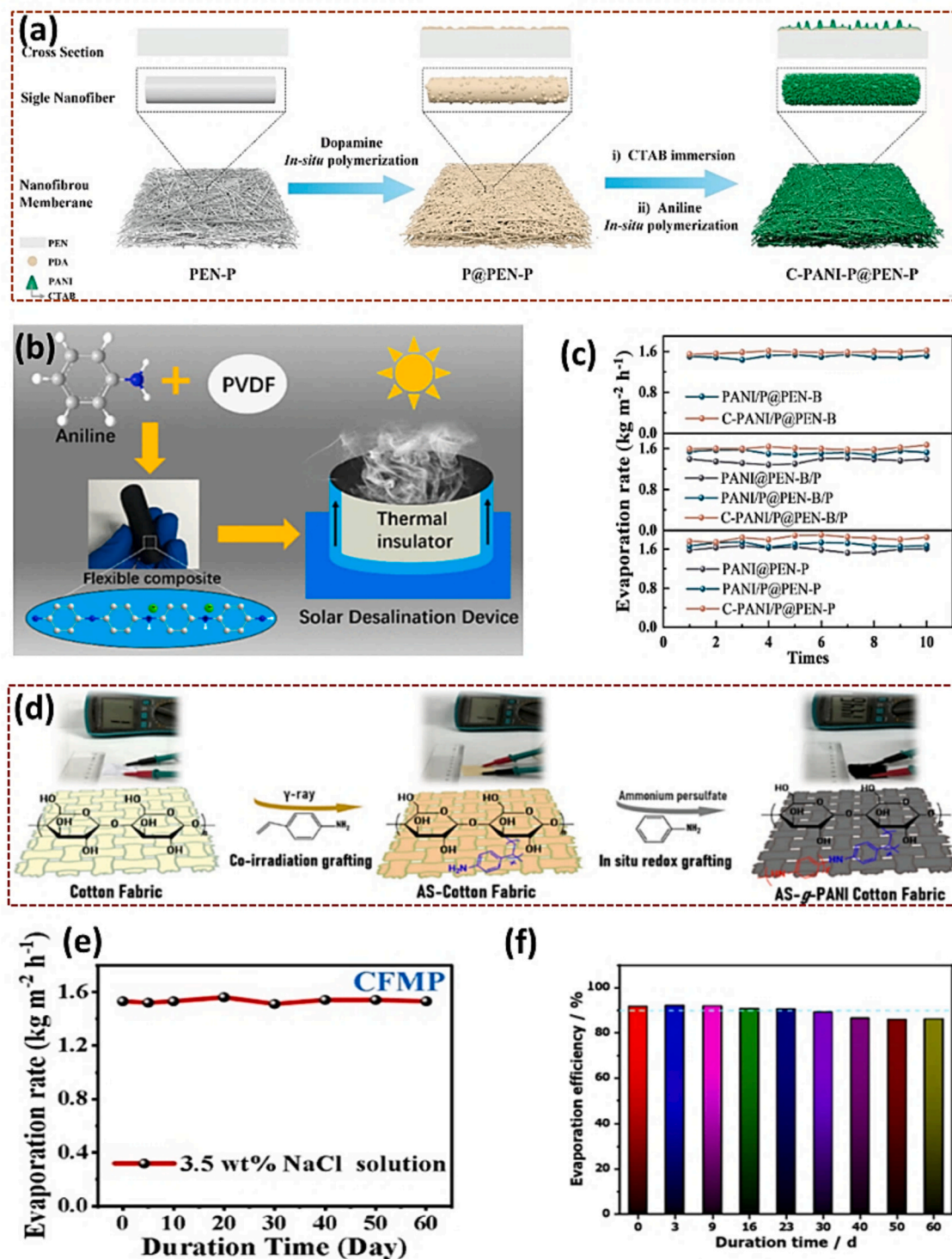


Fig. 4. (a) Fabrication of PANI-modified membrane by *in situ* polymerization. Reproduced under license from [53]. Copyright 2024, Elsevier. (b) Synthesis of flexible photothermal membranes [54]. Reproduced under license from [54]. Copyright 2020, ACS Publications. (c) WER of C-PANI/P@PENs for 10 cycles [53]. Reproduced under license from [53]. Copyright 2024, Elsevier. (d) Illustration for the preparation of PCCFs via graft polymerization. The inserts display the conductivity tests for pristine cotton fabric, AS-cotton fabric, and AS-g-PANI cotton fabric, respectively. [61]. Reproduced under license from [61]. Copyright 2022, Elsevier. (e) WER overtime during the brine durability test of the CFMP in a 3.5 wt% NaCl solution. Reproduced under license from [62]. Copyright 2024, Elsevier. (f) PCE at various time intervals during the brine durability test of the AS-g-PANI cotton fabric. Reproduced under license from [61]. Copyright 2022, Elsevier.

covalently PAM-doped PANI-based photothermal fabric (CFMP) through a three-step synthesis strategy, demonstrating high efficiency in SDIE. The CFMP exhibited evaporation rates of $1.60 \text{ kg m}^{-2} \text{h}^{-1}$ for pure water, $1.54 \text{ kg m}^{-2} \text{h}^{-1}$ for 3.5 wt% NaCl, and $1.49 \text{ kg m}^{-2} \text{h}^{-1}$ even in a 10 wt% NaCl under one-sun irradiation. Notably, the fabric prevented

salt accumulation on its surface, with salt crystallizing on the surrounding support, enabling continuous operation and long-term stability. The average freshwater and salt recovery rates were $1.54 \text{ kg m}^{-2} \text{h}^{-1}$ and $0.03 \text{ kg m}^{-2} \text{h}^{-1}$, respectively, with stable performance over 60 days, highlighting the material's durability and environmental

adaptability (Fig. 4e). This study demonstrates the technological advantage of covalent doping for enhancing photothermal efficiency and preventing salt fouling; however, the reliance on a supporting platform for salt crystallization may limit scalability and integration into compact desalination devices. Future research could focus on designing self-regulating or fully integrated fabrics that manage salt deposition *in situ*, further improving operational simplicity and large-scale applicability. Further, evaporation efficiencies at various time intervals have also been presented in Fig. 4f. This resistance to fouling is attributed to the antibacterial properties of PANI, which imparts intrinsic

antibacterial characteristics to the cotton fabric [64]. PANI itself has been reported to exhibit antibacterial activity against both *Escherichia coli* and *Staphylococcus aureus* under dark and visible-light conditions. This antimicrobial property helps prevent biological contamination in real water environments, thereby minimizing evaporation efficiency losses.

2.3. Polypyrrole

PPy is a black, conjugated conductive polymer synthesized through

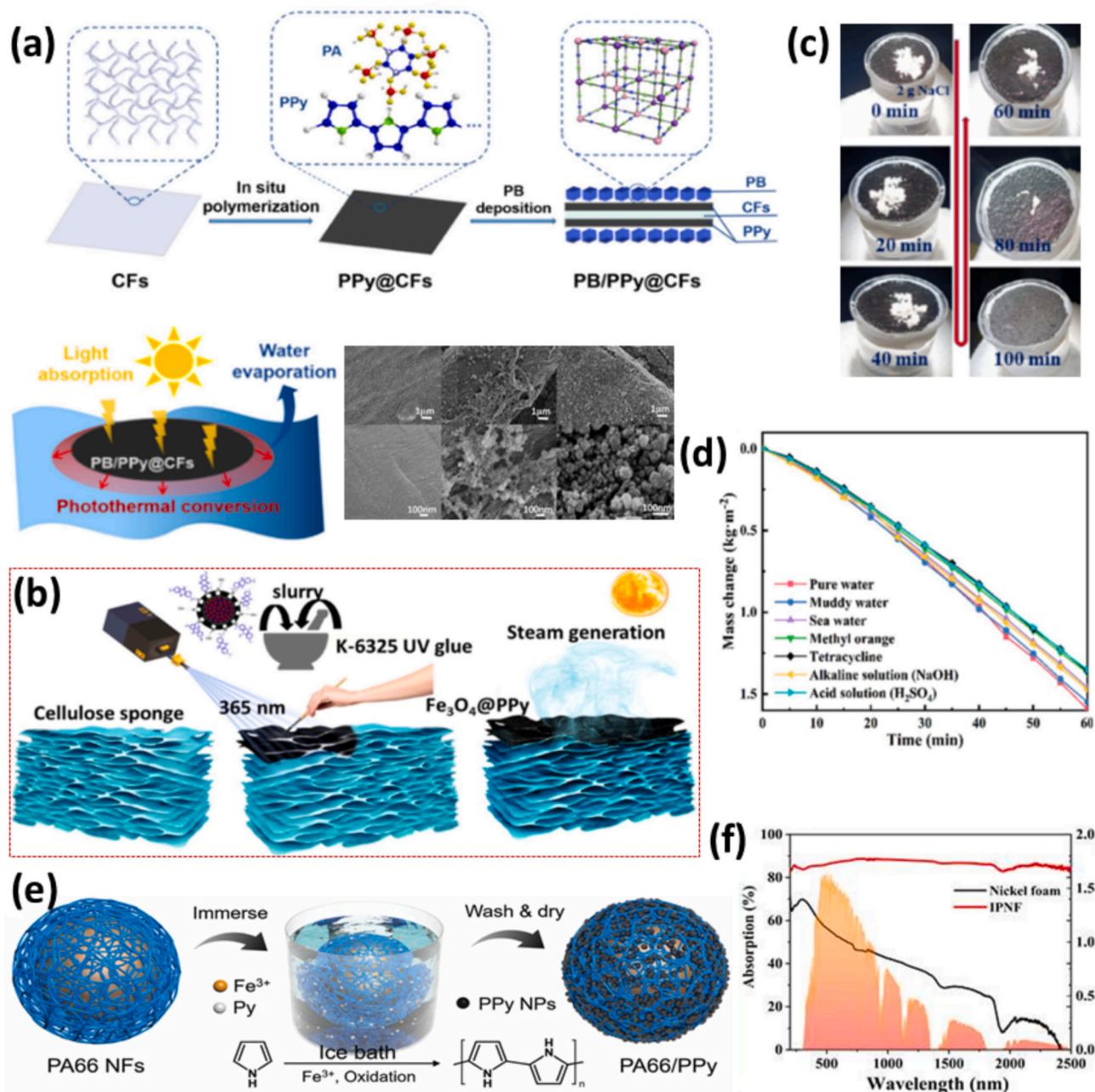


Fig. 5. (a) Diagram showcasing the synthesis and application of PB/PPy@CFs for photothermal interfacial evaporation, with supporting scanning electron micrographs of CFs, PPy@CFs, and PB/PPy@CFs at 20 kx and 150 kx. Reproduced under license from [69]. Copyright 2021, MDPI Polymers. (b) Facile synthesis of cellulose sponge-anchored Fe_3O_4 @PPy nanospheres with high surface charge. Reproduced under license from [70]. Copyright 2023, Elsevier. (c) Under one-sun illumination, solid NaCl undergoes time-dependent thermal dissolution (2 g per 100 min), starting from the surface and gradually penetrating the micro-porous structure of MnCDs@PPy. Reproduced under license from [73]. Copyright 2021, Elsevier. (d) Mass fluctuation of c-GPP in various aqueous media under one-sun conditions. Reproduced under license from [76]. Copyright 2024, Elsevier. (e) Depiction of *in situ* deposition of PPy onto PA66 nanofibers in an ice-cooled environment. Reproduced under license from [78]. Copyright 2021, Wiley. (f) UV-Vis-NIR absorption spectrum of bare nickel and IPNF foam over the broadband solar spectrum (250–2500 nm). Reproduced under license from [79]. Copyright 2021, Wiley.

the polymerization of pyrrole monomers, widely used as a photothermal material in solar evaporation applications [65,66]. It readily forms composites with other materials, making it highly versatile for various applications. Due to its broad-spectrum light absorption, PPy is considered a promising PTM [67]. The $-NH$ groups in PPy play a crucial role in enhancing water absorption and transport in SDIE systems. These amino functionalities can form hydrogen bonds with water molecules, creating intermediate water states that exhibit weaker hydrogen bonding than bound water but stronger than bulk water. Such interactions facilitate faster water diffusion through the polymer network and reduce the vaporization enthalpy, thereby enhancing photothermal conversion efficiency. For instance, in NHRG (nanofibrous hydrogel/rGO) membranes, the presence of amino groups contributed to the formation of intermediate water, lowering water evaporation enthalpy and boosting the interfacial evaporation rate. Furthermore, the hydrogen bonding between $-NH$ groups and the substrate allows strong adhesion of PPy to diverse porous materials, ensuring uniform coating or deposition, which not only improves water transport to the evaporative interface but also maintains efficient solar energy absorption. The bulk water reservoir replenishes intermediate water, sustaining continuous evaporation, while the hydrophilic $-NH$ sites promote rapid water adsorption and diffusion, collectively improving the overall SDIE performance [68]. Wang et al. reported that employing PPy doped with phytic acid (PA) enhanced the deposition of Prussian blue (PB) on CFs. The PB deposition ratio increased from 12.29 % (PB/CFs) to 32.4 % (PB/PPy@CFs), with PA-doped PPy also influencing the PB growth duration. However, high concentrations of PA molecules resided in the active sites on PPy, reducing the PB precipitation ratio beyond certain conditions (Fig. 5a) [69]. The PB growth on PPy@CFs was completed within 4 h, yielding exceptional photothermal properties. Under one-sun illumination, the surface temperature rose to $81.5^{\circ}C$, with a WER of $1.36 \text{ kg m}^{-2} \text{ h}^{-1}$ and a PCE of 90.96 % for PB/PPy@CFs, demonstrating excellent stability. These findings emphasized the significance of precise material design and characterization to optimize performance. Furthermore, Irshad et al. [70] designed a highly charged solar evaporator through depositing Fe_3O_4 @PPy nanospheres onto a self-floating cellulose scaffold (Fig. 5b) to enable *in situ* fresh water and power generation. Under natural conditions, the system maintained long-term stability without salt accumulation, achieving a mass change of 14.66 kg m^{-2} over 8 h. The evaporation rate comparison of 5 distinct solar evaporators at one-sun solar intensity was also recorded, and the evaporation rate experiment conducted outdoors showed remarkable results. It exhibited a high WER of $1.98 \text{ kg m}^{-2} \text{ h}^{-1}$ even under high-salinity conditions (25 wt% $NH_4Cl \cdot H_2O$), while simultaneously generating thermoelectric power with a power density of 45.4 W m^{-2} and solar-to-electric conversion efficiency of 2.27 % under 2 kW m^{-2} solar irradiation. This multifunctional design offered strong resistance to salt corrosion through Donnan exclusion, efficient solar absorption and heat localization, and the ability to deliver both fresh water and electricity, demonstrating clear technological advantages. However, its solar-to-electric conversion efficiency remained relatively modest, and power generation required higher-than-standard solar flux, raising concerns about scalability and practical outdoor performance. Future research should therefore focus on optimizing thermoelectric integration to improve electrical output, validating performance under standard solar intensity (1 kW m^{-2}), and assessing durability over extended use and varied environments.

Moreover, Irshad et al. [71] introduced a hierarchical design for interfacial solar evaporation, achieving enhanced photothermal conversion through worm-like $SrCoO_3$ perovskite oxide anchored onto superhydrophilic PU foam, followed by the *in situ* polymerization of conducting $SrCoO_3$ @PPy. This structure enabled an impressive evaporation rate of $2.13 \text{ kg m}^{-2} \text{ h}^{-1}$ with a 93 % solar-to-vapor conversion efficiency under 1 kW m^{-2} solar irradiation, outperforming conventional solar evaporators by reducing equivalent evaporation enthalpy. Even under intermittent solar irradiation, it sustained a substantial

evaporation rate of $0.85 \text{ kg m}^{-2} \text{ h}^{-1}$. The designed evaporator exhibited good salt rejection under extreme seawater conditions. Moreover, they presented the salt rejection studied through wicks and its performance under 1 kW m^{-2} solar intensity. Furthermore, advanced experimental studies, supported by computational fluid dynamics simulations, confirm the system's effective waste heat recovery and release, along with its excellent salt-resistant capability. Similarly, Ma et al. [72] explored an innovative approach by directly utilizing CuO nanowires as an oxidant to facilitate an *in situ* growth of PPy on Cu foam, thereby catalyzing the polymerization of PPy. This strategy enhanced the hydrophilicity of the surface as well as polymer-inorganic (P-I) heterojunction with CuO, effectively improving the foam's PCE. Building on this, they developed a 2.5D curved evaporator designed to minimize heat dissipation and maximize the water evaporation area. Through optimization to achieve an ideal evaporation-supply balance, the evaporator achieved a remarkable evaporation rate of $2.51 \text{ kg m}^{-2} \text{ h}^{-1}$ under 1 kW m^{-2} solar irradiation.

In a more advanced design, Irshad et al. [73] developed an advanced evaporative system using *in situ* polymerization of PPy on carbon dots (CDs)-modified MnO_2 -decorated ultra-flexible nanowires ($MnCDs$ @PPy), coated onto a non-woven cotton fabric hydrophilic PU foam with 30 % wicking capacity. Salt-rejection studies anticipated in Fig. 5c revealed real-time chemical advection, where hot brine moves from the top surface to the underlying water through a salinity gradient, facilitated by accumulated heat. The prototype demonstrated outstanding salt-rejection efficiency, achieving 2 g in just 100 min or 2 g within 1 min when fully soaked. Additionally, the solar-driven evaporator exhibited exceptional stretchability, withstanding up to 80 % compressive strain, and attained a high evaporation rate of $1.68 \text{ kg m}^{-2} \text{ h}^{-1}$. Sun et al. coated phenolic foam with PPy (PPy-RF) using a spraying technique, and achieved 96.2 % light absorption within the spectral region [74]. The enhanced surface roughness contributed to improved hydrophilicity of the evaporator. Also, PPy-RF foam demonstrated exceptional salt resistance and long-term stability for desalination, even in highly saline brine (20 wt%). To further enhance PCE, Fan et al. developed a 3D porous monolithic PPy (M-PPy) sponge that exhibited nearly 100 % light absorption across the entire spectral region (200–2500 nm). Its superior light absorption is attributed to its porous structure, which consists of black particles and NPs that enhance light capture through multiple scattering. Under 1 solar radiation condition, the M-PPy sponge achieved an evaporation efficiency of 84.72 % [75]. Furthermore, the M-PPy sponge imparts excellent salt resistance and stability, maintaining a constant evaporation rate in pure water and saline solution (20 wt% NaCl) under 1 kW m^{-2} irradiance for 6 h. The absence of salt deposition was also observed, confirming its excellent salt-resistant performance. Recent studies have explored a variety of approaches to enhance the performance of carbon-based PTMs for solar-driven water purification through interfacial evaporation. Li et al. [76] reported PPy with reduced graphene oxide (rGO) to synthesize a 2D, 2D/2D rGO/PPy (c-GPP). This approach effectively prevented the self-stacking of graphene, leading to c-GPP with an increased number of active sites. The resulting aerogel demonstrated exceptional photothermal evaporation performance, attributed to the superior photothermal conversion capabilities of both graphene and PPy, with remarkable mass change demonstrated in Fig. 5d. With an excellent photothermal evaporation rate of $1.59 \text{ kg m}^{-2} \text{ h}^{-1}$, c-GPP proves to be highly effective for water purification across diverse and challenging environments. Irshad et al. [77] also advanced the field by developing bifunctional MnO_2 @PPy NCs integrated with PU wicks for efficient water transport and polyethylene terephthalate foam for superior thermal management. This design offered an effective solution for simultaneous salt rejection and enhanced interfacial heat accumulation ($42.8^{\circ}C$), enabling vapor generation at a rate of $1.69 \text{ kg m}^{-2} \text{ h}^{-1}$ under 1 kW m^{-2} solar illumination and producing freshwater at a rate of 12.31 kg m^{-2} per day.

A 3D spherical evaporator was also fabricated by electrospinning

polyamide 6,6 (PA66) nanofibers onto a plastic sphere, followed by *in situ* growth of a PPy solar absorber (Fig. 5e). This structure provided a high surface area and fibrous network, enhancing light absorption and water wettability. As a result, light-to-vapor conversion efficiency reached up to $\approx 260\%$ and 180% under 1 and 2 kW m^{-2} , respectively, by harvesting energy from non-illuminated regions. Additionally, CO_2 photoreduction using the vapor enabled fuel production via a Cu_2O -modified photocatalytic evaporator [78]. In this study, Irshad et al. [79] developed a solar-driven interfacial evaporator by *in situ* polymerization of PPy on nickel foam (IPNF), which was then combined with a super-hydrophilic PU substrate to enable synchronous water transport and

effective thermal insulation. The 2D ultrablack mesh structure of the IPNF facilitated multiple light scattering within the diffused polymerized surface, resulting in a high solar absorption (Fig. 5f) of 88.5% and efficient heat localization, reaching 49.5°C under one-sun irradiation. The integrated solar evaporator demonstrated a remarkable evaporation rate of $1.74\text{ kg m}^{-2}\text{ h}^{-1}$ and a solar-to-vapor conversion efficiency of 90% (excluding heat losses) under standard solar illumination. Long-term testing further confirmed its stability, showing negligible decline in evaporation performance under seawater conditions, achieving 13.27 kg m^{-2} over 8 h at one-sun, while also exhibiting strong salt rejection capability (3.2 g solid NaCl over 4 h). Furthermore, the study provided

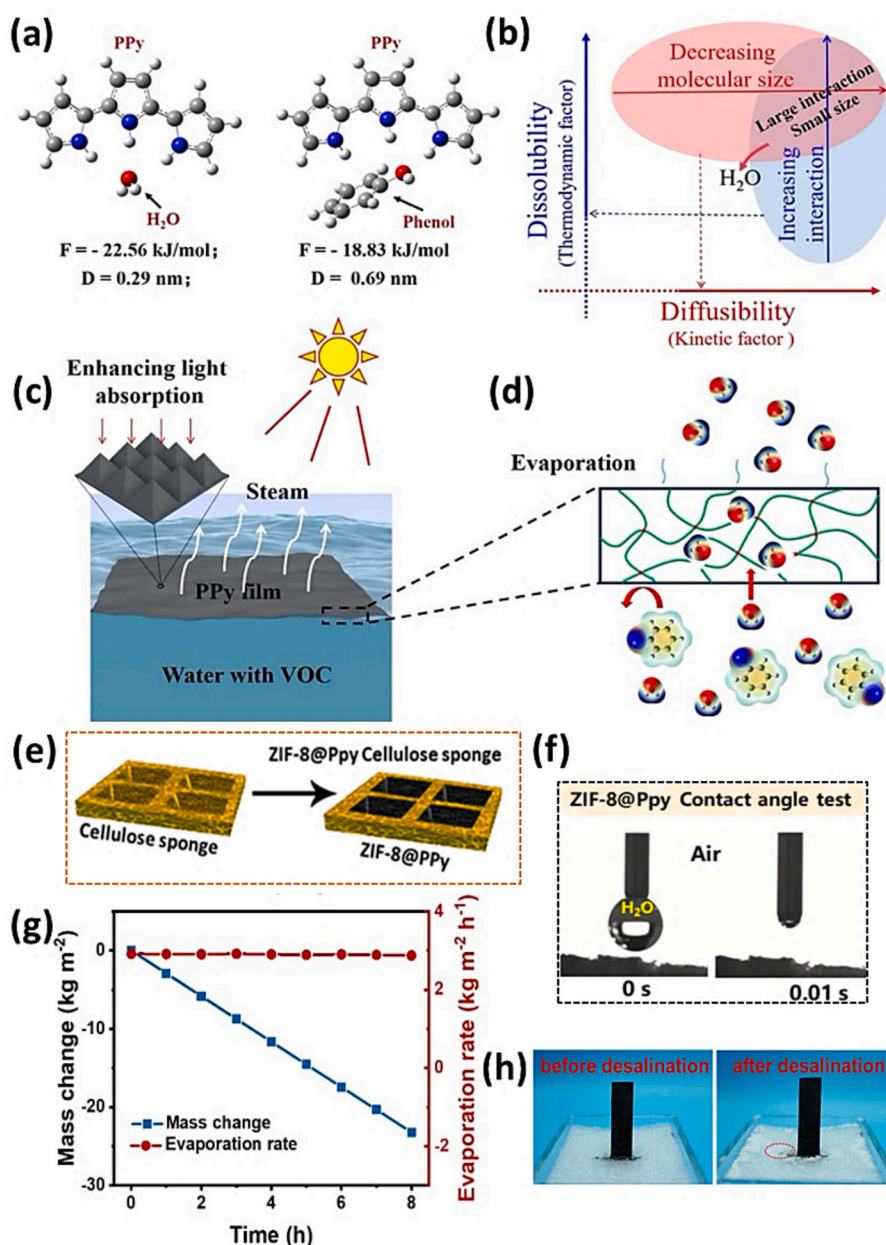


Fig. 6. (a) Affinity of PPy toward water and phenol molecules. Reproduced under license from [81]. Copyright 2020, Wiley. (b) Role of molecular size in solute diffusion and molecule-membrane interactions during selective permeability. Reproduced under license from [81]. Copyright 2020, Wiley. (c) Graphical representation of steam generation with the MPS-PPy membrane. Reproduced under license from [81]. Copyright 2020, Wiley. (d) MPS-PPy membrane's role in selective permeation and evaporation. Reproduced under license from [81]. Copyright 2020, Wiley. (e) Straightforward preparation of cellulose sponges with ZIF-8@PPy coating. Reproduced under license from [83]. Copyright 2024, Elsevier. (f) Assessing the hydrophilicity of ZIF-8@PPy sponge through contact angle measurement. Reproduced under license from [83]. Copyright 2024, Elsevier. (g) Mass variation and evaporation rate of PPy@CuO-3 NAs in saltwater following 8 h of continuous evaporation in a $35\text{ wt\%}$ NaCl solution. Reproduced under license from [89]. Copyright 2024, Elsevier. (h) Digital images of PPy@CuO-3 NAs after 8 h of consecutive experiments in a NaCl solution. Reproduced under license from [89]. Copyright 2024, Elsevier.

valuable insights into the role of different water states within the polymeric network during the evaporation process. Overall, the work highlights the potential of IPNF-based solar evaporators to deliver efficient fresh water production while excluding heavy metals and oil emulsions, underscoring their promise for industrial-scale desalination applications.

Chen et al. developed a PPy-decorated sunflower disc (PPy-SFD) evaporator by a simple *in situ* pyrrole polymerization process, effectively transforming biomass waste into a high-value functional material for solar-driven water purification. The hydrophilic treatment of SFD facilitated uniform PPy coating without damaging its inherent microstructure, while the natural 3D array and microporous channels enabled efficient water pumping and heat localization. The resulting PPy-SFD demonstrated nearly complete broadband light absorption ($\sim 99.3\%$), robust mechanical stability, and scalability up to 18 cm diameter. Under one-sun illumination, the device achieved a high evaporation rate of $1.74 \text{ kg m}^{-2} \text{ h}^{-1}$ with excellent cycling durability and outdoor desalination feasibility, including $\sim 100 \text{ mL}$ of freshwater collection in a day and nearly 100 % dye rejection from mixed wastewater. These features highlight the advantages of using sustainable biomass-derived substrates with engineered surface modifications for efficient and eco-friendly solar evaporation. However, challenges remain in terms of optimizing large-scale fabrication, maintaining long-term fouling resistance under complex natural water conditions, and ensuring cost-effectiveness in real-world deployment. Future work could focus on hybridizing PPy-SFD with additional functional layers to further enhance pollutant removal and extend operational lifetimes [80]. Simulation results showed that PPy interacts more strongly with water than with phenol, a typical volatile organic compound (VOC) (Fig. 6a), making water more easily absorbed and diffused in the PPy membrane due to its smaller molecular size (Fig. 6b). The micro-pyramid structured PPy (MPS-PPy) membrane exhibited selective permeability, allowing water vapor through while blocking VOCs (Fig. 6c and d). The pyramid design reduced light reflection, enhanced light-to-heat conversion, and increased surface area, improving water evaporation. The structure balanced selectivity and water output, achieving 90 % VOC blocking and a WER of $1.12 \text{ L m}^{-2} \text{ h}^{-1}$ under one-sun irradiation. A portable seawater desalination system using an MPS-PPy membrane produced distilled water with ion levels well below WHO drinking water standards [81]. Furthermore, Long et al. [82] took a different approach by developing a composite hydrogel consisting of SA loaded with PPy and CaCl_2 . At night, the hydrogel produced electricity at a power output of 15.1 mW m^{-2} , while during the day, it generated electricity at 141.8 mW m^{-2} . The waste heat from the thermoelectric generator is used to evaporate water from the porous polydimethylsiloxane at a rate of $1.311 \text{ kg m}^{-2} \text{ h}^{-1}$, achieving high-efficiency multi-stage solar energy utilization at 80 %. This integrated system efficiently harnesses solar energy, generating continuous electricity both day and night. Moreover, Arshad et al. [83] designed spatially patterned solar evaporators by anchoring zeolitic imidazolate framework-8 nanocubes (ZIF-8@PPy) onto a cellulose sponge to minimize heat dissipation from the photothermal surface to the environment (Fig. 6e). The incorporation of patterned structures significantly enhanced efficiency, achieving a high evaporation rate of $2.30 \text{ kg m}^{-2} \text{ h}^{-1}$, 10 % higher than a flat evaporator with the same 30.0 cm^2 projected area, by effectively utilizing radiation energy and reduced convection heat loss under one-sun irradiance. Furthermore, a contact angle experiment was also performed to assess the hydrophilicity of the sponge (Fig. 6f). Additionally, heat transfer simulations confirmed that the spatial patterning created photothermal cavities demonstrated effective rejection of salt and ammonium ions under 1 kW m^{-2} , offering a promising solution for efficient and sustainable wastewater treatment. Furthermore, a PPy-NL foam evaporator was developed using natural latex (NL) foam. The resulting foam exhibited an impressive average light absorption of 94.94 % across the full spectrum, significantly improving the NL foam's low light absorption (23.6 %) [84]. This enhanced light-harvesting capability is due to

the irregular surface morphology that reduces light reflection, promoting multiple scattering and reabsorption of incident light [38].

Wang et al. demonstrated the contact angle study of the cellulose layer (35°) and PPy/cellulose layer (5°). These contact angle measurements confirmed that the addition of PPy to the cellulose gel improved its hydrophilicity [85]. Furthermore, after 8 h of continuous evaporation from artificial seawater, no salt crystals were detected on the evaporator's surface, highlighting its long-term resistance to salt buildup and stability. Yin et al. [86] engineered a bionic PPy/ BiVO_4 -PI/MXene aerogel composite featuring a radial center structure to act as the evaporator. This composite merges photothermal and photocatalytic capabilities within the evaporation system. Under 1 kW m^{-2} irradiation, the composite achieved an evaporation rate of $1.64 \text{ kg m}^{-2} \text{ h}^{-1}$, with a PCE of 96.77 %. After 15 days of continuous evaporation, the composite successfully harvested about 26.7 g of salt. This work effectively integrated interfacial evaporation, photocatalysis, and salt collection, presenting a promising solution for high-salinity dyeing wastewater treatment. Additionally, Ren et al. developed a highly efficient solar evaporator using TiO_2 NPs [87]. TiO_2 NPs in combination with PPy achieved an impressive water evaporation efficiency of 97.3 % under two-sun irradiation. Besides, Wang et al. [88] developed the Fe_2O_3 @PPy/chitosan hydrogels as a lightweight evaporative design for SDIE in brine solutions (3.5 wt%). The hydrogel featured a macroporous network that facilitated water transport, enabled self-floating capability, and achieved broad omnidirectional solar absorption (96 %). Advanced evaporation experiments demonstrated a high WER of $1.80 \text{ kg m}^{-2} \text{ h}^{-1}$ and an enhanced PCE of 91 %, outperforming other carbon-based evaporators while minimizing heat loss under one-sun (1 kW m^{-2}). This single-step approach offered an efficient freshwater supply by effectively purifying water from various contaminants, highlighting its potential for real-world applications. Likewise, Li et al. [89] developed a photothermal PPy@CuO nanorod array (NAs) system possessing a dual-structured design. This configuration incorporated a cone-shaped 3D topological architecture to enhance light absorption and a hollow interior to improve thermal insulation. Notably, after 12 h of continuous evaporation testing, the evaporation rate declined by only $0.173 \text{ kg m}^{-2} \text{ h}^{-1}$. Furthermore, PPy@CuO-3 NAs achieved an evaporation rate of $3.3 \pm 0.4 \text{ kg m}^{-2} \text{ h}^{-1}$, decreased by only $0.5 \text{ kg m}^{-2} \text{ h}^{-1}$ in 35 wt% NaCl solution (Fig. 6g). Also, they found no salt deposition under sunlight within 4 h (Fig. 6h), having an energy efficiency of 97.5 %, when exposed to solar illumination at a 75° tilt angle. Ahmed et al. [90] developed a high-performance, self-floatable, and eco-friendly solar steam generator through a single-step fabrication process. This solar evaporator consists of Fe_2O_3 @PPy NPs coated onto a low-cost, commercially available superhydrophilic wood pulp sponge, providing a sustainable approach to address energy and water scarcity challenges. The Fe_2O_3 @PPy-based evaporator exhibited broad solar absorption, efficiently converted light energy into heat energy (42.3°C), and achieved a vapor generation rate of $1.62 \text{ kg m}^{-2} \text{ h}^{-1}$ with a PCE of 93 % under one-sun (1 kW m^{-2}). Additionally, this prototype was directly deployed for wastewater purification and demonstrated a nearly 100 % rejection rate of heavy metal ions. Zhang et al. [91] developed a hydrophobic photothermal membrane by coating a porous stainless steel mesh with PPy. This groundbreaking approach led to a notable increase in the WER, outperforming conventional heating systems. The membrane was fabricated by depositing PPy onto the mesh, followed by fluoroalkylsilane modification to induce hydrophobicity. Its wettability, governed by Wenzel's model, allowed it to stably float at the water-air interface, ensuring efficient interfacial water heating under sunlight. Wang et al. [92] developed a bilayer solar evaporator by decorating balsa wood with PPy, inspired by the natural transpiration process of trees. The PPy coating endowed the wood with broadband light absorption ($>90\%$) and enhanced photothermal conversion, while the intrinsic hydrophilicity and vertically aligned microchannels of the wood enabled continuous water transport and thermal insulation. As a result, the PPy-wood evaporator achieved an evaporation rate of 1.014

kg m⁻² h⁻¹ and a PCE of 72.5 % under one-sun illumination, maintaining stable performance over repeated cycles. Beyond efficiency, the device demonstrated strong desalination and dye-removal capability, producing freshwater that met WHO standards. The main technological advantage lies in the simple fabrication and inherent recyclability of natural wood structures, making this approach cost-effective and sustainable. However, potential challenges include the mechanical durability of wood under long-term operation and scaling up uniform PPy deposition for large-area devices. Future research could focus on improving structural robustness, optimizing hybridization with other polymers or nanomaterials, and testing performance under real outdoor conditions.

In a related effort, Xu et al. [93] designed a biomimetic PPy-coated cotton fabric (PGCF) via a simple dip-coating process followed by GA/APTES modification, yielding an anti-oil-fouling PTM with excellent superhydrophilicity and underwater superoleophobicity. The PGCF achieved a high solar absorption efficiency of 97.8 % and demonstrated an evaporation rate of 1.54 kg m⁻² h⁻¹ with a solar-to-vapor conversion efficiency of 89.7 % under one-sun irradiation. Notably, the device maintained stable performance in oil-contaminated water and showed self-cleaning ability against oil splatters, alongside robust reusability and chemical stability in harsh environments. These features make the system highly suitable for oily wastewater purification, with outdoor trials confirming its large-scale potential. While the low-cost fabrication and scalability are clear advantages, further research is needed to optimize long-term fouling resistance and evaluate real-field deployment under continuously fluctuating environmental conditions. Similarly, Shen et al. [95] fabricated an interface solar vapor generation interfacial substrate by growing PPy on the surface of wood in the presence of deep eutectic solvents (DES), leveraging PPy's broad-spectrum, high-efficiency light absorption properties. While native wood exhibited a relatively low light absorption rate of approximately 43 %, the PPy-coated wood demonstrated a significant enhancement, reaching around 90 % [96]. Further, they evaluated the salt durability and desalting capacity by calculating the WER under one-sun irradiation and demonstrated a slight drop in evaporation rate in high-salinity solutions compared to low-salinity solutions [94]. Further, a Janus-structured woven fabric evaporator integrating PPy-modified luffa fibers (hydrophobic solar absorber) with hydrophilic cotton yarn (water transport) was developed via a scalable weaving technique. The asymmetric wetting design, combined with interconnected micropores, enabled fast vapor diffusion, stable salt rejection, and high solar absorption (>96 %). Under one-sun and convective airflow (3 m s⁻¹), the device achieved an evaporation rate of 2.48 kg m⁻² h⁻¹ with long-term stability and no salt accumulation even at 15 wt% brine over 5 days. However, challenges remain in large-scale fabrication, mechanical durability under continuous operation, and long-term fouling resistance. Further study should explore robust weaving strategies, anti-fouling surface modifications, and integration with energy recovery modules to enable practical deployment of CP-based fabric evaporators [96].

Further advancements in the field include the work of Zhang et al. [97], who developed PPy-based photothermal films using cotton cloth (CC) and paulownia wood as substrates. Indoor experiments indicated that CC photothermal conversion film-monolithic hydrophobic (CCF-MH) was the most effective for outdoor solar evaporation systems (without polyvinyl chloride). In outdoor experiments, CCF-MH achieved a large-scale freshwater recovery rate of 1.1 kg m⁻² in 7.5 h under low light intensity. This study introduces a cost-effective, high-efficiency, and scalable approach for water recovery and nutrient concentration from urine. Furthermore, Asghar et al. [98] presented an innovative approach utilizing natural ore filter cubes (NOFC) anchored with PPy to enhance SDIE. The developed evaporator demonstrated remarkable solar absorption (93 %) across a broad spectral range (200–2500 nm), spanning UV to NIR wavelengths. Additionally, they determined the mass change of 4.63 kg m⁻² under 3 kW m⁻². The PPy-coated NOFC offered excellent salt resistance, scalability, and environmental

sustainability. Meanwhile, Zhang et al. [99] introduced a PPS fibrous membrane that exhibited excellent chemical resistance and mechanical strength. The composite incorporated hydrophilic materials, PDA and polyethyleneimine (PEI), along with the PTM PPy and magnetic material iron oxide (Fe₃O₄). These components were used to assemble a PEI/Fe₃O₄/PPy@PPS composite fibrous membrane, which served as the interfacial evaporator for seawater purification. When exposed to sunlight, the evaporator achieved an evaporation rate of 1.52 kg m⁻² h⁻¹, with an evaporation efficiency of 91.84 %. Under the influence of a 2 kW m⁻² magnetic field, the evaporator demonstrated a high evaporation rate of 4.2 kg m⁻² h⁻¹ and an efficiency of 93.77 %. Li et al. first prepared PPy-coated biomass porous foams made from alkali-treated corn straw (CSA) and microwave-alkali-treated corn straw (CSMA), which showed low thermal conductivities of 0.022 and 0.027 W m⁻¹ K⁻¹, respectively. With high light absorption (95–100 %), superhydrophilicity, and unique aligned channels, foams showed excellent PCE of 89.74, 91.08, and 91.54 % for the PPy-coated CSA (P-CSA) and 96.8, 97.05, and 98.32 % for the PPy-coated CSMA (P-CSMA) at light intensities of 1, 2, and 3 kW m⁻², respectively. Notably, in 20 wt% NaCl, P-CSA, and P-CSMA retained efficiencies of 62.30 and 94.7 % respectively, demonstrating excellent salt-resistance [100]. Peng et al. fabricated a composite polyelectrolyte photothermal hydrogel made from sulfobetaine methacrylate (SBMA), [2-(methacryloyloxy)ethyl] trimethylammonium chloride (METAC), and PPy, which demonstrated both anti-biofouling and antibacterial properties. When exposed to 1.0 kW m⁻² solar irradiation, the hydrogel achieved a rapid WER of ~1.690 kg m⁻² h⁻¹ and a high solar-to-evaporation efficiency of around 95.94 %. The hydrogel also displayed remarkable durability and maintained a stable evaporation rate of ~1.617 kg m⁻² h⁻¹ in real seawater for 6 weeks, conforming to its potential for practical applications in SDIE [101]. Li et al. [102] developed a one-step, cost-effective, and scalable method to synthesize a 3D PPy black rose origami structure through folding and chemical polymerization. This design exhibited an evaporation rate of 2.12 kg m⁻² h⁻¹ and an ultrahigh solar-thermal conversion efficiency of 91.5 % under one-sun illumination, which is substantially higher than the 73 % efficiency of 2D PPy papers.

The enhanced performance originates from the five-fold increase in specific surface area of the 3D origami, which provides more vapor escape pathways and lowers the surface temperature, thereby minimizing radiative energy loss. In addition, the authors introduced a low-pressure solar steam collection system, which further improved both evaporation and collection rates, achieving up to a 52 % enhancement in water yield. This approach shows clear advantages in water purification, desalination, and disinfection, highlighting its potential for household-scale clean water production. However, the system's reliance on vacuum-assisted operation may pose challenges for scalability and long-term field deployment. Future work should focus on simplifying the collection system while maintaining high performance to facilitate practical applications in sustainable water treatment technologies. Beyond pure desalination, multifunctional platforms are emerging, such as a MXene-PPy dual-layer membrane on attapulgite-poly(ionic liquid) (ATP-PIL) support that integrates photothermal evaporation with photocatalytic degradation of organic pollutants. However, its synthesis complexity, interlayer adhesion, and performance validation under real-world VOC exposure remain open challenges. Collectively, these recent studies not only represent the most up-to-date progress in CP-based SDIE but also address key limitations of previous systems, highlighting the field's movement toward scalable, salt-resistant, multifunctional, and industrially viable desalination technologies [103].

To conclude, the comparative analysis of various PTMs highlights the remarkable progress that has been made in SDIE technology. Each material system exhibits unique characteristics, including variations in evaporation rate, PCE, structural stability, salt resistance, and overall durability. Notably, the interplay between morphology and nanostructure plays a pivotal role in optimizing light absorption, water transport, and heat localization; ultimately influencing performance.

Many of these materials PTMs also displayed excellent hydrophilicity and long-term operational stability, making them potential candidates for practical, sustainable water purification solutions. With their ability to harness solar energy efficiently and operate under harsh environmental conditions, these materials hold great potential for real-world deployment in off-grid desalination, wastewater treatment, and clean water generation in remote or resource-limited areas. Key features of representative PTMs, including their morphology, PCE, hydrophilicity, stability, and relevant references for future insight, have been summarized in Table 2.

This comparative table highlights how different material features, such as tailored morphology, engineered nanostructure, and enhanced hydrophilicity, collectively contribute to improved photothermal performance and long-term stability. It serves as a valuable reference for

identifying promising candidates and guiding the rational design of next-generation solar evaporators for efficient and sustainable water purification.

2.4. PTh derivative: poly(3-hexylthiophene)

PTh derivative, such as P3HT, is a π -conjugated polymer [106] known for its excellent optoelectronic properties, processability, and stability. P3HT, one of the most widely studied derivatives, features alkyl side chains that enhance solubility and film formation, making it suitable for applications in organic PVs [107], field-effect transistors, photo-catalysts under solar illumination, and, more recently, in a range of bioelectronics applications [108] and photothermal conversion [109]. Its conductivity can be modulated through electrochemical

Table 2

Summary of PTMs for the SDIE system with their morphology, PCE, hydrophilicity, and stability.

Material	Morphology & nanostructure	Hydrophilicity	PCE (%)	Stability	Ref.
Wood-PEDOT:PSS hydrogel	Hydrogel, Bilayer	Good	90.0	10 cycles	[47]
PEDOT:PSS-NFC	Aerogels	–	–	6 cycles	[48]
PEDOT:PSS composite	Hydrogels	–	96.4	88 h	[50]
PEDOT:PSS-PVA	Hydrogel	–	–	6 h cycle	[49]
PANI@PEN	Membrane	–	–	Higher	[53]
PANI@PVDF composite	Membrane	Super	94.70	1000 cycles	[54]
Ti ₃ C ₂ T _x MXene/PANI composite	Fibers	Good	74.15	10 cycles	[56]
PANI-m@PVDF composite	Membrane	Good	–	60 days	[57]
PANI-PA	Membrane	–	~ 90	–	[58]
g-C ₃ N ₄ @PANI/PS	Micro-nano dendrite	Good	–	15 cycles	[59]
PANI@Ni dendrite fabric	Fibers	Good	–	15 cycles	[60]
AS-g-PANI cotton fabric	Fabric, Microporous	Good	–	–	[61]
PAM-doped-PANI fabric	Hydrogel, Fabric	Good	96.10	–	[62]
AS-g-PANI	Fabric	–	–	–	[64]
PB/PPy@CFs	Composite	Excellent	90.96	3 cycles	[69]
Fe ₃ O ₄ @PPy nanospheres	Nano-spheres	Super	94.0	6 cycles	[70]
SrCoO ₃ @PPy	Worm-like	Super	93.0	–	[71]
PPy on copper	Foam	Super	93.10	7 cycles	[72]
MnCDs@PPy	Fabric, Nanowires	Good	96.40	25 cycles	[73]
PPy-RF	Foam	Good	90.0	10 cycles	[74]
M – PPy sponge	Sponge, 3D macroporous	Super	88.12	10 cycles	[75]
c-GPP aerogel	Aerogel composite	Good	–	3 cycles	[76]
MnO ₂ @PPy NCs	NCs	Super	–	–	[77]
PA66/PPy nanofiber film	Film, 3D spherical fibrous network	–	–	–	[78]
IPNF foam	Foam	Super	90.0	–	[79]
PPy-SFD materials	3D, Sunflower disc	Good	99.30	Good	[80]
MPS-PPy membrane	Membrane	Good	Outstanding	–	[81]
PPy-CaCl ₂ @SA(N) composite	Hydrogel, Foam	–	Good	10 days	[82]
ZIF-8@PPy sponge	–	Excellent	Good	–	[83]
PPy-NL foam	Foam	Good	98.0	–	[84]
PPy/cellulose layer	Layered	Super	97.80	–	[85]
PPy/BiVO ₄ -PI/MXene composite	Aerogel	Good	96.77	10 cycles	[86]
Fe ₂ O ₃ @PPy/chitosan hydrogels	Hydrogels	–	91.0	–	[88]
GR/PPy-30 hybrid	Macro-porous Aerogel	Super	86.30	10 cycles	[104]
PPy@Cu ₃ (BTC) ₂ /Cu composite	Layer-by-layer	Excellent	86.92	30 cycles	[105]
PPy@CuO-3 NAs	3D, Cone-shaped	Excellent	86.70	–	[89]
Fe ₂ O ₄ @PPy NPs-wood pulp sponge	Sponge, NPs	Super	93.0	–	[90]
PPy-stainless steel mesh	Membrane	Super	~ 58.0	5 cycles	[91]
PPy-decorated wood	–	High	–	7 cycles	[92]
PPy-coated carbon fabric	Fabric	Super	–	Good	[93]
PPy-DES wood	–	Good	83.40	Good	[94]
PPy@CCF-MH film	Film	Remarkable	–	–	[97]
PPy@ NOFC	–	High	87.0	10 cycles	[98]
PEI//Fe ₃ O ₄ /PPy@PPS composite	Membrane, Fibers	–	–	8 cycles	[99]
PPy-coated CSMA	Porous foam	Super	94.70	30 days	[100]
PPy/SBMA/METAC	Hydrogel	–	~95.94	–	[101]
PPy black rose structure	–	–	91.50	–	[102]

doping [110]. Due to its strong light absorption capabilities, P3HT has recently attracted significant interest for use in photoactivated bio-interfaces [111], alongside other organic semiconductors developed for similar purposes. For instance, organic semiconductors have been explored for PV prosthetics in neurostimulation, where photo-capacitive stimulation of neurons activates voltage-gated sodium channels without relying on faradaic charge transfer, offering a safer therapeutic route for retinal applications [112]. Similarly, nanocrystal-based organic semiconductor assemblies, such as quinacridone-derived biomimetic structures, enable intimate semiconductor-cell interfaces, achieving

reversible light-induced conductance changes in ion-selective and temperature-gated channels [113]. Moreover, P3HT thin films have been demonstrated as hybrid biointerfaces with living tissues, where light-induced capacitive and thermal effects modulate membrane potential in HEK-293 cells, paving the way for optical control of cellular activity with potential biomedical applications. Additionally, P3HT functions as an effective PTM, capable of converting Vis light into heat [114]. It exhibits strong light absorption, high charge carrier mobility, and tunable electronic properties, making it a promising material for energy and sensing applications. Wang et al. integrated P3HT into non-

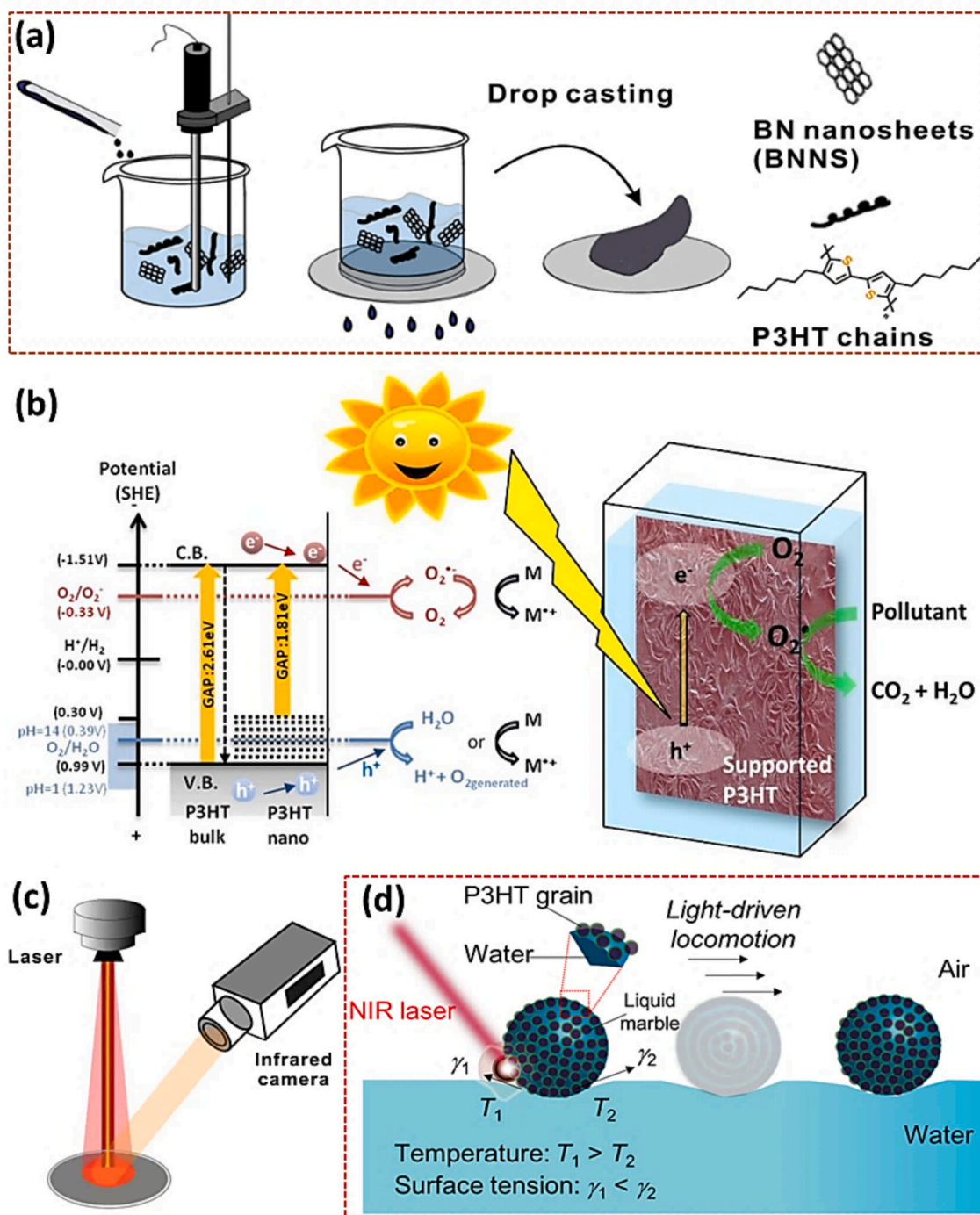


Fig. 7. (a) Fabrication process of the BNNS-P3HT composite. Reproduced under license from [115]. Copyright 2023, Elsevier. (b) Photocatalytic performance of P3HT nanostructures under sunlight. Reproduced under license from [116]. Copyright 2017, Elsevier. (c) Illustration of the setup for photothermal conversion testing. Reproduced under license from [115]. Copyright 2023, Elsevier. (d) Schematic showing the light-induced motion of a P3HT grain-stabilized liquid marble on a flat air-water interface. Reproduced under license from [119]. Copyright 2019, ACS Publications.

woven fabrics to design a device for parallel water evaporation and thermoelectric power generation. Under 1 kW m^{-2} solar radiation, it attained an evaporation rate of $1.04 \text{ kg m}^{-2} \text{ h}^{-1}$ and generated 58 mV. Also, its broad absorption band effectively absorbs sunlight, making it a promising PTM. They evaluated its photothermal properties by infrared (IR) thermal imaging. This study advances the use of PV materials in solar-thermal applications, guiding the development of water-electricity cogeneration devices [106]. Hong et al. experimented to investigate the influence of π - π stacking interactions on the thermal and photothermal performance of a composite comprising boron nitride nanosheets (BNNS) conjugated with P3HT (Fig. 7a). The BNNS-P3HT composite demonstrated a significantly enhanced thermal conductivity of $4.40 \text{ W m}^{-1} \text{ K}^{-1}$ at a 30 wt% BNNS loading; an increase of 511 % compared to pure P3HT film. Moreover, the composite exhibited excellent photothermal properties, with the surface temperature rising to $\sim 98.3^\circ \text{C}$ within 120 s under 808 nm laser irradiation at a power density of 1.31 W cm^{-2} . This enhancement is attributed to the strong Vis-NIR light absorption and efficient photothermal conversion capabilities of the composite [115]. P3HT nanostructures, when synthesized from soft templates derived from hexagonal mesophases, exhibited the remarkable photocatalytic efficiency for the deterioration of contaminants under both UV and Vis light. These photocatalysts demonstrated remarkable stability, maintaining their performance even after multiple cycles. Mechanistic investigations, including the use of scavengers, revealed that superoxide radicals ($\text{O}_2^{\cdot -}$) play a dominant role in the degradation of phenol, used as a model pollutant, as illustrated in Fig. 7b. Notable, the photocatalytic performance of P3HT nanostructures was improved significantly when immobilized on solid surfaces, offered exciting prospects for their application in photocatalytic reactors and self-cleaning surfaces [116]. The schematic for photothermal conversion testing has also been illustrated in Fig. 7c [115]. Loubiri et al. [117] investigated the effect of ZnSe NPs concentration on the optical and thermal properties of P3HT thin film using the photothermal deflection technique. The study showed that incorporating 10 %, 40 %, and 80 % ZnSe NPs into P3HT led to a progressive decrease in the band gap energy from 2.01 eV (pristine P3HT) to 1.86 eV (P3HT:80 % ZnSe), attributed to energetic disorder and charge-transfer interactions within the hybrid layers. Furthermore, the incorporation of ZnSe significantly altered the thermal behavior of the films, as the thermal diffusivity and conductivity decreased for lower concentrations due to interfacial thermal resistance, while at 80 % loading, values approached those of pristine P3HT owing to crystallinity effects. These findings highlight the potential of P3HT: ZnSe NCs for optoelectronic and photothermal applications, given their tunable bandgap and strong absorption in the 580–680 nm range. However, the observed reduction in thermal transport at intermediate loadings could limit long-term device stability. Furthermore, this work should focus on controlling NPs dispersion and interfacial compatibility to balance optical performance with robust thermal management. Meng et al. prepared the P3HT/rGO composite suspensions, which showed higher photoluminescence of the P3HT component when completely quenched by rGO. This clearly demonstrated that photoinduced energy or electron transfer played a significant role in the temperature rise of the P3HT/rGO composite suspensions. The grafting of P3HT onto the surface of the rGO composite was utilized to form the photothermal layer [118]. Upon irradiation with a 532 nm laser, the composite achieved a high PCE of 82 % and functioned as a photoswitchable bimetallic strip to control a light-emitting diode bulb. Further, Inoue et al. presented a single-step, solvent-free oxidative coupling polymerization method for synthesizing hydrophobic P3HT grains, using FeCl_3 solid particles as the oxidant. The photothermal performance of P3HT under NIR laser irradiation was also investigated. The light-induced Marangoni flow-driven motion of liquid marbles at the air-water interface was demonstrated and further supported by numerical analysis (Fig. 7d) [119]. Photothermal NPs have been shown to introduce photosensitivity into living organisms. Tortiglione et al. presented the P3HT NPs that were tested as light-activated

bioactuators in *Hydra vulgaris*, a freshwater polyp commonly used as a model organism due to its tissue-level structural organization [120]. Following efficient internalization of P3HT NPs via micropinocytosis, the eyeless polyp displayed no morphological abnormalities, such as body or tentacle contraction or tissue damage, indicating minimal toxicity. However, under light exposure, the presence of P3HT NPs rendered the animals light-responsive. Specifically, the treated *Hydrae* exhibited a light-induced modulation in body shrinkage and elongation behavior through a gene that encodes a member of the 7-transmembrane G protein-coupled receptor family capable of binding a retinaldehyde chromophore involved in photoreception [121].

Additionally, further studies by Moros et al. demonstrated that photoexcitation of P3HT NPs in *Hydrae* alters the intracellular redox balance, increasing markers of oxidative stress at the deoxyribonucleic acid and protein levels without causing Vis damage to the organism [122]. They also demonstrated that the antioxidant defense system in *Hydra* can be precisely modulated by continuous light exposure. Building on these results, P3HT NPs have been explored as potential replacements for degenerated retinal photoreceptors, a leading cause of visual impairment in aging populations. Common conditions associated with such degeneration include age-related macular degeneration and retinitis pigmentosa [112]. Thomas et al. investigated the photo-modulation of membrane potential cultured on conjugated polymer films. These cells served the isolation of the direct effects of photo-stimulation on plasma membrane potential while minimizing measurement errors from space-clamp artifacts, thanks to their small size and minimal cellular processes [113]. The cells were cultured on a thin film of P3HT. The findings offered promising insights for the development of novel platforms for light-controlled cell manipulation, with potential applications in neuroscience and medicine [114]. Zhengliang et al. conducted time-resolved *in situ* optical probing to investigate the dynamics of the dissolution process, i.e., 2,3,5,6-tetrafluoro-7,8-tetracyanoquinodimethane (F4TCNQ) and P3HT. Then the obtained P3HT: F4TCNQ thin film was immersed in tetrahydrofuran (THF) under 532 nm laser irradiation. This setup ensured the dissolution was only driven by the photothermal effect. Organic semiconductors (OSCs) are gaining traction in next-generation electronics and energy systems. A novel lithographic etching approach has been developed for OSCs, where molecular dopants reduce polymer solubility and direct-write lasers locally remove dopants. The study on F4TCNQ-doped P3HT revealed that patterning occurs through both photochemical reactions at low photon doses and a photothermal mechanism at higher excitation rates, enabling high-speed fabrication up to 1 m s^{-1} [123]. In parallel, structuring strategies have been explored to enhance the electrochemical and photoelectrochemical performance of P3HT. Blending with PS followed by selective removal generated nano/microstructured P3HT, which, combined with oxygen plasma treatment, improved wettability, capacitance, and photocurrents for the oxygen reduction reaction. Notably, P3HT consistently produced H_2O_2 with $>90 \%$ faradaic efficiency, though challenges such as low photovoltage and photobleaching remain [124].

In a recent breakthrough, the research groups led by Lanzani and Benfenati introduced the first “liquid retina device,” comprising a water-based suspension of P3HT NPs [125]. Subretinally injected P3HT-NPs distributed homogeneously in both young and aged dystrophic rats and maintained close contact with bipolar and horizontal cells, enabling light-induced charge polarization and subsequent neuronal stimulation. Importantly, these NPs restored multiple visual functions even in animals with fully degenerated and remodeled retinas, including pupillary reflexes, cortical visual evoked potentials, light-driven behavioral responses, and partial visual acuity. A key advantage of this approach lies in the biocompatibility and long-term stability of P3HT-NPs, which showed no significant inflammatory response or retinal toxicity. However, limitations remain in the incomplete restoration of high-resolution spatial vision, and challenges persist regarding the scalability of NPs delivery and long-term functional integration. These outcomes point

toward promising future directions, such as optimizing NP-neuron interfaces and combining P3HT-NPs with neuroprotective or regenerative strategies for more comprehensive vision restoration. The performance of P3HT NPs matches that of leading 2D retinal implants [126], making them a highly promising candidate for treating degenerative retinal diseases. Their advantages include minimally invasive application, long-lasting efficacy, and the potential for high spatial resolution. Moskvina et al. thoroughly investigated the behavior of P3HT films containing trace amounts of oxygen under photothermal aging conditions (60 mW cm⁻², 85 °C) and during subsequent dark storage. The dark electron spin resonance spectra of the P3HT film showed no significant signals.

However, photothermal aging led to a notable increase in the concentration of radical species, reaching up to 6×10^{16} spin cm⁻³ [127]. Moreover, in this study, CdSe NPs were capped with tributylphosphine oxide (TBPO) ligands, and the focus was placed on investigating how varying the concentration of CdSe NPs affects the optical properties of P3HT films. This analysis was carried out using UV-Vis spectroscopy and photothermal deflection spectroscopy. Moreover, in this study [128], the photothermal performance of P3HT:TBPO-capped CdSe NCs was systematically investigated by analyzing the effect of NPs concentration on sub-bandgap absorption using UV-vis spectroscopy and photothermal deflection spectroscopy (PDS). The results showed that increasing the TBPO-capped CdSe concentration up to 40 % enhanced light absorption and reduced the sub-bandgap energy, thereby improving PCE by facilitating interconnected electron pathways within the polymer matrix. At higher concentrations (60 %), aggregation and morphological disorder led to decreased absorption and reduced photothermal efficiency, highlighting the importance of controlled NPs dispersion. This work demonstrates the advantage of combining PDS with UV-vis techniques to evaluate photothermal-active materials precisely.

Limitations include potential challenges in maintaining uniform NP distribution and stability over extended use. Further research should focus on optimizing NP-polymer interfaces, minimizing aggregation, and exploring scalable fabrication methods to enhance long-term photothermal performance in solar-driven applications [129]. Furthermore, Ilahi et al. [130] exemplify the critical importance of photothermal characterization, specifically PDS, in evaluating nascent materials. Their key finding, that increased boron composition in BGAs alloys reduces thermal conductivity, is significant, as it demonstrates a pathway to engineer enhanced thermal confinement. However, the same structural disorder that suppresses thermal transport also introduces detrimental band tails and non-radiative defects, as evidenced by the discrepancy between PDS and photoluminescence data. This duality creates a fundamental trade-off: the material becomes an excellent passive absorber of light and a heat trap, yet is presently unsuitable for applications requiring subsequent electronic signal transduction. Thus, while this work successfully benchmarks the properties of BGAs, it primarily outlines a materials engineering challenge; future work must focus on correlating growth parameters with structural data to selectively promote beneficial disorder for thermal confinement while mitigating defect densities that cripple electronic performance, ultimately guiding the targeted integration of these alloys into purpose-built photothermal devices. Further study underscores the photothermal deflection (PTD) technique's pivotal role as a non-contact probe for quantifying critical electronic transport properties, non-radiative lifetime (τ_{nr}), diffusivity (D), and surface recombination velocity (S), in semiconductors. The strong coincidence between its generalized 1D model and experimental data validates PTD's significant advantage in directly characterizing non-radiative processes, the very mechanisms that drive photothermal conversion. However, a key limitation lies in the model's inherent simplicity; its 1D nature may obscure complex, multi-dimensional carrier and heat dynamics, particularly at nanostructured interfaces or in anisotropic materials like GaSb. Furthermore, accurately deconvoluting the intertwined parameters (τ_{nr} , D, S) from a single fit presents a challenge, potentially obscuring their individual values. For the field to

progress, upcoming work must focus on correlating PTD-derived parameters with other transport measurements to solidify their accuracy and on developing more sophisticated multi-dimensional models [131]. P3HT has been widely explored as a PTM in diverse fields such as medicine, neuroscience, photocatalysis, and optoelectronics, owing to its favorable properties, including tunable morphology, broad light absorption across the Vis spectrum, high power density, and thermal and chemical stability. However, its potential in the area of SDIE remains relatively unexplored. Given these advantageous characteristics, P3HT holds great promise as an efficient PTM for interfacial SDIE. Its ability to harvest and convert solar energy effectively, combined with its structural versatility, suggests that P3HT can serve as a high-performance material in future water purification and desalination technologies. In Table 3, we have summarized the key properties of P3HT as a PTM, including its morphology, nanostructure, absorption, power density, stability, and applications. This table provides an overview of the material's potential, particularly in SDIE technology for water purification.

While P3HT exhibits excellent properties such as broad light absorption, good thermal stability, and tunable morphology, its overall performance can still be influenced by factors like nanostructure uniformity, mechanical strength, and surface wettability, a deep insight into the structure-property correlation is essential, as variations in the molecular organization, crystallinity, and nanostructuring that can significantly impact its PCE and water transport behavior. Achieving an optimal balance between light absorption, water management, and structural stability requires thoughtful material design and engineering to fully realize the potential of P3HT in SDIE and related applications.

In addition, Table 4 provides a comparative overview of four widely studied conductive polymers, PEDOT:PSS, PANI, PPy, and P3HT, highlighting their key advantages, limitations, and performance in seawater desalination. This comparison highlights how the unique photothermal properties, surface functionality, and salt tolerance of each polymer influence their practical applicability in SDIE systems.

2.5. Conjugated microporous polymers for SDIE

Recent advancements have positioned conjugated microporous polymers (CMPs) as promising next-generation PTMs for SDIE. Their extended π -conjugation enables efficient light harvesting across the UV-Vis-NIR spectrum. At the same time, intrinsic microporosity facilitates rapid water transport and vapor escape, resulting in superior solar-to-vapor conversion efficiency. For instance, sulfone-linked CMPs show broadband light absorption, robust stability, and high evaporation rates (1.82 kg m⁻² h⁻¹) without degradation under long-term brine exposure, making them promising for solar desalination. Carbonized CMP hollow microsphere-based composite hydrogel membranes (CCMPsHM-CHM), prepared via Sonogashira-Hagihara coupling and hard-template synthesis, offer 3D hierarchical porosity, >89 % solar absorption, low thermal conductivity (0.32–0.42 W m⁻¹ K⁻¹), superhydrophilicity (WCA = 0°), high conversion efficiency (89–91 %), and evaporation rates of 1.48–1.51 kg m⁻² h⁻¹ under one-sun. They maintain >80 % performance after 10 cycles, >83 % efficiency in concentrated brine, and remove >99 % of metal ions, meeting WHO and United States EPA standards. These features indicate excellent photothermal conversion and stability with scalable potential, though challenges remain in simplifying synthesis, improving mechanical robustness, antifouling ability, and cost-effectiveness for large-scale applications [138]. The aerogels feature robust C=C conjugated skeletons and electron-donating -OH groups, endowing them with excellent PCE (95.6 %), a high evaporation rate of ~1.55 kg m⁻² h⁻¹ under one-sun, and strong chemical stability in acidic, alkaline, and brine environments. The hydrophilic porous channels of the aerogels facilitate fast mass transfer, enabling efficient uranyl ion adsorption (up to 1200 mg m⁻² in simulated seawater). The 3D cross-linked networks allow easy integration with other functional materials, highlighting their versatility for seawater desalination and uranium extraction. Despite these

Table 3
Properties of P3HT as a PTM.

Material	Morphology & nanostructure	Absorption (nm)	Power density	Stability	Application	Ref.
P3HT-loaded non-woven fabrics	Fabric	300–2500	1 kW m ⁻²	5 cycles	PV materials	[106]
BNNS-P3HT composite	Composite	400–800	1.31 W cm ⁻²		Water-electricity cogeneration	
P3HT nanostructure	Nanostructure	550	–	4 cycles	Biosystems	[115]
					Photocatalytic reactors	[116]
					Self-cleaning surfaces	
P3HT:ZnSe NCs	Layers	580–680	–	–	LEDs	[117]
P3HT/rGO composite	–	234, 300, and 268	–	Several cycles	Photo-switchable bimetallic strip to control the LED bulb	[118]
P3HT grains	NPs	800	–	–	Living organisms	[119]
P3HT NPs	NPs	–	0.43 mW mm ⁻²	–	Biomedical	[120]
P3HT NPs	NPs	400–600	0.124 mW mm ⁻²	–	Therapeutic	[122]
P3HT film	Film	475	–	–	Neuroscience	[114]
P3HT:PCBM film	Film	435	–	–	Medicine	
					Neuroscience	[114]
					Medicine	
F4TCNQ-doped P3HT films	Film	532	–	10 h	Measuring photon-initiated chemical reaction rates	[132,133]
					Bioelectronics	
P3HT NPs	NPs	638	–	–	Retinitis pigmentosa treatment	[125]
P3HT NPs	NPs	–	222 mW mm ⁻²	–	Retinitis pigmentosa treatment	[126]
P3HT films	Film	–	–	–	–	[127]
P3HT:TBPO-capped CdSe NCs	NCs	530–650	–	–	Bandgap engineering, Optoelectronic integration	[134]

Table 4

Comparative analysis of PEDOT:PSS, PANI, PPy, and P3HT, showing their advantages, disadvantages, and performance in seawater desalination applications.

Conductive polymer	Advantages of SDIE	Limitations	Performance	References
PEDOT:PSS	High conductivity, good film-forming ability, and stable in saline water.	Limited NIR absorption, moderate long-term stability.	Enhanced desalination performance with improved salt removal efficiency.	[49,135]
PANI	Strong solar absorption, –NH ⁺ groups enhance salt tolerance, tunable conductivity.	Moderate mechanical flexibility, moderate long-term stability.	Significant reduction in energy consumption for redox-flow desalination.	[123,124]
PPy	Broad solar absorption, facile synthesis, and hydrophilic surface enhance water transport.	Moderate photothermal stability under prolonged irradiation.	High desalination capacity with excellent salt resistance and cyclic stability.	[136]
P3HT	Strong NIR absorption, tunable hydrophilicity, and can be functionalized for salt resistance.	Lower processability, limited long-term stability.	High solar-thermal conversion efficiency with effective utilization of sunlight.	[137]

advantages, the limited processability and collectability of as-synthesized sp²C-CPP powders remain a challenge, which the aerogel formation strategy effectively addresses, improving usability and broadening practical applications [139]. Building on advances in CMPs for SDIE, a CMP hollow microsphere-based solar evaporator encapsulating hexadecylamine (HDA) as a phase-change material was reported. The microspheres, synthesized via Pd(II)/Cu(I)-catalyzed

Sonogashira–Hagihara cross-coupling using SiO₂ templates, exhibited high surface area ($\approx 573\text{--}591\text{ m}^2\text{ g}^{-1}$) and hierarchical porosity, enabling efficient HDA loading (energy storage density $\approx 174.88\text{ J g}^{-1}$). With an asphalt photothermal layer, the composite (CMP2-HDA-A) achieved $>93.9\%$ solar absorption, low thermal conductivity ($\approx 0.064\text{ W m}^{-1}\text{ K}^{-1}$), and evaporation rates of $1.59\text{ kg m}^{-2}\text{ h}^{-1}$ under 1 kW m^{-2} illumination and $0.76\text{ kg m}^{-2}\text{ h}^{-1}$ in the dark. It maintained stable performance in saline brine, strong acid/alkali, and dye wastewater, and produced condensate meeting WHO standards, suitable for irrigation. This approach effectively addresses intermittent solar input and demonstrates scalable potential for sustainable freshwater production [129]. Similarly, porphyrin/aniline-based CMPs (PACMPs) were synthesized via Buchwald–Hartwig coupling and coated on PU sponges to form porphyrin/Aniline-based conjugated sponge systems (PACSSs). The optimized PACS-120 exhibited broad UV–Vis–NIR absorption (84.7 %), low thermal conductivity ($0.047\text{ W m}^{-1}\text{ K}^{-1}$), and high thermal stability (char yield $\sim 60\%$) (Fig. 8a–e). Under 1 sun, it achieved a seawater evaporation rate of $1.31\text{ kg m}^{-2}\text{ h}^{-1}$ with 86.3 % solar-to-vapor efficiency, producing 10.55 kg m^{-2} fresh water per day under natural sunlight—sufficient for four adults' drinking needs (Fig. 8f and g). PACS-120 also showed $>99.9\%$ salt rejection, excellent dye decolorization, mechanical robustness (>1000 compression cycles), and long-term stability without salt accumulation. These attributes make PACSSs highly promising for scalable solar desalination and wastewater treatment [128]. Moreover, a composite solar interfacial evaporator was developed by combining MXene nanosheets with conjugated microporous polymer hollow microspheres and cetyl alcohol as a phase change material (PCM). This design achieved evaporation rates of $1.57\text{ kg m}^{-2}\text{ h}^{-1}$ (1 sun) and $2.79\text{ kg m}^{-2}\text{ h}^{-1}$ (2 sun) with $>91\%$ solar evaporation efficiency in saline water. The PCM enabled continuous evaporation under intermittent illumination, providing an additional 0.36 kg m^{-2} water evaporation at 2 sun compared to a system without PCM. This approach addresses the intermittency of solar irradiation, demonstrating the potential of MXene–CMP–PCM composites for stable, all-weather desalination [140]. Recent work by Wang et al. demonstrated a 3D cotton-based photothermal evaporator incorporating MXene nanosheets modified with porphyrin-based conjugated microporous polymer (PPCMP) as the photothermal layer. Inspired by the ginseng plant's trunk-to-branch water supply system, the evaporator was designed with

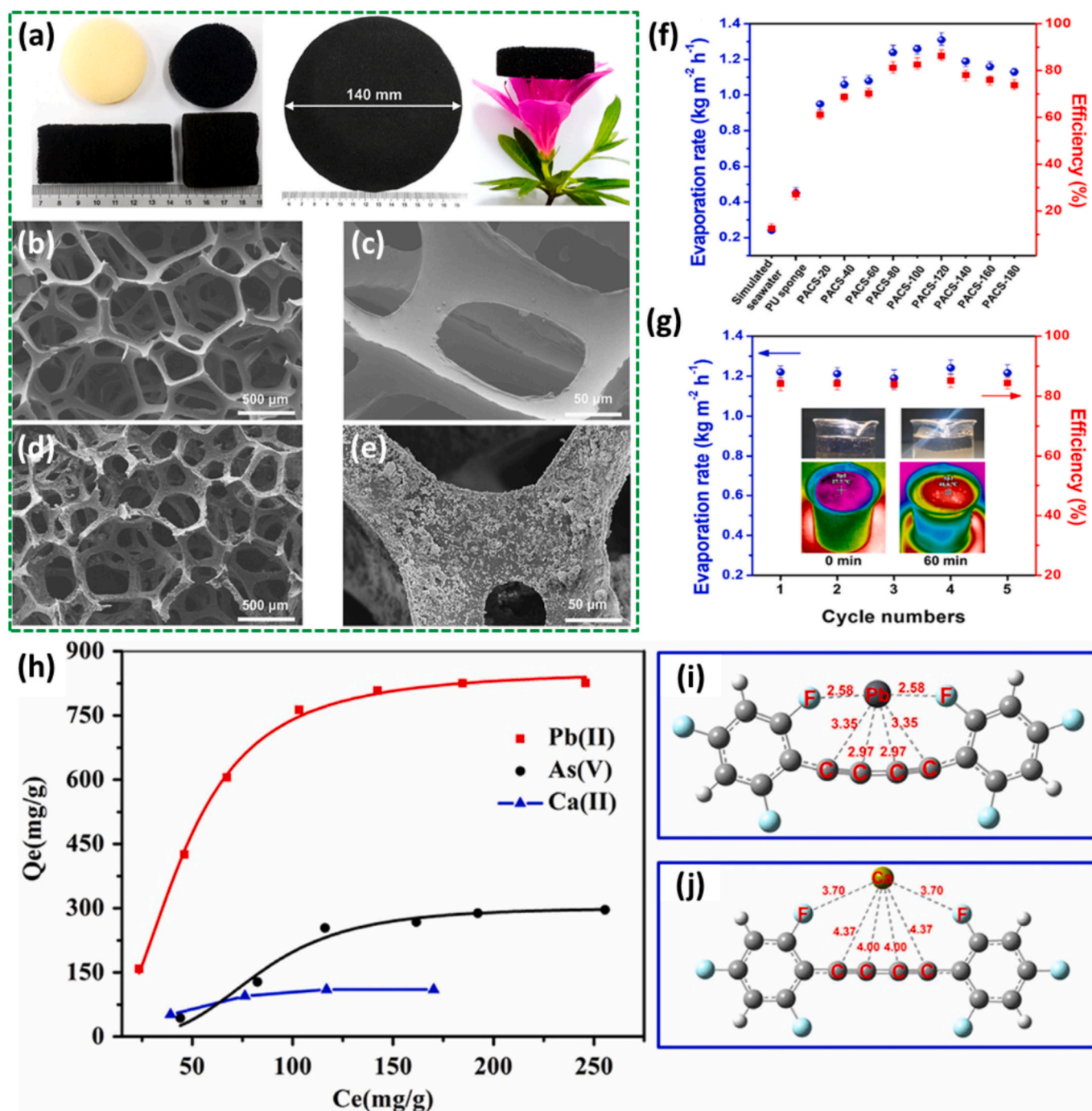


Fig. 8. (a) Photographs of pristine PU sponge and PACS-120, demonstrating flexibility and ability to form different shapes and sizes. Reproduced under license from [128]. Copyright 2022, ACS Publications. (b, c) SEM images of PU sponge showing its porous skeleton. Reproduced under license from [128]. Copyright 2022, ACS Publications. (d, e) SEM images of PACS-120 illustrating uniform PACMP coating on the sponge framework. Reproduced under license from [128]. Copyright 2022, ACS Publications. (f) Seawater evaporation rate and solar-to-vapor conversion efficiency of PACSs. Reproduced under license from [128]. Copyright 2022, ACS Publications. (g) Durability test showing the stability of evaporation rate and SDIE efficiency of PACS-120 over multiple cycles. Reproduced under license from [128]. Copyright 2022, ACS Publications. Adsorption properties of PFCMP-0 for metal ions. (h) Adsorption isotherms. Reproduced under license from [144]. Copyright 2015, Nature. (i) A model of the combination state between the PFCMP-0 and Pb(II). Reproduced under license from [144]. Copyright 2015, Nature. (j) A model of the combination state between the PFCMP-0 and Ca(II). The marked values represent the distances between PFCMP-0 atoms and cations. Reproduced under license from [144]. Copyright 2015, Nature.

a cloak-like weaving of PPCMP to enable tunable water transport, balancing the water supply flux with the evaporation rate. This design effectively mitigates salt accumulation on the photothermal surface and reduces heat dissipation losses associated with direct water immersion. As a result, the system achieves a high evaporation rate of $2.81 \text{ kg m}^{-2} \text{ h}^{-1}$ and a photothermal conversion efficiency of 155 % under 1 sun

illumination, highlighting the potential of 3D porous organic polymer-based fabrics for efficient seawater desalination [131]. Chen et al. developed a reduced graphene oxide (RGO)/CMP hollow sphere composite aerogel with tetradecanol (RCMP@TD-HA) coated on hollow glass microspheres. This material stores solar energy in the PCM, enabling continuous evaporation even after the light source is dimmed,

with an evaporation rate of $1.68 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ and an additional $0.76 \text{ kg} \cdot \text{m}^{-2}$ of water released post-irradiation. The oleophobic variant (ORCMP@TD-HA) allows efficient evaporation in oily water, achieving 90 % efficiency and $1.62 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$. These results demonstrate the potential of PCM-assisted CMP-based aerogels for continuous SDIE, including challenging environments like oily wastewater [141]. Similarly, Chen et al. reported fully conjugated sp^2 -carbon conjugated porous polymer ($\text{sp}^2\text{C-CPP}$) aerogels—DHA-TMT (2,5-dihydroxyterephthalaldehyde-trimethyl-1,3,5-triazine) and DBD-TMT (3,5-dibromo-2,4-dihydroxybenzaldehyde-trimethyl-1,3,5-triazine)—synthesized via surface-initiated aldol polycondensation (SI-AP), showing high surface area and efficient photothermal properties for SDIE. In addition, positively charged CMPs were developed for selective uranium extraction from seawater, with a sorption rate of $0.46 \text{ mg} \cdot \text{g}^{-1} \cdot \text{day}^{-1}$, high uranium/vanadium selectivity (8.4), enhanced binding via oxime and carboxyl ligands, and antibiofouling activity against *Escherichia coli* and *Staphylococcus aureus*. These CMPs can be loaded onto microfiltration membranes, demonstrating multifunctional environmental applications [142].

Extending the utility of CPPs, Chen et al. developed CPP-1 and CPP-2 with phosphate ester functionalization via Sonogashira-Hagihara coupling, forming 3D hierarchical networks. CPP-2 featured hollow nanotubes alongside solid nanospheres, enhancing accessibility to adsorption sites. Both polymers exhibited superhydrophilicity (wetting time 0.2 s), high chemical and thermal stability (decomposition $>250\text{--}300^\circ\text{C}$), and retained performance under harsh conditions. CPP-2 achieved a maximum La^{3+} adsorption of $7.81 \text{ mg} \cdot \text{g}^{-1}$ (91.64 % efficiency) at pH 5, with a selective adsorption coefficient up to 10-fold higher than competing ions. Adsorption followed a pseudo-second-order kinetic model and Langmuir isotherm ($R^2 > 0.9999$), indicating monolayer chemical adsorption via electrostatic and phosphate ester coordination. Thermodynamics confirmed a spontaneous, endothermic process, and both CPPs maintained stable adsorption over 20 cycles. Additionally, CPPs could be fabricated into monolithic foams and nanomembranes, enhancing processability and practical applicability [143]. Similarly, CCMP-based interfacial evaporators have been applied for advanced wastewater treatment, particularly for radioactive iodine removal. A CCMP-1 evaporator, combined with an expandable polyethylene sponge, exhibited a photothermal conversion efficiency of 95.39 % and a stable evaporation rate of $1.5879 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ under 1 sun.

The porous structure and strong light absorption accelerated water transport and mass transfer, reducing iodine concentration in the condensate from $0.2 \text{ mmol} \cdot \text{L}^{-1}$ to $0.0027 \text{ mmol} \cdot \text{L}^{-1}$, a nearly three-order-of-magnitude decrease, demonstrating almost complete iodine enrichment. This study highlights CCMP-based SDIE as an efficient, green strategy for simultaneous freshwater production and selective removal of hazardous ions [145]. Beyond photothermal applications, perfluorous CMP (PFCMP-O) has demonstrated exceptional water purification capabilities. With superhydrophobicity and high surface area, it efficiently adsorbs oils, organic solvents, dyes, and heavy metal ions, achieving $1376.7 \text{ mg} \cdot \text{g}^{-1}$ for Congo red, $808.2 \text{ mg} \cdot \text{g}^{-1}$ for Pb(II), and $303.2 \text{ mg} \cdot \text{g}^{-1}$ for As(V), outperforming previously reported materials. Its superior performance is attributed to fluorination and triple bonds, enabling selective adsorption of toxic ions while sparing essential ions like Ca(II). Benchmark experiments confirm its ability to remove multiple pollutants simultaneously (Fig. 8h–j), highlighting its potential for reusable and portable water purification [144]. Despite these advances, challenges remain, including high synthetic complexity, limited large-scale production, and mechanical brittleness of CMP films, which may compromise durability under prolonged operation. Further research should target scalable synthesis, mechanically robust, flexible CMP composites, and hierarchical. Structuring to improve interfacial water transport and long-term stability.

2.6. CP-based metal–organic frameworks for SDIE

CP-based metal–organic frameworks (MOFs) are emerging as efficient PTMs for SDIE. Fe-based MOF-decorated wood evaporators show broadband light absorption, rapid temperature rise within 10 min, and evaporation rates of $1.81 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ with 89 % efficiency under 1 sun. Likewise, MOF-303 membranes integrated with carbon black, PDA, and perfluoro-functionalized PEDOT achieve $2.36 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ evaporation flux and 97 % energy conversion efficiency. These hybrid systems combine enhanced photothermal conversion, salt resistance, and durability, underscoring MOF–CP composites as promising candidates for scalable, multifunctional SDIE applications [146]. Moreover, Hydrophilic MOFs such as MOF-303 have shown great potential for SDIE due to their high water uptake, ordered porosity, and ability to lower the enthalpy of vaporization via nanoconfinement. A MOF-303-based Janus membrane, integrating MOF-303 with carbon black (CB), PDA, and a perfluoro-functionalized PEDOT (PEDOT-F) layer, achieved rapid water transport, excellent photothermal conversion, and effective salt rejection. Under one sun, it delivered an evaporation flux of $2.36 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ with 97 % efficiency, which increased to $5.7 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ under natural sunlight (Fig. 9a–d). These results highlight the advantages of MOF–CP composites, including reduced energy demand, high stability, and resistance to fouling. Remaining challenges include complex fabrication, limited long-term durability data, and modest vapor collection efficiency. Future work should focus on scalable synthesis, optimizing the porosity–hydrophobicity balance, and integrating with efficient condensation systems, while exploring conductive MOFs and redox-active hybrids to couple SDIE with photocatalytic or electrochemical purification [147].

Emerging CP-based metal–organic frameworks (CP-MOFs) have shown great potential for SDIE. A bioinspired $\text{Ni}_3(\text{HIB})_2$ -chloranilic acid (CHL) cocrystal exhibits excellent photothermal properties due to 2D conjugation and persistent anion radicals, achieving an evaporation rate of $4.04 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$. Molecular dynamics simulations indicate that CHL rotation tunes pore sizes, enabling ultra-fast water transport (1.11×10^{11} and $3.21 \times 10^{11} \text{ H}_2\text{O} \cdot \text{s}^{-1}$ per channel at 298 K and 323 K), exceeding aquaporin channels. The high performance arises from the synergistic effect of fast water-transporting pores and strong photothermal conversion, offering a biomimetic strategy for designing CP-MOFs for efficient SDIE [148]. Recent advances in SDIE have highlighted the potential of conducting polymer-based metal–organic frameworks (CP-MOFs) as efficient photothermal materials. A notable example involves Cu-BTC MOFs grown on flexible polyester textiles and coated with PPy to form hierarchical porous composites (PCCT and PCAT, Fig. 9e). The hierarchical architecture and synergistic effect of Cu-BTC MOFs with PPy provide high solar absorption ($>92\%$), superhydrophilicity, and low thermal conductivity ($\sim 0.11 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$), which together enable efficient water transport, multiple internal light reflections, and high photothermal conversion efficiency ($\sim 89\%$). PCCT exhibited superior evaporation performance with rates up to $2.85 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ under 2 sun illumination, outperforming PCAT due to its more hierarchical surface, better hydrophilicity, and lower thermal conductivity. The materials also demonstrated excellent salt resistance, maintaining high efficiency even in solutions up to 15 wt% NaCl. Furthermore, CP-MOFs enabled simultaneous wastewater treatment, effectively removing organic dyes and heavy metal ions during SDIE, with PCCT showing higher pollutant removal due to its hierarchical porous structure. This work underscores that integrating CPs with MOFs creates multifunctional PTMs capable of high-efficiency solar evaporation and water purification, suggesting a promising route for next-generation SDIE systems [105].

Complementarily, a free-standing Zr-Fc MOF/SWCNT/Gelatin (ZSG) membrane couples photothermal evaporation ($\sim 96.5\%$ light absorption, $1.53 \text{ kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$, 95.6 % efficiency) with photo-Fenton degradation, completely mineralizing VOCs ($k = 0.0762 \text{ min}^{-1}$) and reducing phenol-contaminated water to $\text{COD} = 2.3 \text{ mg} \cdot \text{L}^{-1}$, meeting drinking-water standards. The ZSG membrane maintains structural integrity

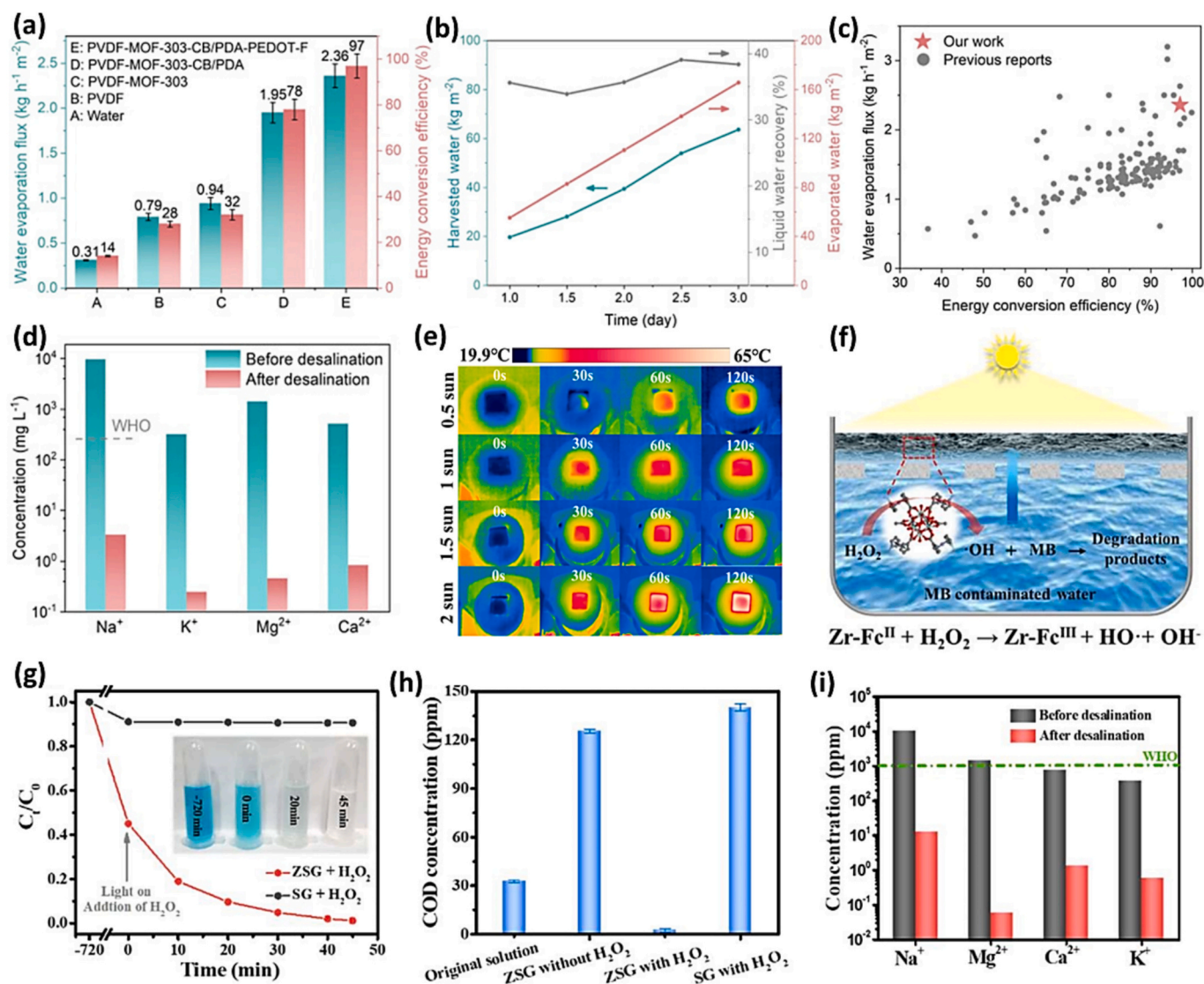


Fig. 9. (a) Water evaporation flux and photothermal energy conversion efficiency of different membrane samples under 1 sun illumination using deionized water. Reproduced under license from [147]. Copyright 2024, ACS Publications. (b) Time-dependent profiles of evaporated water, collected water, and liquid water recovery under 1 sun illumination with deionized water. Reproduced under license from [147]. Copyright 2024, ACS Publications. (c) Comparison of water flux versus energy conversion efficiency for our membrane device (MOF-303-CB/PDA-PEDOT-F) against previously reported devices. Reproduced under license from [147]. Copyright 2024, ACS Publications. (d) Ion concentrations in the initial seawater and post-desalination water. Reproduced under license from [147]. Copyright 2024, ACS Publications. (e) Evaporation performance of PCAT under different solar irradiation intensities. Reproduced under license from [105]. Copyright 2024, Elsevier. (f) Schematic representation of ·OH generation catalyzed by Zr-Fe MOF and subsequent degradation of methylene blue (MB) by ·OH radicals. Reproduced under license from [149]. Copyright 2020, RSC Publications. (g) Degradation of MB using SG and ZSG membranes with 0.5 M H₂O₂. Reproduced under license from [149]. Copyright 2020, RSC Publications. (h) Chemical oxygen demand (COD). Reproduced under license from [149]. Copyright 2020, RSC Publications. (i) Ion concentrations of VOC-contaminated seawater before treatment and in the regenerated water. Reproduced under license from [149]. Copyright 2020, RSC Publications.

and salt resistance over extended use (Fig. 9f–i). Together, these studies demonstrate promising pathways toward reusable, high-efficiency systems for simultaneous desalination, pollutant removal, and VOC degradation in SDIE [149]. Expanding the scope to emerging materials, CP-MOFs have been utilized to enhance interfacial polymerization for ultrasensitive PA membranes. Amphiphilic copper(II) benzene-1,4-dicarboxylate (CuBDC) MOF nanoflakes self-assemble at the water/hexane interface, accelerating monomer transport and trapping heat and gas nanobubbles, resulting in ultrathin (~5 nm), highly cross-linked (~98 %), crumpled PA nanofilms with outstanding desalination performance. These membranes achieve >90 % rejection of boron and *N*-nitrosodimethylamine (NDMA), along with enhanced water permeance, demonstrating the potential of CP-based MOFs in SDIE and advanced water purification [150].

2.7. Other CPs and their derivatives

Recent advancements in solar-driven seawater desalination have focused on improving photothermal fabrics, evaporator designs, and multifunctional applications. A recent study employed PDA-modified carbon fiber membranes (CFM@PDA) to construct a hanging-model evaporator, addressing key challenges of salt accumulation and inefficient water transport in conventional floating systems. The PDA coating endowed the carbon fibers with superhydrophilicity, hierarchical porosity, and enhanced light absorption (96.7 %), enabling a high water-transfer rate (26.35 g h⁻¹, ~3.6 × higher than cotton fabric) and strong photothermal performance. Under one-sun irradiation, the system achieved a solar evaporation rate of 1.79 kg m⁻² h⁻¹ with 92.6 % efficiency, maintaining stable performance even in highly saline conditions (21 wt

% NaCl) without salt deposition. This work highlights the potential of CP-based surface engineering in hybrid SDIE systems, offering both scalability and durability for practical seawater desalination [151]. Manganese oxide-L-lysine (MnO₂/PLL) co-decorated carbon-fiber cloth (CFC) was developed to address limitations of high evaporation enthalpy, poor photoabsorption, and biofouling in solar desalination. Hydrothermally grown MnO₂ nanosheets, further modified with PLL, converted hydrophobic CFC into a superhydrophilic fabric with reduced water evaporation enthalpy (2132.34 kJ kg⁻¹) and enhanced light absorption (97.8 %). PLL's amino functionality also imparted strong antibacterial properties, achieving >99 % inactivation of *E. coli* and *S. aureus* within 60 min, ensuring long-term antifouling stability. As a hanging evaporator, CFC/MnO₂/PLL achieved a high evaporation rate of 2.20 kg m⁻² h⁻¹ under one-sun, maintaining stability across variable NaCl concentrations (3.5–21 wt%), extended cycles (40 h), and under bacterial contamination. Desalination tests with simulated brine and real seawater produced freshwater with ion concentrations well below WHO standards, confirming both high efficiency and water quality [152]. Recent innovations have also focused on biomimetic 2D photo-thermal fabrics that enhance evaporation performance and salt resistance. In one study, a breathable carbon-nanotube-hydrogel-coated polyester (PET) fabric, designed with fiber pillars and stomatal hole arrays, achieved 96.1 % solar absorption and a reduced water-evaporation enthalpy of 1664.6 kJ kg⁻¹. Its heliotropic hanging configuration enabled multi-plane evaporation (2.6 kg m⁻² h⁻¹ under one-sun, up to 4.2 kg m⁻² h⁻¹ with airflow) while simultaneously preventing salt crystallization by allowing concentrated brine to drop away. This design underscores the promise of bioinspired hybrid systems for scalable and stable solar desalination [153]. Inspired by natural honeycomb structures, a double-layer fabric (DLF) knitted from CNT-graphene decorated polyester yarns and reinforced with an electro-spun PAN/C nanofibrous mat demonstrated broadband light absorption (~97 %), high conductivity, and robust mechanical strength. The DLF exhibited an evaporation rate of 2.23 kg m⁻² h⁻¹ under one sun, which increased to 6.18 kg m⁻² h⁻¹ with a 10 V electrothermal input, highlighting effective photo-electro-thermal synergy. The system exhibited excellent salt resistance and >99.9 % desalination efficiency at 21 wt% salinity, maintaining long-term operational stability. However, dependence on external voltage input may limit off-grid applications, suggesting that future work should integrate self-powered energy modules or optimize the fabric design for higher solar-only performance [154]. Bioinspired designs provide advanced strategies for controlling fluid transfer via wettability contrast, oriented micro-/nano-structures, and geometry gradients. Such fluid-manipulating interfaces (FMIs) enable spontaneous, continuous, and smart liquid transport, enhancing applications in heat transfer, microfluidics, heterogeneous catalysis, and water harvesting. A comprehensive understanding of FMI development, classification, fabrication, and interfacial chemistry is crucial for designing materials with optimized liquid pathways for practical applications [155].

Additionally, photothermal fabrics prepared via surface modification, high-temperature carbonization, electrospinning, and weaving provide flexible, low-cost, and high-surface-area evaporators. These fabrics enable floating, hanging, and 3D structured evaporators that enhance light absorption, heat retention, and salt-resistance. Multifunctional systems integrating desalination with electricity generation or saline soil remediation further expand their practical application potential [156]. Recent advancements in CP-based evaporators have focused on combining rapid fabrication, structural optimization, and multifunctionality to enhance SDIE. A speedy photoinitiated platform using carbon-fiber felt and polyacrylonitrile-co-Poly(*N*-isopropylacrylamide) (PAN-co-PNIPAAm) hydrogel was synthesized within 15 s, achieving a high evaporator rate of 1.34 kg m⁻² h⁻¹ under one-sun and benefiting from thermoresponsive microphase transitions that promote water release. However, the long-term stability of PNIPAAm under saline and outdoor conditions remains a concern [157]. To further

address salt accumulation, salt-resistant modified polyethylene (SRMPE) was developed, with hierarchical pore gradients that achieved a record-high evaporation rate of 3.47 kg m⁻² h⁻¹ and 94.3 % efficiency, maintaining salt resistance even in 25 wt% NaCl for 12 h, though its mechanical endurance under prolonged stress and the life-cycle cost of production require further assessment [158]. In terms of durability, a polyimide/MXene composite aerogel demonstrated excellent mechanical stability and a solar evaporation rate of 1.459 kg m⁻² h⁻¹ with 95.6 % efficiency, supported by robust photothermal conversion and fast charge transport; however, MXene's susceptibility to oxidation poses challenges for long-term outdoor deployment [159].

3. Addressing the water-energy-health nexus

3.1. Water applications

To address global water scarcity, solar distillation technologies have gained significant attention for their application in both wastewater treatment and seawater desalination over recent decades. Among these, SDIE systems stand out for their ability to treat domestic and industrial wastewater, directly converting contaminated water into clean, usable water. However, removing organic pollutants from complex water sources remains a challenge. During the SDIE process, elevated temperatures can cause volatile organic substances to evaporate together with water, resulting in contamination of the condensate. To overcome this, integrating pollutant removal technologies with SDIE systems has been shown to improve water quality and support sustainable ecological recovery, as demonstrated in previous studies (Table 5). Additionally, solar evaporation-based applications are increasingly being developed for high-efficiency performance in environmental and energy-related areas, including water purification, seawater desalination, and photothermal-assisted wastewater treatment [160,161]. For example, cellular carbon sponges can enhance solar-to-vapor conversion and enable electricity generation during desalination [162]. MXene-based hierarchical absorbers provide efficient water transport and salt rejection, achieving high solar-vapor conversion efficiency [163]. Photocatalytic nanofiltration membranes with β -FeOOH nanorods offer self-

Table 5
Reported solar evaporator for water treatment.

Materials	WER (Kg m ⁻² h ⁻¹)	Sunlight (kW m ⁻²)	PCE (%)	Temperature (°C)	Ref.
TiO ₂ -PANI-decorated bilayer melamine foam	2.12	1	–	–	[187]
PPy/g-C ₃ N ₄ /PVA hydrogel	2.27	1	–	–	[188]
rGO/PPy hybrid aerogel	2.08	1	–	–	[104]
Ti ₃ C ₂ Tx MXene/PANI non-woven fabrics	2.65	1	93.70	~53.00	[56]
PEDOT:PSS-PVA hydrogel	2.84	1	98.00	~50.00	[49]
PEDOT:PSS Hydrogels	2.43	1	96.40	~86.90	[51]
PPy/cotton-foam	1.20	1	82.40	~42.20	[177]
Ag/PPy layer	1.55	1	92.60	~45.20	[179]
M – PPy sponge	1.48	1	84.72	~44.40	[75]
PPy-NL foam	1.76	1	98.00	~36.80	[84]
PPy/cellulose-based bilayer	1.42	1	97.80	~43.80	[85]
PANI/CNTs fabric	2.81	1	91.74	–	[182]
PPy-coated filter paper	1.08	1	92.2	82.3	[189]
PEDOT:PSS/NFC aerogel	1.61	1	81.00	~90.00	[48]
PEDOT:PSS-PAAm hydrogel	2.15	1	97.20	~44.00	[184]
PEDOT:PSS hydrogel	2.76	1	93.20	~40.40	[43]
PPy-RF foam	1.55	1	90.00	~38.40	[74]

cleaning properties and efficient removal of organic pollutants [165]. Co-MOF/CNT evaporators demonstrate high evaporation rates ($\sim 2.25 \text{ kg m}^{-2} \text{ h}^{-1}$) with near-complete contaminant removal [165,166], and CuFeMnO₄-coated honeycomb structures facilitate both water evaporation and VOC removal [167].

3.1.1. Wastewater purification

During the SDIE process, the temperature rise can cause VOCs with low boiling points to evaporate along with water, resulting in their co-accumulation in the condensate. This presents a serious concern for water quality and safety. To address this challenge, *in situ* degradation of VOCs during solar interfacial evaporation has emerged as a potential solution. Various approaches have been explored, including photocatalytic degradation [155], where catalysts such as g-C₃N₄, Fe₃O₄, and CdS are engineered through morphology modulation, heterojunction construction, and doping to enhance light absorption, charge separation, and catalytic activity. A separate strategy involves the use of a novel bifunctional photothermal membrane, Co-N-C/CF [150], which is applied for water evaporation and photocatalytic water purification. The vertically aligned nanosheet arrays enhance sunlight absorption, Co NPs provide electrons to the outer carbon layer, and weak interactions in the system were revealed via interaction region indicator analysis, contributing to efficient pollutant degradation. In particular, the 3D honeycomb structure of CuFeMnO₄-coated materials has been shown to enhance light trapping and energy recycling. The CuFeMnO₄ layer provides efficient performance in both solar-driven water evaporation and heterogeneous photo-Fenton reactions. This study also demonstrated, for the first time, the issue of VOC enrichment in distilled water and showed that VOCs can be effectively removed using multifunctional CuFeMnO₄-coated honeycomb ceramic materials [152]. In addition, the use of external oxidants like persulfate [156] can further promote radical generation and enhance the degradation efficiency of organic pollutants during solar evaporation. Heterogeneous electric fields have also been applied to enhance non-radiative relaxation, improving the production of sunlight-clean water and enabling stable desalination of deionized water, seawater, and oily water. Additionally, this approach can effectively address chemical oxygen demand, NH₃-N, total phosphorus, and NH₃-N wastewater, particularly reducing VOC enrichment in the distilled water [167]. Recent studies have shown that activating peroxymonosulfate (PMS) and peroxodisulfate during interfacial solar distillation effectively suppresses the transfer of volatile organic compounds (VOCs) like phenol into condensed freshwater, reducing its distillation rate from 74.4 % to 14.3 % (PMS) and 20.5 % (peroxodisulfate). PMS exhibited superior performance due to its lower dosage requirement and minimal chlorinated by-products, producing freshwater that meets WHO and USEPA quality standards [168]. Cui et al. reported a novel Co-N-doped CNT evaporator that utilized spontaneously induced internal convection, achieving a remarkably high evaporation rate of $3.85 \text{ kg m}^{-2} \text{ h}^{-1}$. In addition to efficient water production, the system generated abundant active sites for PMS activation, leading to enhanced VOC removal. This dual action highlights its promise but also underscores the need to evaluate long-term PMS stability and potential secondary by-products [169]. Similarly, Cui et al. [160] introduced a 3D bifunctional evaporator capable of harnessing both solar energy and additional environmental heat. This design achieved an evaporation rate of $3.16 \text{ kg m}^{-2} \text{ h}^{-1}$ with an impressive 99 % phenol removal efficiency. Mechanistic analysis confirmed that pyrrolic-N sites played a crucial role in phenol binding, although the complexity of selective site engineering remains a challenge for scaling. Fenton-assisted reactions [62] are also effective, leveraging Fe²⁺/Fe³⁺ cycling to enhance radical generation but requiring careful pH control to avoid sludge formation. Among these, the synergistic integration of PTMs and photocatalysts has shown significant potential. The photothermal effect enhances photocatalytic efficiency by increasing the localized temperature, thereby accelerating reaction kinetics [170]. Plasmonic MoO₃_x nanosheets, prepared via a surfactant-free non-aqueous route, exhibited

tunable localized surface plasmon resonances (LSPR). These nanosheets acted as efficient catalysts, significantly boosting hydrogen generation from ammonia borane under Vis light irradiation [164]. As a light-driven interfacial process, photocatalysis is highly compatible with solar evaporation, enabling the efficient removal of VOCs during water purification [171,172]. Unlike traditional solar evaporators, photocatalytic solar evaporators can generate reactive oxygen species on their surfaces, enabling fast degradation of organic contaminants. This makes photocatalysis particularly attractive for sustainable water purification, as it operates without the need for additional chemical reagents [173,174]. Song et al. [154] reported a dual-scale porous, oxygen vacancy-rich TiO_{2-x} nanofibrous membrane (m-TiO_{2-x} NFM) that integrates photothermal and photocatalytic functions for solar-driven water purification. The membrane exhibited strong light absorption ($\sim 82.2 \%$) and achieved stable evaporation rates of $1.05 \text{ kg m}^{-2} \text{ h}^{-1}$ for flat membranes and $1.71 \text{ kg m}^{-2} \text{ h}^{-1}$ for cone-shaped architectures under one-sun illumination, with superior VOC-intercepting capability, reducing residual phenol in distilled water to below 0.5 mg L^{-1} . Its dual-scale porous structure, mesoporous, provides abundant photocatalytic sites and tortuous micrometer pores extending VOC retention, enabling effective *in situ* degradation of volatile organics while maintaining high desalination efficiency ($>98 \%$ salt rejection). The flexibility and mechanical durability further ensured stable performance after multiple folding cycles, outperforming conventional paper-supported TiO₂ membranes. This design demonstrates a promising pathway for coupling photothermal evaporation with photocatalysis to address VOC contamination in hybrid systems. However, scaling fabrication while ensuring long-term durability in real wastewater environments remains a challenge, and future studies could explore polymer-metal oxide hybrid architectures to enhance multifunctionality and structural robustness. In a notable advancement, Qi et al. [81] developed a microstructured ultrathin MPS-PPy membrane, influenced by the controlled permeation behavior of water and VOCs. Their study demonstrated that differences in diffusion dynamics on the polymer surface allowed effective separation, achieving up to 90 % VOC removal efficiency. Similarly, several advanced solar evaporators with integrated photodegradation functionality have been reported. For instance, a rGO/PPy (GR/PPy) hybrid aerogel [104] was also identified as an excellent PTM. The aerogel was fabricated through a combined hydrothermal reduction and freeze-drying process, which enabled the successful integration of rGO nanosheets with PPy. The strong π - π interactions between the two components not only prevented the stacking of rGO nanosheets, thereby creating abundant water transport channels and enhancing mechanical stability, but also promoted effective interactions with organic molecules. This structural design endowed the aerogel with wide-spectrum light harvesting and an excellent photothermal effect. When evaluated for solar-driven evaporation, the rGO/PPy hybrid aerogel achieved a high WER of $2.08 \text{ kg m}^{-2} \text{ h}^{-1}$. Furthermore, it demonstrated efficient photocatalytic activity, achieving a phenol removal efficiency of 94.8 % from VOC-contaminated water (Fig. 10a). The synergistic combination of solar-driven photothermal evaporation and photocatalytic degradation highlights the dual functionality of the GR/PPy hybrid aerogel in both freshwater generation and wastewater decontamination (Fig. 10b). Besides these advantages, the stability of PPy under prolonged irradiation and the potential loss of photocatalytic activity due to surface fouling remain concerns. Furthermore, future studies should focus on enhancing the structural durability of PPy, incorporating antifouling strategies, and scaling up the synthesis of GR/PPy aerogels to facilitate their practical deployment in real-world wastewater treatment applications.

The design and selection of catalytic materials deeply influence the overall efficiency of photothermal water evaporation systems. Key considerations for optimizing interfacial SDIE include the careful selection of active sites, surface area, porosity, and compatibility with photothermal materials. Active sites, provided by functional groups such as -OH, -COOH, -NH₂, and sulfonic acids, facilitate hydrogen bonding

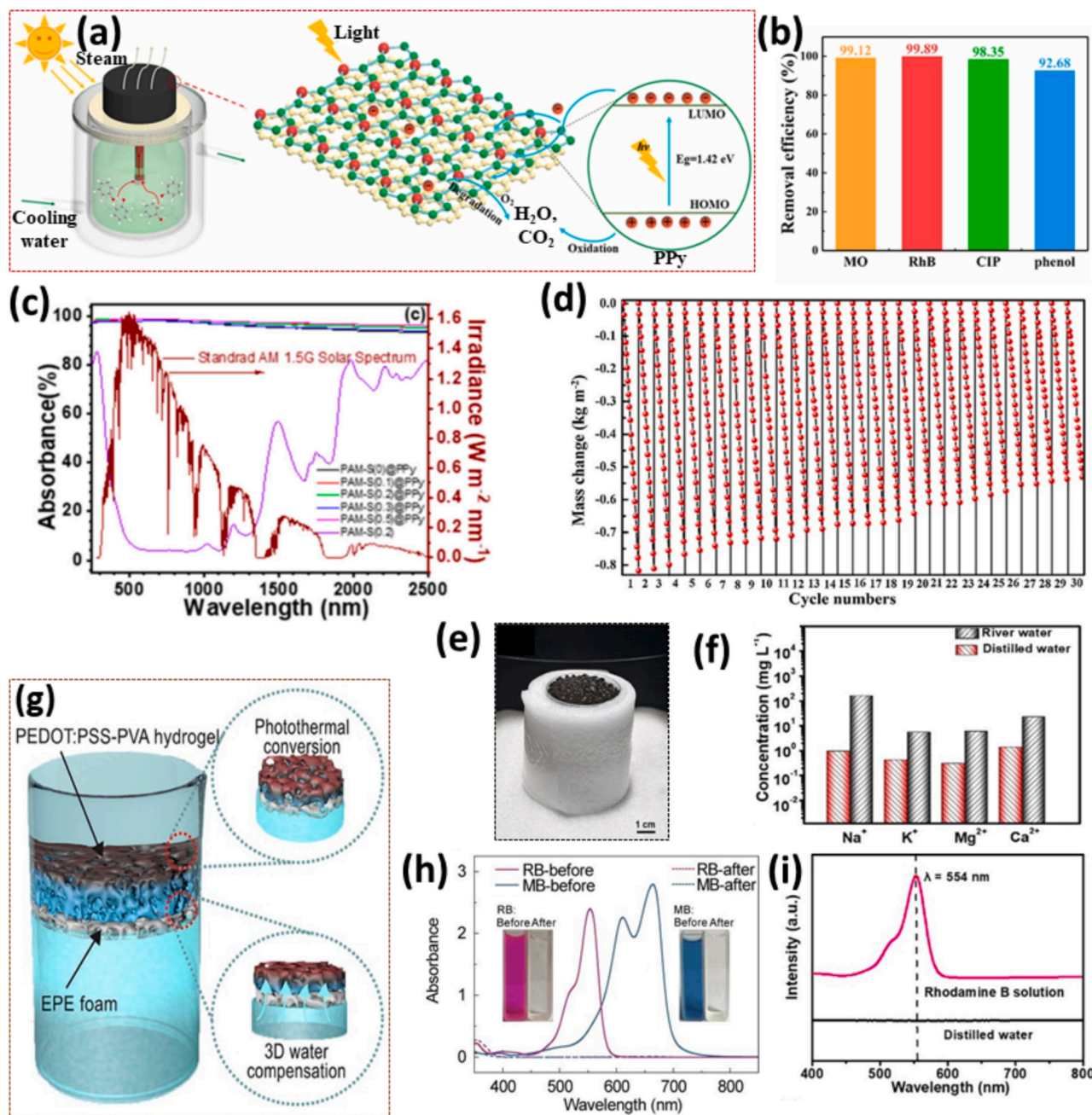


Fig. 10. (a) Demonstration of high-efficiency photodegradation and exceptional solar-driven water evaporation for parallel freshwater generation and treatment of wastewater. Reproduced under license from [104]. Copyright 2022, Elsevier. (b) Organic pollutant removal efficiency in complex wastewater using the GR/PPy-30 solar evaporator. Reproduced under license from [104]. Copyright 2022, Elsevier. (c) UV–vis-NIR absorbance (left Y-axis) of cryogels with solar spectral radiance (right Y-axis). Reproduced under license from [176]. Copyright 2023, MDPI Polymers. (d) Comparison of evaporation rate and PCE. Reproduced under license from [177]. Copyright 2018, Elsevier. (e) Photograph of the constructed solar evaporator device. Reproduced under license from [85]. Copyright 2022, Elsevier. (f) Measured concentrations of four key ions (Na⁺, K⁺, Mg²⁺, and Ca²⁺) in real river water before and after purification. Reproduced under license from [179]. Copyright 2020 Elsevier. (g) PEDOT:PSS-PVA hydrogel applied in solar-driven water purification systems. Reproduced under license from [49]. Copyright 2022, Elsevier. (h) UV–Vis absorption spectra and visual images of wastewater containing methylene blue and RhB (20 mg L⁻¹) before and after solar purification. Reproduced under license from [49]. Copyright 2022, Elsevier. (i) UV–Vis spectra showing RhB-contaminated water and the corresponding purified sample. Reproduced under license from [179]. Copyright 2020, Elsevier.

with water, generating bound and intermediate water states that lower vaporization enthalpy and enhance evaporation efficiency [175]. Surface area and porosity govern water transport and salt diffusion: highly porous and macro-/microstructured substrates, such as freeze-dried hydrogels or vertically micro-patterned foams, enable rapid replenishment of evaporated water and prevent salt accumulation, directly improving performance metrics (e.g., 1.85 kg m⁻² h⁻¹ at 95.4 % efficiency in NHRG membranes, 1.41 kg m⁻² h⁻¹ at 88.3 % efficiency in PPy-

coated vertically macroporous foam foams). Compatibility between the water-absorbing substrate and photothermal component ensures effective heat localization, minimizing conduction losses to the bulk water and maximizing interfacial evaporation. For instance, integrating GO or rGO sheets within hydrophilic polymer matrices promotes both intermediate water formation and photothermal heat conversion, demonstrating that structural, chemical, and photothermal synergies are critical for high-performance, stable, and scalable SDIE systems. Hou

et al. [176] fabricated sulfonated polyacrylamide/PPy (PAM-S(x)@PPy) cryogels, which exhibited remarkable solar absorption and photothermal performance. Before pyrrole loading, the absorbance of PAM-S (0.2) cryogel was below 20 % in the 500–1300 nm wavelength range, indicating limited solar capture. After incorporation of PPy, the PAM-S@PPy cryogel demonstrated a dramatic increase in absorbance (Fig. 10c), reaching ~98 % due to the sharp decrease in transmittance and reflectance. This high solar absorption underpins its efficient photothermal conversion, while the cryogel's structure enables effective heat management and enhanced fluid handling. These core functions and innovations make PAM-S@PPy suitable for applications such as solar-driven metal ion removal, water purification, and other solar-thermal processes. Further extending the application potential, Hao et al. [177] developed a PPy/cotton-foam composite that exhibited excellent reusability and strong solar heating capability for freshwater generation, as shown in Fig. 10d. These advances collectively highlight the importance of material innovation in achieving efficient, sustainable, and multifunctional solar-driven water purification systems. Furthermore, as shown in Fig. 10e, PPy-NL foam has demonstrated excellent performance in purifying various types of wastewater and organic solvents, achieving nearly 100 % rejection of ions, oils, and dyes. This material has been effectively applied in both wastewater treatment and seawater desalination.

For instance, the concentrations of 5 major ions: sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and boron (B^{3+}), in seawater were measured before and after treatment using inductively coupled plasma optical emission spectrometry, revealing significant metal ion removal efficiency. Expanding on this, Xu et al. developed a PPy-NL foam evaporator using natural latex (NL) foam. The resulting foam exhibited an impressive average light absorption of 94.94 % across the full spectrum, significantly improving the NL foam's low light absorption (23.6 %) [84]. This enhanced light-harvesting capability is due to the irregular surface morphology that reduces light reflection, promoting multiple scattering and reabsorption of incident light [38]. Their findings showed substantial improvement in water purity, as confirmed by the absence of absorption peaks around 465 and 663 nm, corresponding to methyl orange and methylene blue, respectively, in the collected condensate. Optical microscopy was also employed to assess the behavior of oil-in-water emulsions with one-sun intensity, further supporting the purification capability of the system [84]. In another research, Wang et al. developed a PPy/cellulose-based bilayer structure for wastewater treatment and desalination. The evaporated water was collected using a closed evaporation–condensation setup, and the concentrations of four primary ions (Na^+ , Mg^{2+} , Ca^{2+} , and K^+) were quantified. After desalination, the concentrations dropped significantly from 16,400, 1970, 667, and 493 mg L^{-1} , respectively, in raw seawater to 0.13, 0.03, 0.43, and 0.05 mg L^{-1} in the condensed water [85]. These values are well below the taste thresholds set by the WHO (approximately 200 mg L^{-1} for Na^+ and 100–300 mg L^{-1} for Ca^{2+}) [178], highlighting the potential of PPy/cellulose aerogels for generating potable water through desalination.

Additionally, Xu et al. fabricated Ag/PPy-coated substrates for wastewater purification and desalination applications. They tested the concentrations of four major ions (Na^+ , K^+ , Mg^{2+} , and Ca^{2+}) in real river water samples before and after treatment, observing notable improvements in water quality, as illustrated in Fig. 10f [179]. Beyond PPy-based materials, PEDOT:PSS-PVA hydrogels have also shown great promise. This hydrogel displayed excellent light absorption (~99.7 %) across a broad range of 250–2500 nm (Fig. 10g). The UV–Vis absorption spectra and digital images in Fig. 10h illustrate the effectiveness of the hydrogel-based evaporator in purifying wastewater samples infused with methylene blue and rhodamine B (RhB) (20 mg L^{-1}) before and after solar treatment. Furthermore, a 60-day continuous experiment emulating natural seawater conditions demonstrated the long-term stability and efficiency (~93.3 %) of the hydrogel [49]. The UV–Vis spectra of contaminated RhB solution and the corresponding purified

water are presented in Fig. 10i, reinforcing its potential for sustainable water purification [179]. However, a key limitation of the SDIE system lies in its inability to fully retain VOCs, as the photocatalytic reactions typically occur only at the light/photocatalyst interface. This allows VOCs to escape via the photocatalytic coating and contaminate the condensate. To address this, advanced oxidation processes, particularly those based on sulfate radicals ($\text{SO}_4^{\cdot-}$), have been recognized as highly effective for VOC removal. These systems have shown excellent performance in degrading VOCs and other persistent pollutants in water and air. Despite their potential, issues such as secondary sulfate accumulation and catalyst stability must be addressed. Researchers should focus on designing robust, recyclable PMS-activation catalysts and integrating them into photothermal membranes for simultaneous solar evaporation and VOC degradation [180]. PMS-based advanced oxidation processes (AOPs) generate highly reactive sulfate radicals ($\text{SO}_4^{\cdot-}$) that effectively degrade VOCs and other persistent organic pollutants. Electrochemical and activated carbon-based PMS activation methods have shown broad applicability in environmental remediation, offering high efficiency under mild conditions, though issues like sulfate accumulation and catalyst recovery still need optimization [173]. The SDIE process naturally provides favorable conditions, such as high salinity, elevated temperatures, and sufficient light at the air–water interface, which can promote persulfate activation and enhance VOC degradation. In parallel, the SDIE system also faces challenges in removing dissolved metal ions. Since these ions do not evaporate, they remain in the residual brine, necessitating further treatment or careful disposal. Moreover, the accumulation of metal salts on the photothermal surface can lead to fouling, reducing evaporation efficiency, and increasing the need for maintenance or material replacement.

Despite these drawbacks, SDIE systems have the advantage of not requiring complex post-treatment steps. However, in real-world applications, system performance can be influenced by fluctuating meteorological conditions, which may disrupt heat supply and affect evaporation efficiency. To ensure reliability, SDIE systems must be designed with the flexibility to adapt to varying types of wastewater containing both VOCs and metal ions. In summary, while SDIE technology shows considerable promise for the treatment of VOCs and dissolved metal ions, overcoming these technical and engineering challenges is crucial for its broader practical implementation.

3.1.2. CP-enabled solar-driven desalination systems

Desalination is a widely recognized approach for generating potable water, particularly in regions facing freshwater scarcity. Among the various approaches, solar distillation has emerged as a potential, sustainable “low-carbon” technology for desalination, leveraging abundant solar energy to drive water purification. Desalination primarily involves the elimination of dissolved salts and minerals from seawater, and the resulting water typically meets drinking standards [181]. In recent years, advancements in PTMs and device engineering have significantly improved the efficiency of solar-driven desalination systems. For instance, Wang et al. developed a hanging-mode solar evaporator using a PANI/CNTs-based fabric. In this design, the photothermal fabric serves as the evaporation surface, while micropores in the cotton fabric facilitate water transport. The hanging configuration effectively minimizes heat loss, enabling dual-interface evaporation and enhancing overall performance. This system exemplifies a novel and efficient approach to sustainable desalination [182]. Building on this concept, Wang et al. also introduced a novel PPy-FexOy-chitosan (CTS) gel membrane through *in situ* polymerization of PPy in a CTS sol, forming a hierarchically micro/nanoporous network that facilitated efficient water transport, as shown in Fig. 11a [183]. PPy, serving as the primary photothermal conversion material, was uniformly dispersed within the gel matrix, significantly enhancing solar absorption and localized heat generation. The optimized system achieved a high evaporation rate of 1.93 $\text{kg m}^{-2} \text{h}^{-1}$ under one-sun irradiation (1 kW m^{-2}) at 25 °C and 30 % relative humidity, outperforming conventional vacuum-filtered

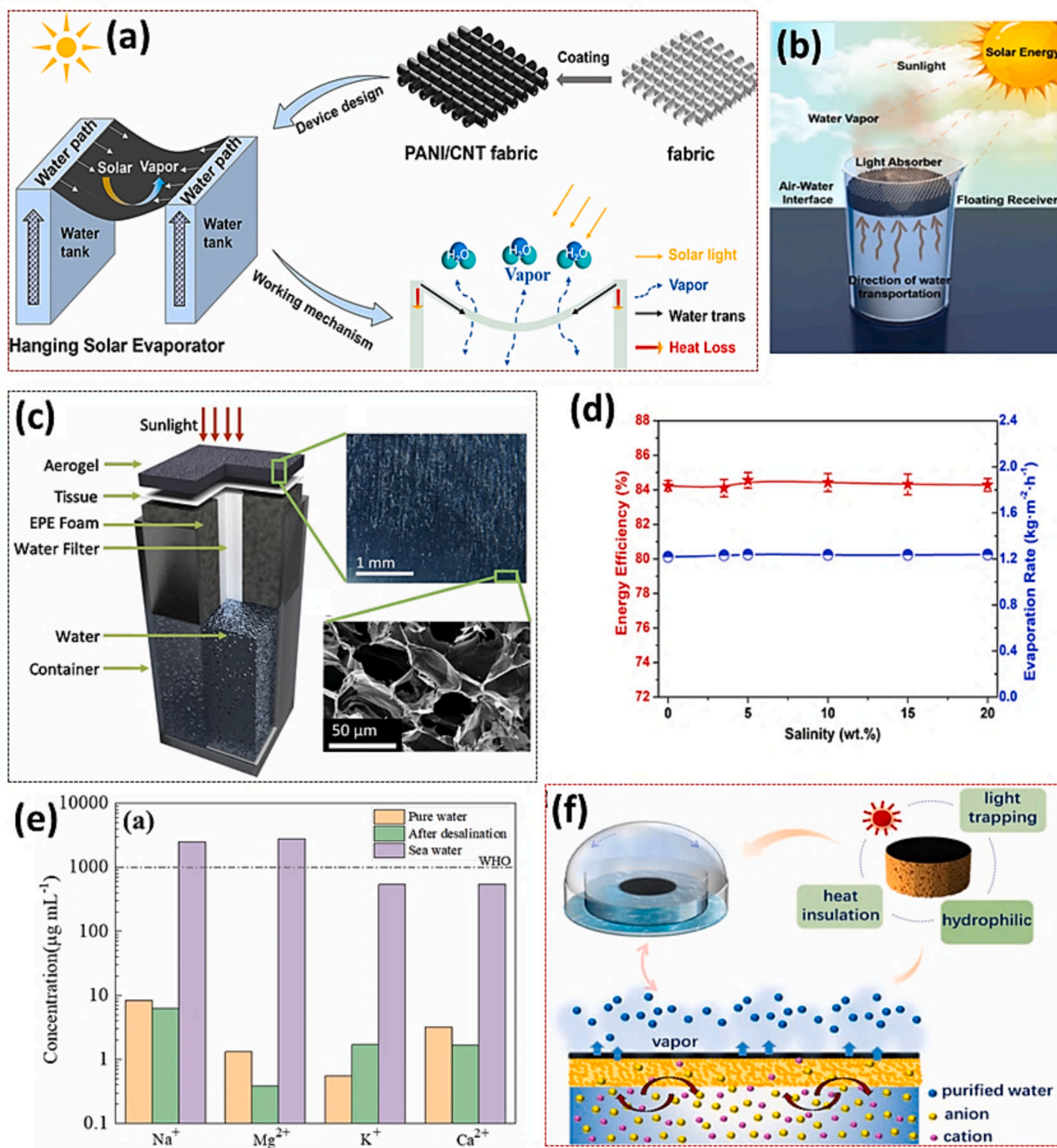


Fig. 11. (a) Illustration of the novel PPY-FexOy-CTS gel membrane developed for desalination applications. Reproduced under license from [183]. Copyright 2019, Elsevier. (b) Schematic representation of a solar steam generator. Reproduced under license from [75]. Copyright 2020, Elsevier. (c) Diagram of a typical SDIE system with an optical microscope image of the PEDOT:PSS-NFC aerogel, and scanning electron microscopy image of the same aerogel material. Reproduced under license from [48]. Copyright 2023, MDPI Polymers. (d) Evaporation rate (blue) and energy conversion efficiency (red) of the M-PPy sponge in solutions of varying salinity under 1 kW m^{-2} solar illumination. Reproduced under license from [75]. Copyright 2020, Elsevier. (e) Concentrations of major ions in simulated seawater before and after purification using PPY-RF foam under one-sun illumination. Reproduced under license from [74]. Copyright 2021, Elsevier. (f) Schematic illustration of the steam generation and desalination process. Reproduced under license from [74]. Copyright 2021, Elsevier.

photothermal membranes. The enhanced performance was attributed to the synergistic effects of PPy's broadband light absorption and the cross-linked CTS nanostructure, which lowered the enthalpy of water evaporation. Notably, the large-area membrane fabricated via simple coating

technology demonstrated practical scalability, yielding $13.68 \text{ L m}^{-2} \text{ day}^{-1}$ freshwater from domestic sewage under natural sunlight, with a significant reduction in total dissolved solids (TDS). While this strategy offers environmentally friendly materials, scalable processing, and

superior photothermal performance, its long-term mechanical stability in real saline or contaminated water conditions, as well as the cost of FexOy precursor, needs further investigation. Moreover, this study should focus on enhancing the mechanical robustness of CTS networks, improving recyclability, and exploring hybridization with other light-harvesting nanomaterials to further boost solar-to-vapor conversion efficiency. Their solar steam generator demonstrated impressive desalination capabilities, as illustrated in Fig. 11b [88]. Notably, this plasmonic film-based evaporator achieves one of the highest WERs among organic aerogel systems by confining heat at the air-water interface and minimizing bulk losses. Its photothermal conversion efficiency ($\sim 44\%$) is over twice that of Au NPs solutions, resulting in faster, more stable evaporation with fewer particles. The film is recyclable and maintains performance during extended operation. However, partial light transmission through its $\sim 40\%$ porosity and thermal diffusion still reduces efficiency. Further research should focus on film density optimization, solar absorption broadening, and integrating CPs (e.g., PANI, PEDOT:PSS) to improve durability and multifunctionality in hybrid solar-driven systems. Further advancing this field, Han et al. validated the high potential of PEDOT:PSS-NFC aerogels for seawater desalination. Their system successfully purified both artificial salt water and natural seawater to salinity levels below the threshold for potable water. PEDOT:PSS was used for photothermal conversion due to its excellent light absorbance, while NFC acted as the aerogel matrix, contributing to water retention and transport. The aerogel's open porous structure facilitated a large evaporation interface and rapid water replenishment, achieving substantial water uptake—up to 46 g per gram of aerogel as shown in Fig. 11c [48]. In another innovative approach, Zhao et al. developed a PEDOT:PSS-PAAm hydrogel-integrated solar steam generator, combining PEDOT:PSS with polyacrylamide (PAAm). This system not only exhibited excellent desalination performance but also successfully removed metal cations and organic pollutants [184]. Moreover, modified monolithic PPy materials have shown remarkable salt resistance in high-salinity environments, achieving an evaporation efficiency of 84.43 % with excellent recyclability. This makes them highly suitable for diverse applications such as power generation and desalination, as presented in Fig. 11d [75]. Complementing these developments, He et al. fabricated a PDA nanosphere-functionalized fabric-based photothermal membrane (PDANSS@fabric) for solar-driven water purification [185]. The fabric substrate provided a porous network for efficient water transport and vapor diffusion, while the PDA nanosphere imparted excellent light-to-heat conversion and strong adhesion, enhancing structural stability. The PDANSS exhibited controlled sizes (240–900 nm), with optimal nanospheres (~ 650 nm) achieving the highest solar absorption ($\sim 78\%$) and WER ($1.48 \text{ kg m}^{-2} \text{ h}^{-1}$) under one-sun illumination.

Notably, the membrane demonstrated rapid water wicking, superhydrophilicity, and robust stability, retaining performance after prolonged solar exposure and ultrasonic washing, making it suitable for practical wastewater treatment. The evaporator effectively removed model dyes (rhodamine B, methylene blue) and heavy metal ions (Cu^{2+} , Cr^{6+}), as well as desalinated seawater with ion rejection $>99\%$. Despite these benefits, the approach relies on precise nanosphere size control and the adhesion of PDA to maintain long-term durability, which may limit scalability. Further study could explore integrated CPs, such as PANI or PEDOT:PSS, with PDA-functionalized fabrics to further enhance photothermal efficiency, mechanical robustness, and multifunctionality for large-scale solar-driven water purification systems. PANI, a well-known conjugated polymer, has been effectively employed for the separation of different ionic and liquid mixtures. Due to the “Donnan repulsion” effect, PANI-based materials with surface charge can strongly repel negatively charged ions, thereby enhancing the desalination performance of solar evaporators. Notably, CuO-rGO/PANI membranes demonstrated excellent salt resistance, with no salt crystallization observed on the surface even after a 20-day test under natural sunlight. Kospa et al. fabricated the CuO-rGO/PANI membranes to evaluate oil

fouling resistance. Total organic carbon analysis revealed minimal oil fouling in the condensate when compared to the original petroleum-contaminated water. Furthermore, the evaporation rates for both freshwater and oil-polluted water remained consistent, indicating the membrane's robustness against oil interference [186]. In a related development, Ge et al. [43] reported that PEDOT:PSS hydrogels facilitate efficient water evaporation due to strong polymer–water interactions, where the PSS segment activates water molecules and reduces the energy required for phase change.

The positively charged PEDOT framework also intercepts chloride anions, reducing the risk of salt accumulation and maintaining stable operation. Similarly, PPy-RF foam has shown remarkable salt-rejection capability and long-term operational stability, even in highly saline brine solutions (up to 20 wt%). As illustrated in Fig. 11e, the concentration of major ions in simulated seawater significantly decreased after purification under one-sun illumination. The foam's porous, flexible, and monolithic architecture, coupled with its scalable fabrication, efficient solar-thermal conversion, and salt resistance, makes it a strong candidate for potable water generation and saline water desalination. A schematic of the steam generation and desalination process using PPy-RF foam is presented in Fig. 11f [74].

4. Advantages of conducting polymers

CPs such as PANI, PPy, PEDOT:PSS, and P3HT offer several distinct advantages over traditional solar-thermal materials, including carbon-based absorbers (e.g., CNTs, graphene, biochar), plasmonic metals (e.g., Au, Ag, Cu), and inorganic semiconductors (e.g., TiO_2 , WO_3 , MoS_2). While carbon-based materials are widely used due to their broadband absorption and thermal stability, they often suffer from bulk heat dissipation, limited tunability, and susceptibility to surface fouling. Plasmonic metals provide excellent light harvesting through LSPR, but their high cost, oxidation/corrosion issues, and poor scalability hinder practical use. Similarly, inorganic semiconductors exhibit good photothermal performance and photocatalytic activity but are brittle, rigid, and difficult to process into large-area flexible devices. In contrast, CPs combine strong and tunable broadband solar light absorption with high photothermal conversion efficiency, processability, and mechanical flexibility. Their π -conjugated backbone allows for adjustable optical and electronic properties through molecular design or doping, enabling synergistic control over light absorption, thermal management, and water transport. CPs can be easily integrated with porous substrates (foams, membranes, textiles) *via in situ* polymerization, coating, or spraying, providing intimate contact and minimizing interfacial heat loss. Furthermore, their intrinsic conductivity enables multifunctionality, such as electrochemical modulation, sensing, and photocatalytic enhancement, beyond simple photothermal conversion. Hybrid systems combining CPs with carbon nanostructures or metal oxides further improve durability, salt resistance, and antifouling properties while maintaining high evaporation rates. This unique combination of tunability, multifunctionality, mechanical compliance, and scalability positions CP-based systems as a superior and versatile alternative to conventional solar-thermal materials for next-generation SDIE technologies. Table 6 summarizes the key advantages of CP over traditional polymeric materials, highlighting their enhanced conductivity, photothermal stability, and tunable properties.

CPs uniquely integrate broadband solar absorption, controllable electronic/thermal properties, mechanical flexibility, and multifunctionality, enabling not only efficient photothermal conversion but also enhanced water transport, salt resistance, and scalability, making them a superior choice for next-generation SDIE systems compared to conventional materials.

5. Challenges and limitations

CPs frequently suffer from limited environmental stability, breaking

Table 6

Advantages of CP over traditional materials.

Category	Examples	Strengths	Limitations	Advantages
Carbon-based materials	CNTs, graphene, biochar, activated carbon [190].	Broadband solar absorption, thermally stable, low cost.	Bulk heat dissipation, limited optical/electronic tunability, prone to salt fouling [191].	CPs offer tunable absorption, better interfacial integration, and reduced heat loss [192].
Plasmonic metals	Au, Ag, Cu, Al [193].	Strong LSPR absorption, efficient hot-electron generation.	High cost, oxidation/corrosion, reduced performance over time, and poor scalability.	CPs are cost-effective, chemically stable, and easier to scale into large-area devices.
Inorganic semiconductors	TiO ₂ , WO ₃ , MoS ₂ , black silicon [194,195].	Good photothermal and photocatalytic performance.	Brittle, rigid, difficult to process into flexible systems, and limited NIR absorption [196].	CPs provide mechanical flexibility, simple processing, and tunable light-harvesting [197].
CPs	PANI, PPy, PEDOT:PSS coatings.	Easy fabrication, lightweight [198].	Poor thermal stability, photodegradation, and intrinsic conductivity [199].	CPs add conductivity, electrochemical tunability, and improved photothermal stability [199].

down upon exposure to oxygen, moisture, or heat. Achieving long-term durability in practical conditions remains challenging, emphasizing the importance of developing protective coatings or more chemically stable polymer designs. Significant progress has been achieved over the last decade in developing photothermal evaporators and substrate materials, along with various structural engineering approaches that enhance light absorption, water transportation, thermal insulation, and interfacial properties. Advances in material design and engineering, including CP-based composites, hydrogels, foams, and membranes, have been explored for clean water production. These examples demonstrate that PTMs offer superior capabilities and can outperform traditional alternatives in many applications. While these achievements are noteworthy, further exciting advancements are anticipated in the coming years. However, several challenges remain, particularly concerning real-world deployment. Both basic research and real-world use are essential to achieving environmentally friendly, sustainable, and efficient technology. To accelerate progress, the following issues must be addressed [200].

5.1. Scalability and cost considerations for CPs

Many CPs are insoluble or require complex synthesis, which hinders scalable fabrication and increases production cost. Developing solvent-free or eco-friendly processing routes (e.g., 3D printing or green chemistry approaches) is still underexplored. For practical implementation, the scalability and economic viability of CP-based SDIE systems are as crucial as their laboratory efficiency. However, most studies neglect detailed techno-economic assessments and real-world illumination conditions, leaving a gap between laboratory results and field performance. Equally important is the lack of standardized efficiency metrics and testing protocols, which makes cross-study comparisons unreliable and often leads to overestimation of performance. Future research should adopt unified efficiency definitions that account for realistic solar flux (~0.6 sun), energy input, and evaporation rate, alongside comparative benchmarking of materials under identical conditions. Establishing consensus guidelines—similar to those used in PVs for reporting efficiency, stability, and cost—would greatly enhance reproducibility, accelerate material screening, and provide a clear pathway toward commercialization.

5.2. Stability and durability of CPs

CPs often suffer from poor environmental stability, degrading under oxygen, moisture, or thermal stress. Long-term durability in real-world conditions remains a challenge, necessitating research into protective coatings or chemically stable polymer designs. The long-lasting stability of PTMs in real-world aquatic sources (e.g., ocean, river water, industrially polluted water) is a major challenge. While much research on solar evaporation has focused on improving efficiency, less attention has been given to the durability of the material against water, heat, salt, bacteria, and weather. Stability is crucial for practical applications, and

solutions like protective coatings, surface chemistry modifications, and structural designs (e.g., pore engineering) can improve longevity. Salt clogging, especially in high-salinity water, is a significant issue, but methods like the Janus membrane [201–203] and specialized solar steam generators [204] offer potential solutions. Surface wettability and pore structure engineering help mitigate clogging, though this can reduce evaporation efficiency. Additionally, biomass-based materials need improvement in their resistance to water, heat, and bacterial degradation. Contaminated water with VOCs also presents a challenge, as these compounds could evaporate with the water, resulting in impure water. Beyond materials development, the field lacks standardized efficiency metrics, which hinders direct comparison across studies. Establishing unified testing protocols (e.g., under identical solar intensity, water depth, and salinity) and consensus guidelines for reporting efficiency would allow benchmarking of new materials and designs on a common scale, ensuring that proposed solutions—whether for salt rejection, stability, or VOC removal—translate effectively into scalable and reproducible systems.

5.3. Kinetics and structure-property relationship in PTMs

Balancing conductivity with mechanical robustness (e.g., stretchability, fatigue resistance) is challenging. Research into hybrid composites or self-reinforcing polymer architectures could address this gap. Although significant advancements in novel materials and architectures have been made in the last decade, a basic understanding of dynamic kinetics and the relationships between structure and properties continues to be a major challenge in designing these materials. Optimizing light transfer, water transport, evaporation rates, and thermal diffusion behaviors requires corresponding pore structure, surface properties (e.g., hydrophilicity), and conduction, radiation, and convection roles. While research often focuses on minimizing thermal conduction, convection, and radiation are less explored. Simulations complement experimental observation, offering insights into the fundamental kinetics of these processes. However, the absence of standardized evaluation protocols limits the comparability of kinetic data across studies. Developing consensus guidelines for reporting parameters—such as water depth, ambient conditions, and solar flux, and adopting unified efficiency metrics would enable fair benchmarking of different PTM designs and accelerate the identification of structure–property correlations that genuinely enhance performance.

5.4. Inconsistent metrics in solar evaporation studies

CPs in solar evaporation studies often face inconsistent performance matrices due to non-uniform testing conditions and methodologies. A persistent challenge in assessing the efficiency of solar evaporation devices is the absence of standardized measurement techniques and unified methods for calculating evaporation efficiency. Beyond simply noting this gap, it is essential to advocate for a consensus framework that defines key parameters, such as solar intensity, water depth, salinity,

and ambient temperature, under which tests should be conducted. Implementing unified testing protocols and reporting standards can resolve these inconsistencies and ensure accurate performance evaluation. CPs' tunable properties can also be optimized for specific testing conditions, helping to achieve more consistent and comparable results across different setups. Although current reports often claim PCE exceeding 100 %, the specific calculation formulas and the determination of key parameters remain unclear. Establishing a universal efficiency formula, with explicit subtraction of natural evaporation rates, would prevent overestimation and allow direct comparisons between studies. This lack of clarity makes it challenging and inconsistent to directly compare results across studies, hindering the consistent advancement of the field. Moreover, the natural evaporation contribution must be subtracted from the overall evaporation rate to eliminate environmental influences such as wind, humidity, and temperature. Comparisons are further complicated by differing experimental conditions, with some studies not even disclosing key performance parameters. Collaborative efforts, such as multi-laboratory benchmarking studies and open-access databases of standardized results, could accelerate the development of reliable performance baselines and foster reproducibility across the community.

5.5. Need for continuous SDIE operation

Many CPs often fail to sustain continuous SDIE due to structural degradation, poor photothermal and mechanical stability, limited water transport, and susceptibility to surface fouling and salt accumulation, leading to a decline in performance under prolonged exposure to light and water. To overcome these challenges, developing CPs-based hybrids by integrating them with stable materials such as carbon-based nanostructures or metal oxides can significantly enhance structural integrity, photothermal stability, and water transport properties, thereby supporting sustained and efficient SDIE operation. Currently, most research is focused on daytime operations, where sunlight is available. However, PCE drastically decreases in the absence of sunlight and is highly affected by factors like humidity, rainfall, and nighttime darkness, often rendering the system inactive. Future work should include standardized long-term testing protocols that evaluate stability under real-world conditions, continuous operation cycles, fluctuating solar intensities, and saline water exposure, to allow meaningful cross-study comparisons of material endurance and device performance. Therefore, the development of SDIE systems that can operate continuously, regardless of the time of day, is essential to expand the practical applicability and future potential of this technology. Strategies such as integrating energy storage modules (e.g., phase-change materials or battery-assisted photothermal systems) and reporting continuous-operation performance under unified metrics would provide a clearer benchmark for practical deployment.

5.6. Toxicity and eco-friendly concerns

Various CPs face challenges like stability, toxicity, and environmental concerns due to their inherent chemical and physical properties. Many CPs, such as PANI, PPy, and PTh, degrade under prolonged exposure to sunlight, oxygen, and water, leading to structural breakdown and loss of conductivity. Their photothermal stability is often low because they absorb heat but cannot withstand high temperatures over time. Mechanically, CPs are brittle and prone to cracking and delamination under repeated thermal cycling. A practical solution to overcome these limitations is to develop CPs-based hybrids by combining CPs with stable, eco-friendly materials such as carbon-based nanomaterials (e.g., graphene, CNTs) or metal oxides (e.g., TiO_2 , WO_3). These hybrids enhance structural stability, photothermal performance, and mechanical strength, while also improving water transport and reducing toxicity. Additionally, using green synthesis methods and selecting biocompatible polymers or dopants can further reduce environmental concerns. To

ensure these solutions are practically relevant, standardized protocols for assessing material toxicity, biodegradability, and environmental persistence should be adopted. Metrics such as leaching of degradation products, photothermal stability under natural sunlight, and life-cycle impact assessment would allow for direct comparison across studies and guide safer material selection. This hybrid approach ensures more durable, efficient, and sustainable materials suitable for continuous and safe SDIE operation. While CP-based hydrogels, foams, and membranes show great potential because of their outstanding photothermal conversion, mechanical flexibility, and water-retention abilities, concerns around material toxicity, environmental persistence, and end-of-life disposal remain critical. Traditional synthetic polymers may pose risks to aquatic and terrestrial ecosystems if not properly managed. Establishing unified evaluation guidelines and reporting standards for ecotoxicity and sustainability would accelerate the development of SDIE materials that are not only high-performing but also safe and environmentally responsible.

5.7. Barriers to large-scale water-evaporation power generation

One major challenge for CPs in large-scale water-evaporation power generation is their limited photothermal stability, mechanical fragility, and difficulty maintaining consistent performance across extensive surface areas. Additionally, issues like high production costs, salt fouling, and environmental degradation further hinder their scalability and long-term reliability. Developing CP-based hybrids with durable materials like carbon nanostructures or metal oxides can enhance stability, mechanical strength, and scalability. Additionally, adopting cost-effective, eco-friendly synthesis methods and implementing anti-fouling surface designs can improve long-term performance and practical applicability. SDIE has been employed in various applications such as desalination, water purification, electricity generation, and sterilization; however, translating these technologies to large-scale manufacturing remains a significant challenge. To overcome these barriers, establishing standardized protocols for large-scale performance testing, including continuous operation, energy conversion efficiency, fouling resistance, and mechanical durability under real-world conditions, would allow direct comparison across studies and guide material optimization. Developing consensus guidelines for scaling up fabrication, cost evaluation, and environmental impact assessment would facilitate the practical translation of lab-scale systems to industrial-scale deployment.

Water-evaporation-induced electricity generation using nanostructured conducting polymeric materials offers the potential for continuous, all-weather electricity and freshwater production. This approach holds promise for large-scale implementation, particularly in warm regions of the world. One major limitation, however, is the low short-circuit current density (J_{sc}). This issue may be mitigated by incorporating cationic or anionic species into the solution. Yet, the introduction of ionic solutions can cause surface fouling and clogging, reducing evaporation rates. Standardized testing protocols that quantify both electricity generation and water production under controlled conditions would allow meaningful comparison of different material designs and operating strategies. Therefore, a careful balance between electricity generation and freshwater production must be maintained [23].

Despite the numerous challenges facing CPs, we expect that the coming decade will witness significant growth in this eco-friendly technology, with its adoption expanding across diverse application fields. CPs are anticipated to play a vital role in addressing global challenges, particularly the urgent need for clean water and sustainable energy. Future progress will rely on consensus guidelines for evaluating J_{sc} , water-evaporation efficiency, long-term stability, and scalability, ensuring that laboratory advancements translate into practical, cost-effective, and reproducible systems. With continued efforts to bridge the gap between cutting-edge solar evaporation systems and future scalable, cost-effective solutions, CPs hold great promise for achieving

an optimal balance of efficiency, affordability, scalability, stability, and adaptability in the near future (Fig. 12) [28].

6. Conclusion

In conclusion, this review comprehensively highlights the advancements in SDIE systems using CP-based PTMs, inspired by natural evaporation processes and aimed at addressing the global water-energy crisis. CPs, *i.e.*, PEDOT:PSS, PANI, PPy, and PTh derivatives like P3HT, offer broad solar absorption, efficient photothermal conversion, and flexible structural tenability. Their engineered morphology, including hydrogels, foams, and fibrous networks, enhances water transport, thermal confinement, and evaporation rates. Among them, PPy and PANI-based composites dominate current research due to their versatility and performance, while PEDOT:PSS and P3HT show potential for multifunctional applications. Although P3HT has limited direct applications in solar evaporation, its established use in PVs, biomedical devices, and hybrid systems reflects its promise in future integrated water purification platforms. The review also emphasizes various synthesis strategies, *i.e.*, chemical oxidative polymerization, *in situ* polymerization, and template-assisted fabrication aimed at improving light-to-heat conversion efficiency, salt rejection, anti-biofouling properties, and mechanical durability. These developments align with the broader need for low-cost, eco-friendly, and scalable materials suitable for real-world deployment.

Beyond material design, several environmental and physical factors influence the evaporation rate and PCE of solar-driven systems. Factors like humidity, wind speed, ambient temperature, and solar intermittence significantly affect vapor generation and must be carefully considered in evaporator design. This review also explores the

interdisciplinary potential of these systems, including water-electricity cogeneration, water purification, and desalination. Such integration of water-energy-health functions into a single platform opens the door to next-generation smart materials and devices for decentralized and off-grid applications. Despite considerable progress, challenges related to long-term operational stability, environmental safety, and system scalability remain. The integration of CPs with carbon-based or inorganic materials, combined with advanced fabrication methods such as 3D printing and biomimetic structuring, holds promise for next-generation solar evaporators. Ultimately, the convergence of materials science, systems engineering, and environmental responsiveness will shape the future of smart, multifunctional solar evaporation technologies, paving the way for resilient water purification solutions aligned with the Sustainable Development Goals.

6.1. Research questions for future perspectives

1. How can the structural engineering of PEDOT: PSS be optimized to further enhance its photothermal conversion efficiency in solar-driven water evaporation systems?
2. What role do dopants play in tuning the salt resistance of CPs like PANI and PPy under high salinity conditions?
3. How does the morphology of CP-based composites influence water transport and light absorption during interfacial evaporation?
4. Can bio-derived or biodegradable dopants be used to improve the sustainability of CP systems for solar applications? Does the evaporation rate of P3HT compare with other PTMs under varying solar intensities and environmental conditions?

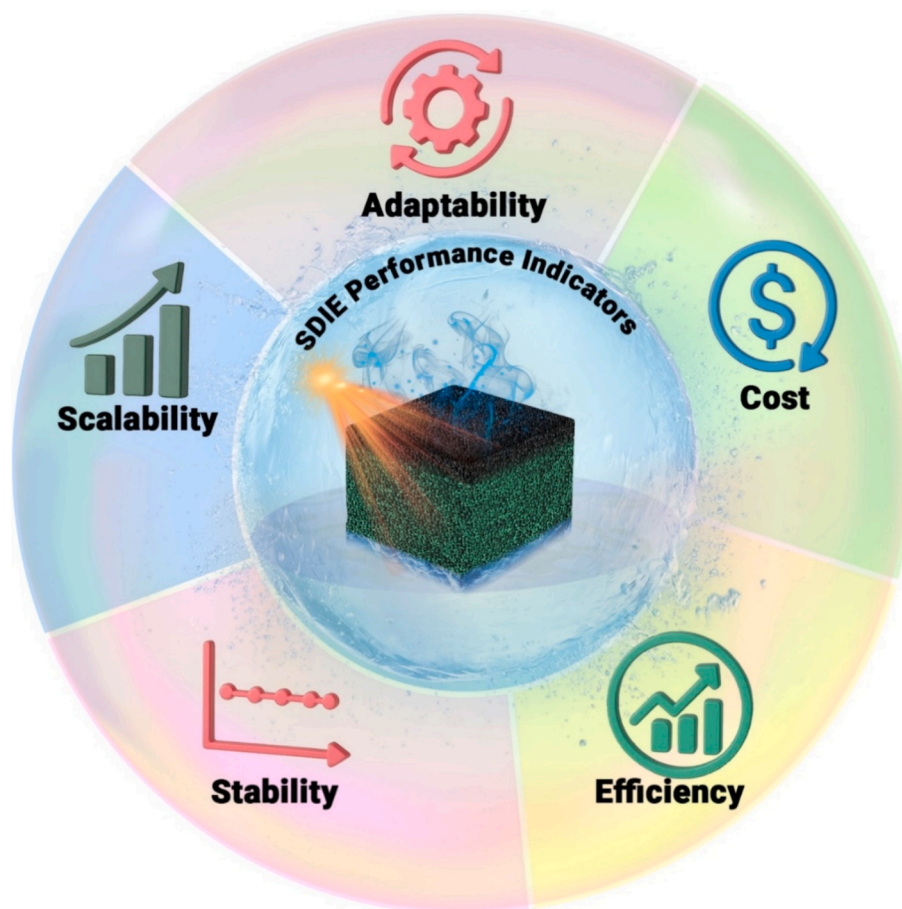


Fig. 12. Challenges associated with CP-based SDIE systems.

5. How can hybridizing CPs with carbon-based materials (e.g., graphene, CNTs) improve the stability and performance of solar evaporators?
6. How do the nanoscale features of PPy and P3HT films affect their photothermal and wetting properties?
7. What synthesis strategies offer the best trade-off between scalability, cost-effectiveness, and performance in polymer-based photothermal materials?
8. Can CP-based evaporators be integrated with energy harvesting or desalination systems for multifunctional water purification setups?
9. How does the pore structure of polymer composites affect the capillary-driven water transport and salt rejection efficiency?
10. Can 3D printing or inkjet printing be used to fabricate complex structures of CP films for tailored photothermal performance?
11. How does the hydrophilicity-hydrophobicity balance affect both water transport and thermal management in these systems?
12. What are the comparative advantages and limitations of P3HT over other semiCPs in optoelectronic and photothermal applications?

CRediT authorship contribution statement

Bushra Shakoor: Conceptualization, Writing – original draft. **Muhammad Sultan Irshad:** Conceptualization, Project administration, Resources, Supervision, Visualization, Writing – original draft. **Uzma Ghazanfar:** Formal analysis. **Humaira Razzaq:** Formal analysis, Funding acquisition, Supervision. **Naila Arshad:** Conceptualization, Writing – original draft. **Ghazala Maqsood:** Conceptualization. **Iftikhar Ahmed:** Writing – review & editing. **Muhammad Atif Ali:** Conceptualization. **Muhammad Sohail Asghar:** Formal analysis. **Irshad Husain:** Writing – review & editing. **Tao Mei:** Visualization. **Tran Vinh Dieu:** Writing – review & editing. **Nang Xuan Ho:** Writing – review & editing. **Van-Duong Dao:** Conceptualization, Project administration, Resources, Validation. **Xianbao Wang:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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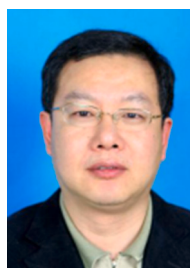
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