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Research Article

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# Advancing resource sustainability with green photothermal materials: Insights from organic waste-derived and bioderived sources

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**Abstract:** Recently, there has been a surge of interest in developing new types of photothermal materials driven by the ongoing demand for efficient energy conversion, environmental concerns, and the need for sustainable solutions. However, many existing photothermal materials face limitations such as high production costs or narrow absorption bands, hindering their widespread application. In response to these challenges, researchers have redirected their focus toward harnessing the untapped potential of organic waste-derived and bioderived materials. These materials, with photothermal properties derived from their intrinsic composition or transformative processes, offer a sustainable and cost-effective alternative. This review provides an extended categorization of organic waste-derived and bioderived materials based on their origin. Additionally, we investigate the mechanisms underlying the photothermal properties of these materials. Key findings highlight their high photothermal efficiency and versatility in applications such as water and energy har-

**Graphical abstract**

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vesting, desalination, biomedical applications, deicing, waste treatment, and environmental remediation. Through their versatile utilization, they demonstrate immense potential in fostering sustainability and support the transition toward a greener and more resilient future. The authors' perspective on the challenges and potentials of platforms based on these materials is also included, highlighting their immense potential for real-world implementation.

**Keywords:** photothermal materials, organic waste valorization, bioderived materials

## Abbreviations

| | |
|---|---|
| AA | asiatic acid |
| ACCF | all-carbon conductive foam |
| AlP | aluminum phosphate |
| BBB | blood–brain barrier |
| BLB | bilayer bamboo |
| C-CSS | centerless carbonized sunflower stalk |
| CDs | carbon dots |
| CFMA | cardanol-furfural-18-*p*-mentanediamine adduct |
| CINPs | cuttlefish ink natural nanoparticles |
| CL | carbonized loofah |
| CQDs | carbon quantum dots |
| CSS | carbonized sunflower stalk |
| CPS | carbonized PSP |
| Cu-CAT | copper-based metal–organic framework |
| DRM | dry reforming of methane |
| EA | enteromorpha aerogel |
| EAA | enteromorpha aerogel aerator |
| FAO | Food and Agriculture Organization |
| $Fe_3O_4$ | iron(II,III) oxide |
| FCPP | fractal carbonized pomelo peel |
| H-CSS | hollow carbonized sunflower stalk |
| $H_3PO_4$ | phosphoric acid |
| ICG | indocyanine green |
| ISSG | interfacial solar steam generator |
| MLM | melanin-like materials |
| MNPs | melanin nanoparticles |
| MIL-53(Fe) | metal–organic framework – Fe(III) benzene dicarboxylate |
| MOF | metal–organic framework |
| $N_2$ | nitrogen |
| NIR | near-infrared |
| Ni | nickel |
| Ni-DTA | nickel-dithiooxamidato |
| $Ni(NO_3)_2$ | nickel nitrate |
| NPs | nanoparticles |
| PDA | polydopamine |
| PLA | polylactic acid |
| PNIPAM | poly(*N*-isopropyl acrylamide) |
| PPy | polypyrrole |
| PVDF | polyvinylidene fluoride |
| PSP | peanut shell powder |
| PTT | photothermal therapy |
| SCGs | spent coffee grounds |
| S-CD | sulfur-doped carbon dots |
| SF | silk fibroin |
| SSG | solar steam generator |
| SFNPs | silk fibroin nanoparticles |
| $SiO_2$ | silica |
| SS | sunflower stalk |
| SU | sea urchin |
| TA | tannic acid |
| TDDS | transdermal drug delivery systems |
| TiN | titanium nitride |
| TS | tea saponin |
| 3D | three-dimensional |

## 1 Introduction

The urgent demand for sustainable energy and environmental solutions has increased the interest in innovative photothermal materials. Photothermal materials, which can efficiently convert light energy into heat, are pivotal for a myriad of applications, from water purification to medical therapies.

Among the current state-of-the-art photothermal materials, plasmonic particles [1–3], carbon nanomaterials [4–6], black phosphorus [7,8], and copper sulfide [9,10] have been extensively studied. Among plasmonic particles, gold nanorods, with their unique optical properties, have been employed in various biomedical applications, including environmental remediation, disinfection, imaging, and therapy [11–14]. However, their synthesis often uses toxic chemicals, which limits their use in biological applications [15]. Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, exhibits strong light absorption across a wide range of wavelengths [16–18]. Yet, the scalable production of this carbon nanomaterial remains a challenge, often requiring complex processes and high costs [19]. A particular hurdle in its fabrication is the requirement for polymer binders when creating coatings, which can introduce complications in both the production process and the material's final properties, thus hindering its practical application and scalability [20]. Copper sulfide, while effective in certain conditions, often necessitates specific environments for optimal performance, limiting

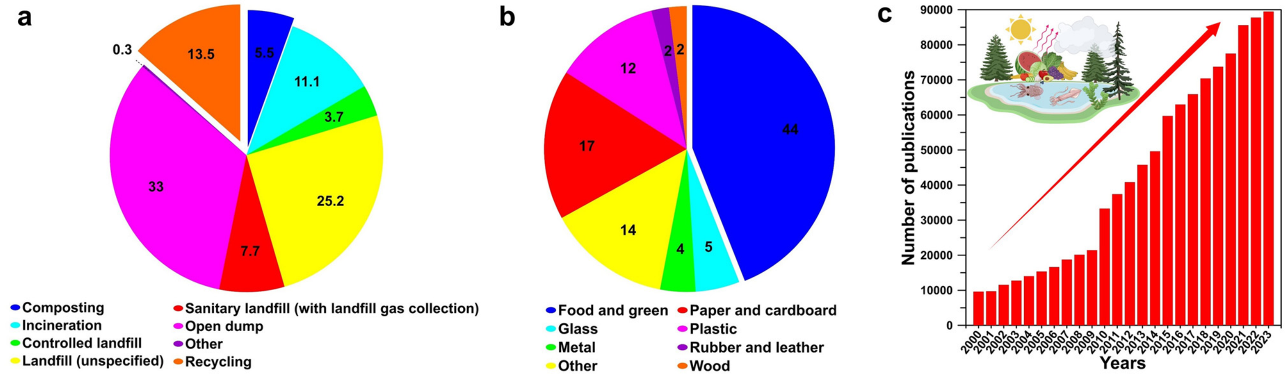

**Figure 1:** The abundance of organic waste-derived and bioderived materials and the research trend on the subject. (a) The portion of the recovered biowaste from approximately 2 billion tonnes of municipal solid waste produced annually. (b) The composition of global waste with an emphasis on the large fraction of food and green waste [29], Copyright 2024, The World Bank Group. (c) The number of published articles on platforms developed from organic waste-derived and bioderived materials with photothermal properties in the period of 2000–2023, obtained from the Web of Science database.

its versatility [9,10,21]. Black phosphorus, another promising material, has shown potential in a variety of applications, including photoacoustic imaging, photothermal therapy (PTT) of cancer, and combating environmental bacterial pathogens [22–24]. Its tunable bandgap makes it suitable for these advanced applications. However, its instability in ambient conditions, leading to rapid degradation, poses significant challenges [25].

The drawbacks of conventional photothermal materials have led researchers to seek efficient, sustainable, and scalable alternatives [26–28]. On the other hand, the global crisis of waste mismanagement poses a mounting challenge, with a vast majority of waste ending up in landfills and only 19% recovered through recycling or composting (Figure 1a) [29]. Organic waste, making up a large part of global waste (Figure 1b), offers a chance to apply circular economy principles and turn waste into valuable products. These materials stand out as particularly promising due to their inherent sustainability and potential for low-cost and large-scale production. By repurposing waste materials, these photothermal agents not only reduce environmental pollution but also provide a sustainable source of advanced materials for practical applications. For instance, using agricultural residues, food processing by-products, and industrial waste to create photothermal materials aligns with circular economy principles, transforming waste into valuable resources. These sustainable materials have the potential to revolutionize fields such as solar-driven water purification, where traditional materials often face challenges of high cost and environmental impact. Moreover, their biocompatibility makes them ideal candidates for biomedical applications, providing safer and more sustainable options for treatments [26,30,31]. Therefore, these materials allow us to tackle the dual challenges of waste management and resource scarcity. In a broader context, the investigation of organic waste-derived and bioderived materials within the photothermal sphere exemplifies the intersection of sustainability, innovation, and scientific inquiry. Positioned at the juncture of environmental demands and technological progress, the investigation and utilization of these materials indicate optimistic outlook for the future.

A diverse array of organic waste-derived and bioderived materials has been investigated, revealing a vast potential for sustainable photothermal applications. As shown in Figure 1c, the number of published articles on these materials has steadily increased from 2000 to 2023, indicating growing research interest and advancements in this field. For instance, Cuttlefish ink, a naturally occurring bioderived material, has been recognized for its impressive photothermal properties [32–34]. Derived from cephalopods, cuttlefish ink contains melanin nanoparticles (MNPs), which are responsible for its dark color and broad absorption spectrum. Recent studies have showcased its potential in solar steam generation, where it achieved a remarkable solar-to-vapor conversion efficiency [32,35,36]. Furthermore, its biocompatibility makes it an attractive candidate for biomedical applications, including PTT [33]. Another example is spent coffee grounds (SCGs), a prevalent organic waste generated in vast quantities due to the global consumption of coffee, which is often discarded without a second thought. However, they recently garnered attention in the scientific community for their potential applications beyond their primary use [37–39]. Direct utilization of SCGs as a photothermal material has been explored, with studies demonstrating its promising light conversion efficiency. These findings are noteworthy, especially considering that the SCGs do not require any carbonization treatment [40,41].

On the other hand, the intrinsic porous structure of many organic waste-derived and bioderived materials enhances their ability to absorb and convey fluids, making them suitable for applications that require fluid management, such as water purification [30,42]. For instance, non-carbonized wood, with its intrinsic porous structure, can be employed in such applications that require managing large amounts of fluids [42–44]. The natural porosity of the wood allows for efficient absorption and retention of fluids, ensuring a steady and controlled flow, which is crucial in such applications [45].

In addition to these natural properties, advancements in materials science have enabled the transformation of organic waste-derived and bioderived materials through processes like pyrolysis and calcination, further enhancing their photothermal properties and expanding their application potential [30]. An example is carbonized wood, transformed through pyrolysis, which exhibits enhanced thermal conductivity [46,47]. The carbonization process imparts a graphitic structure to the wood, enabling it to absorb a broader spectrum of light and efficiently convert it into heat.

While the scientific community has made considerable steps in the development of photothermal materials, there remains a conspicuous gap in the comprehensive review of organic waste-derived and bioderived materials specifically tailored for photothermal applications. This review highlights not only the photothermal properties of these materials but also emphasizes their sustainable sourcing from organic waste, addressing both material efficiency and environmental sustainability. We also provide a comprehensive categorization of organic waste-derived and bioderived materials based on their origin, which is not covered in the current literature. This structured approach aids in understanding the broad spectrum of available sustainable materials and their respective advantages. A novel aspect of this review is the integration of waste management principles with materials science. It showcases how waste materials can be repurposed into high-value photothermal materials, thereby presenting a dual benefit of environmental remediation and resource utilization. Moreover, this review distinguishes itself by discussing both intrinsic photothermal properties and process-enhanced properties of these materials. This dual perspective is crucial for understanding the full potential and versatility of organic waste-derived and bioderived materials in various applications. It should be noted that existing literature has explored various aspects of these materials, such as their role in wastewater remediation [30], interfacial solar steam generation (ISSG) [27], and the multifunctional uses of bioderived compounds like eumelanin [26]. However, there is a discernible absence of a unified review that encapsulates both organic waste-derived and bioderived materials, their unique photothermal properties, practical applications across multiple domains, and the challenges they face in a single discourse. Our review stands out by not only discussing the theoretical aspects but also highlighting real-world applications and case studies where these materials have been successfully implemented, thereby providing a pivotal reference point for future research and development in this field.

The primary objective of this review is to explore the potential of organic waste-derived and bioderived materials in addressing critical environmental and biomedical challenges. It aims to provide a comprehensive overview of the unique characteristics, applications, and advantages of these sustainable materials. By examining recent advancements and practical implementations, this review seeks to highlight the significance of utilizing waste-derived and bioderived materials for photothermal applications. The scope of this review encompasses a wide range of materials sourced from marine, plant, and animal origins, detailing their preparation methods, photothermal properties, and diverse applications in areas such as water purification, energy harvesting, biomedical treatments, and environmental remediation. We aim to catalyze further innovation and to foster a deeper understanding of these materials' roles in advancing sustainable solutions within the photothermal domain.

## 2 Types of organic waste-derived and bioderived materials

This section categorizes organic waste-derived and bioderived materials based on their origin: marine, plant, and animal. It also presents their abundance and annual production statistics, as well as their structure and topology.

### 2.1 Marine-derived materials

The marine environment, covering 72% of Earth's surface and holding 97% of its water, extends beyond vast saline waters. It is a critical source of food, medicinal compounds, and diverse raw materials, anchoring substantial economic value through its rich biodiversity [48]. It includes over 80% of the planet's species, many of which are pivotal for the wealth of marine-derived biomolecules (polysaccharides, proteins and amino acids, fatty acids, minerals, and vitamins) [49]. These biomolecules have garnered significant attention for their potential in medical and engineering applications, reflecting a growing interest in marine bioprospecting, which is the "exploration of biodiversity for commercially valuable genetic and biochemical resources" [50]. Additionally, the exotic biological materials found in marine environments are foundational for the development of manmade materials inspired by nature, called biomimetic materials, which offer innovative solutions to current challenges in the field of biomaterials science [51].

The escalating global demand for seafood underlines the intricate relationship between the marine ecosystem and human resource extraction activities. Global seafood production reached 184.6 million metric tons in 2022, with China leading at 44.9 million metric tons, as reported by the Food and Agriculture Organization (FAO) of the United Nations [52]. This marks a modest increase from the 178.1 million metric tons in 2021. The past few decades have seen a 3% annual increase in seafood consumption, surpassing population growth rates. With the expected surge in the global population to 9.8 billion by 2050, seafood demand is predicted to rise by 60%, leading to more and more marine biowastes [53].

In 2022, the FAO estimated that seafood waste comprised 35–50% of total production, amounting to 64–92 million metric tons [52]. This by-product, particularly prevalent at the processing stage, represents not only an environmental burden but also a loss of valuable nutrients. Since the large quantities of seafood waste remain underexploited, their utilization can bring ecological and economic benefits [53]. For example, marine-derived biowaste is an overlooked resource containing materials that can be utilized to create biomaterials with photothermal properties. Figure 2a showcases the step-by-step conversion of seafood waste into valuable materials. The process begins with the collection of seafood, followed by chemical and enzymatic treatments to extract and purify the target materials that also have photothermal properties or can be modified to have such properties.

### 2.1.1 Chitin and chitosan from crustacean shells

Each year, crustaceans produce an estimated 6–8 million tons of shell waste [54]. This substantial amount of waste is not only primarily composed of calcium carbonate, but it also contains a significant amount of chitin, a biopolymer that is second only to cellulose in terms of abundance among natural organic polymers [54,55]. The role of chitin in crustacean shells is to provide strength and rigidity. It is a linear polysaccharide composed of *N*-acetylglucosamine units linked by β-[1,4] glycosidic bonds [54]. This natural polymer is gaining attention for its biocompatibility, biodegradability, and non-toxic properties [56].

The extraction of chitin and its deacetylated form, chitosan, typically involves chemical processes such as decalcification in dilute hydrochloric acid, deproteinization in dilute sodium hydroxide, and decolorization or sunlight exposure [55]. These methods are well-established for scalability in industrial settings [48]. Chitin can be transformed into various nanostructured materials like chitin whiskers, nanocrystals, and nanofibers through different isolation processes [54,60,61]. Moreover, the nanofibrous form of chitin contains nitrogen derived from the chitin acetyl-amino groups. This unique structure makes chitin nanofibers promising candidates for photothermal materials. Additionally, chitin nanofibers exhibit high thermal stability against the collapse of their morphology during carbonization [62]. A recent study by Yeamsuksawat *et al.* demonstrated the exceptional ability of chitin nanofibers to convert solar energy into heat [62]. The researchers successfully fabricated a nitrogen-doped carbon nanopaper from chitin nanofibers by a controlled carbonization process. This resulted in a material with enhanced solar absorption and outstanding solar thermal heating performance [62]. The carbonized chitin nanopaper has nitrogen-containing functional groups, which in the paper was found to be responsible for lowering the optical band gap to 0.75 eV. A lower bandgap can facilitate light absorption at lower energies (longer wavelengths), consequently enhancing its solar absorption performance. The subwavelength nanoporous structure of the chitin nanofibers also played a crucial role in promoting light scattering and absorption, maximizing the conversion of solar energy into heat [62].

In another recent study, Wan *et al.* demonstrated the exceptional photothermal capabilities of chitin-derived carbonaceous nanofibrous aerogels [63]. The researchers developed a process that involved dissolving chitin and regenerating it, followed by lyophilization and, ultimately, pyrolysis to create aerogels. These aerogels, characterized by a multimodal porous structure, exhibited outstanding properties, including elasticity, mechanical strength, pressure responsiveness, and thermal insulation. Remarkably, they demonstrated a good photothermal conversion efficiency of up to 96.4% [63]. This high efficiency was attributed to the synergistic interplay of their structural features and composition. The nanofibers within the aerogel allowed for efficient scattering and absorption, while the carbonaceous structure transformed solar energy into heat. Furthermore, the multimodal porous structure maximized the heat transfer and utilization efficiency across the material [63].

Chitosan, which is derived from chitin found in the exoskeletons of crustaceans like shrimp and crabs, has

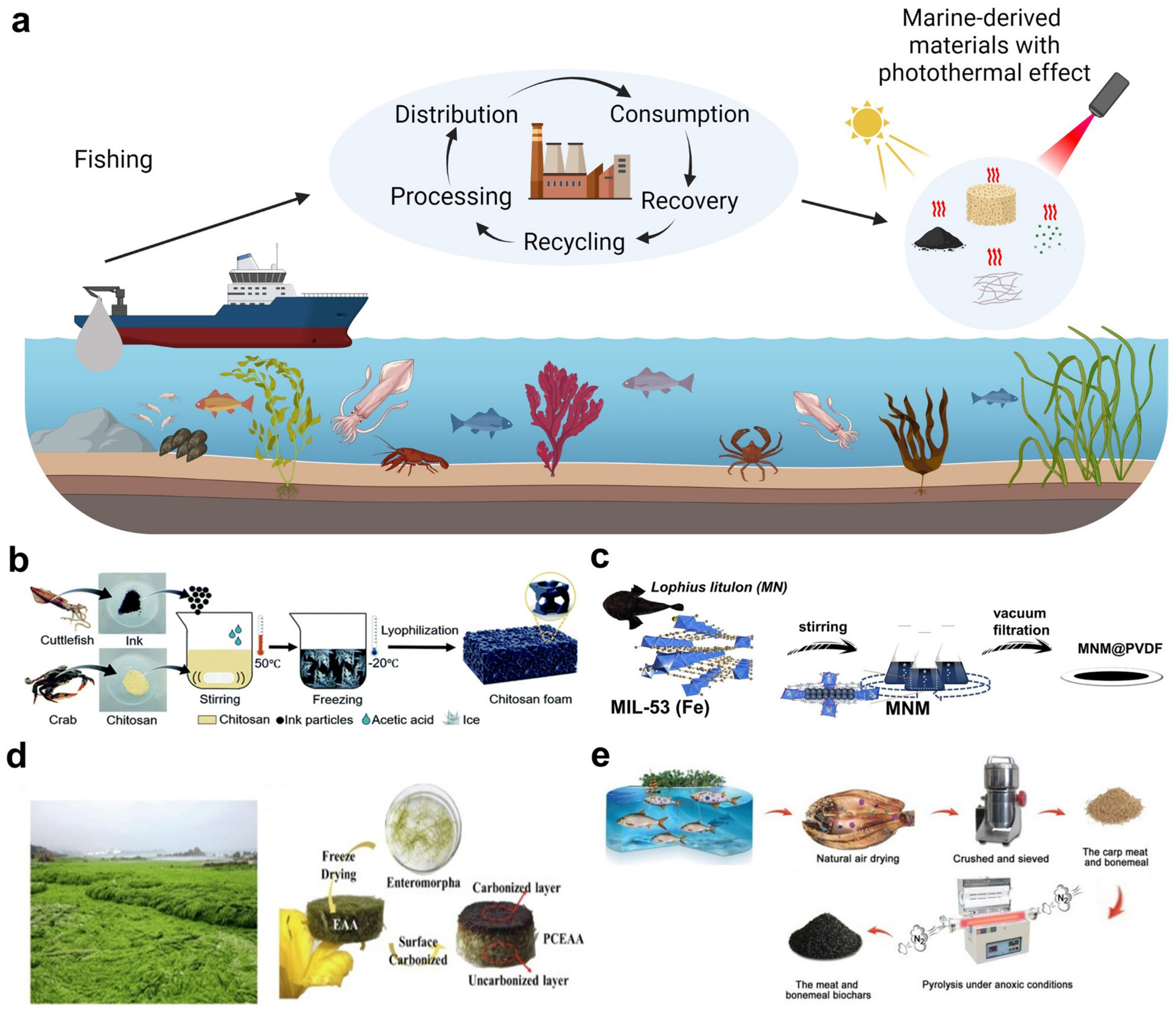

**Figure 2:** Marine-derived photothermal materials. (a) Illustration of the valorization process of materials from the sea to obtain materials that have or can be modified to have photothermal properties. (b) Schematic presentation of the fabrication of a porous scaffold by mixing cuttlefish ink powder with a chitosan solution at high temperatures. The material is later frozen at −20°C and subjected to lyophilization to obtain a porous material with photothermal properties. Reproduced with permission from Liu *et al.* [35], Copyright 2021, The Royal Society of Chemistry. (c) Schematic illustration portraying melanin particles that were extracted from *Lophius litulon* fish skin in water and combined with a metal–organic framework – Fe(III) benzene dicarboxylate (MIL-53 (Fe)). The homogeneous suspension is then poured into a suction filtration device equipped with a polyvinylidene fluoride (PVDF) membrane to obtain a photothermal evaporator. Reproduced with permission from Wang *et al.* [57], Copyright 2023, Elsevier B.V. (d) Photograph of the Enteromorpha algae bloom polluting the shores of the Yellow Sea, China, and illustration of the transformation of Enteromorpha algae bloom into a scaffold using the freeze-drying method to obtain a porous material and subsequently developing a partially carbonized surface for photothermal properties. The resulting porous scaffold exhibits self-floating characteristics, resembling jellyfish. Reproduced with permission from Wang *et al.* [58], Copyright 2022, Elsevier Inc. (e) Illustration of the utilization process of naturally air-dried dead fish by crushing to obtain a powder from carp meat and bonemeal. Later, meat and bonemeal biochars with photothermal properties are obtained through pyrolysis in controlled anoxic conditions. Reproduced with permission from Qiao *et al.* [59], Copyright 2021, the Authors.

garnered significant attention for its versatility across various fields. Chitosan is known for its biocompatibility, biodegradability, and ability to form gels and films [56]. Its distinct structural properties, particularly ability to form intricate porous architectures, have been leveraged to develop hydrogels, scaffolds, and foams with enhanced functionality [56,64].

While chitosan does not exhibit photothermal properties, its porous structure provides an ideal platform for incorporating photothermal agents [35]. These agents can be well-dispersed in the porous chitosan scaffold, enhancing light absorption and heat generation. Additionally, the porous structures provide structural support and facilitate efficient heat transfer, making them particularly well-suited for solar energy harnessing applications [35,65]. In a study by Liu *et al.*, chitosan was used to create a porous scaffold with photothermal agents from cuttlefish ink, showing potential for seawater desalination (Figure 2b) [35]. The approach utilized the photothermal properties intrinsic in cuttlefish ink, detailed further in the subsequent section, to convert light energy into heat. Simultaneously, the inclusion of a porous chitosan scaffold improved heat transfer efficiency, thereby optimizing the material's desalination capacity.

### 2.1.2 Cephalopods ink

Among the numerous marine organisms, cephalopods, including squids, cuttlefish, and octopuses, are of interest due to their unique ink [66]. The dark hue of cephalopod ink is attributed to melanin, a complex polymer that absorbs light effectively, making it nearly opaque [67]. The synthesis of melanin in cephalopods is facilitated by specialized melanocytes, which oxidize the amino acid tyrosine, culminating in polymerization [67]. At the end of this process, MNPs are stored within ink sacs.

Due to the high global consumption of cephalopods, especially squids and cuttlefish, a large amount of ink is discarded each year. However, in many cultures, this ink – referred to as "sepia" – is not treated as waste but rather highly prized as a culinary delicacy in dishes like "arroz negro" and "risotto al nero di seppia" [67,68]. Beyond culinary uses, in recent years, cephalopod ink has attracted attention for its other potential applications. Its unique properties, including high viscosity, low surface tension, and ability to absorb light, have led to investigations into various applications such as solar-based water purification systems or potential biomedical implementations. Recent studies have indicated promising advancements in biomedical uses, including reported antibacterial properties [69], potential in cancer treatment [70], prevention of biofilm formation in food [71], and potential for use in biosensors [33] within the food industry.

As previously mentioned, chitosan and cuttlefish ink were combined in a recent study by Liu *et al.* to create a self-floating scaffold used for a solar steam generator [35]. A solution of chitosan dissolved in acetic acid was mixed with the MNPs to ensure an even distribution of nanoparticles (NPs) in the resulting solution. Subsequently, the black non-Newtonian fluid was frozen at −20°C overnight. Following a conventional lyophilization procedure, during which ice crystals within the frozen composite were removed through the sublimation of ice crystals, the chitosan–cuttlefish ink composite with a porous structure was achieved. The schematic presentation of the preparation of this platform is presented in Figure 2b [35].

Another study examined the biomedical applications of cuttlefish ink to develop advanced hydrogel patches for wound healing [72]. The research team successfully isolated MNPs from cuttlefish ink using a series of purification steps. The hydrogel patches were fabricated by incorporating MNPs into a fish gelatin pregel resulting in an inverse opal scaffold, followed by infiltrating a mixture of asiatic acid (AA) and agarose pregel. The MNPs contribute to the patches' properties of photothermal antibacterial and antioxidant effects and also improve the visibility of structural colors. The photothermal effect of MNPs can trigger the release of the loaded proangiogenic AA, leading to the controllable release of the drug. This drug release induces refractive index variations in the patch, which can be detected as visible structural color shifting, allowing for monitoring of the delivery process [72].

Beyond cephalopods, the *Lophius litulon*, a common marine fish, has been recognized as a promising source of melanin [57]. In Wang's study, a cost-effective and eco-friendly evaporator was developed for efficient solar water purification, constructed from the metal–organic framework (MOF) and MNPs derived from *Lophius litulon*. MOFs are materials made up of metal ions, which coordinate with organic molecules, creating a porous structure. These frameworks are highly valued for their tunable porosity, meaning the size of their pores can be adjusted, and their high surface area, which makes them useful for applications like gas storage and catalysis. The process of extracting melanin from Lophius *litulon* skin involved pulverization with an ultrasonic breaker, followed by removal of cells through vacuum filtration [57]. Melanin powder was then combined with Fe(III) benzene dicarboxylate MOF material (MIL-53(Fe)) and incorporated with PVDF to form the MNM@PVDF composite membrane [57]. PVDF membranes are used for their hydrophobic properties, meaning they repel water. This characteristic makes them suitable for applications where water resistance is important, such as in waterproof coatings and membranes. This procedure is illustrated in Figure 2c. The MNM@PVDF was subsequently tested for solar water purification [57]. The estimated cost of the evaporator was found to be economical, making it a promising solution for addressing clean water scarcity and environmental challenges [57].

### 2.1.3 Algae

Algae, or seaweeds, are classified into three groups: Rhodophyta (red algae), Chlorophyta (green algae), and Phaeophyceae (brown algae). They play a vital role in aquatic ecosystems by forming the energy base of the food chain for all aquatic organisms [73]. Despite their ecological roles, algae can also be problematic. Algal blooms, often resulting from ecosystem disturbances, can devastate local fisheries and tourism by creating large biomasses that are difficult to manage. To mitigate these effects, there is a growing interest in harvesting algae for practical solutions [74,75].

For example, to mitigate the severe consequences of the blooms of *Enteromorpha prolifera* (*E. prolifera*) type of green algae on coastal environments and fisheries in China, Yang *et al.* conducted research successfully transforming this biomass into biochar-based solar absorbers [76]. The study explored various methods of preparing carbonized biochar, resulting in four materials with slightly different microstructures and porosities. The research involved examining the porous structure of carbonized *E. prolifera* through the pyrolysis of its dry thalli at around 600°C under an inert atmosphere [76].

A different study, which addressed the pollution crisis caused by Enteromorpha blooms, is shown in Figure 2d. It utilized algae to create a foam-like enteromorpha aerogel (EA) [58]. Inspired by the concept of transforming waste into materials with photothermal capabilities, this study utilized EA as the raw material to create carbonized material. As illustrated in Figure 2d, the upper surface of the cylindrical EA aerator (EAA) transformed into a structurally stable carbonized layer, while the lower part retained its hydrophilic cellulose composition [58]. The partially carbonized EAA, when placed on the water surface, resulted in a self-floating jellyfish-like solar steam generator (SSG).

### 2.1.4 Sea urchins (SUs) and dead fish

SUs are marine creatures that have thrived for over 450 million years and can be found from tropical to polar seas and from shallow waters to depths of 5,000 m [77]. Evolution through natural selection has optimized their skeletons, which feature a porous design. This structure enables them to withstand the extreme conditions of the deep sea, support their shell's weight, and conserve energy efficiently [77]. The study by Xia *et al.* introduces a three-dimensional (3D) evaporator made from a modified SU shell with a polydopamine (PDA) photothermal layer. This design allows the evaporator to absorb over 90% of light across a wide range of angles and achieve a high-water evaporation rate under sunlight [77]. Additionally, the material demonstrates strong mechanical properties and salt resistance, maintaining its performance over multiple extended use cycles [77].

The aquaculture industry continuously faces a significant by-product challenge, including the disposal of dead aquatic products, residual fishing bait, and manure [59]. Traditional methods of burning or burying these by-products not only contribute to biomass energy waste but also pose environmental pollution risks and potential health hazards for humans [59]. In the study by Qiao *et al.*, a novel approach to address this issue is proposed by utilizing pyrolysis of dead fish, specifically carp, to obtain biochar that can be later used to improve both SSGs and water purification processes. Figure 2e presents a schematic of how the dead fish are naturally dried, then crushed, and sieved to obtain the carp meat and bonemeal [59]. Finally, the conversion of carp fish carcasses into biochar, a carbon-rich material, is obtained through the thermal decomposition of organic material in an oxygen-limited environment [59]. The study not only proves that carbonized biomass is a promising method for photothermal conversion but also provides a new way for waste biomass utilization in the aquaculture industry.

The key properties and applications of marine-derived materials are summarized in Table 1. A key issue for future research on these materials will be ensuring reproducibility and scalability of production. Variability between batches and potential contamination from heavy metals are significant concerns regarding the quality and safety of these products. Understanding biocompatibility, toxicity, and tissue interactions is crucial for clinical applications. Moreover, increased efforts are directed toward sustainability and eco-friendly practices, with the development of advanced machinery tailored for producing biomaterials. Despite these challenges, the future appears promising for multifunctional platforms from marine-derived materials that can combine high safety and performance under severe conditions.

## 2.2 Plant-derived materials

Plant-derived materials, as well as animal-derived materials (described in Section 2.3), are gaining attention due to their unique properties and sustainability. This section will explore materials derived from plants, such as SCGs, plant oils, and wood. Figure 3a highlights these materials, showcasing their structural properties and potential applications in various photothermal processes.

**Table 1:** Key properties and applications of photothermal marine-derived materials

| Photothermal agent | Source | Type | Photothermal attribute | Application | Key properties | Ref. |
|---|---|---|---|---|---|---|
| Chitin and chitosan | Shrimp shells | Bioderived | Process-enhanced | Solar steam generation | High solar absorption, multimodal porous structure, good elasticity and mechanical strength, pressure responsiveness, thermal insulation | [63] |
| | Crustacean shells | Bioderived | Process-enhanced | Solar thermal heating | High solar absorption, low optical band gap (0.75 eV), nitrogen-containing groups, subwavelength nanoporous structure | [62] |
| Melanin | Cuttlefish ink | Bioderived | Intrinsically photothermal | Solar evaporator, wound healing | High solar absorptance, adequate water transportation, good salt drainage, heat localization, environmentally friendly, antibacterial, antioxidant | [35,72] |
| | *Lophius litulon* skin | Organic waste-derived | Intrinsically photothermal | Solar evaporator | High evaporation rate, antibacterial property, biocompatibility, recyclability, low-cost, long-term stability | [57] |
| Meat and bonemeal | Dead fish (carp) | Organic waste-derived | Process-enhanced | Solar steam generation, water purification | High solar absorption, excellent evaporation of seawater and heavy metal wastewater, cost-efficient | [59] |
| Algae | Algae bloom | Organic waste-derived | Process-enhanced | Solar steam generation | High solar absorption, high porosity, cost-efficient | [58,76] |
| Shell of SUs | SU | Bioderived | Process-enhanced | Solar steam generation | High absorption in various angles, microneedles array structure, low-cost, high-stability | [77] |

### 2.2.1 SCGs

SCGs are one of the interesting plant-based organic waste materials that can be recycled. It can be estimated that one coffee typically leaves behind an average of 8–10 g of SCGs. As a result, large amounts of dry SCGs, approximately 6,000,000 tons/year, are produced worldwide [78]. Melanin is a biomacromolecular pigment that serves various functions in biological systems. It has also been found to possess a strong ability to absorb near-infrared (NIR) light due to its coupled structures [79]. For this reason, melanin and melanin-like photothermal reagents are attracting increasing attention. Since coffee is rich in melanoidins, it aroused the curiosity of Chien and Chen, inspiring them to investigate the possible photothermal properties of SCGs [41]. The researchers have, for the first time, demonstrated that SCGs exhibit a rapid photothermal effect, reaching temperatures of up to 344°C within 2 min of NIR irradiation. Furthermore, SCGs showed excellent heating repeatability and photothermal stability for at least 12 cycles. The surface morphology of SCGs powder was found to be rough, with many irregular particles. After fading using bleach solutions, the surface became smooth, the particles lost their dark color, and the material lost its ability to photothermal response. The impact of the photothermal effect of SCGs on bacterial killing and biofilm elimination was also investigated. The generated heat killed 6 log of planktonic bacteria and removed over 90% of the biofilm within 30 min [41]. It is worth noting that over time, SCGs accumulate in the environment and have adverse effects, which is why the development of methods for their recycling and reuse is particularly important.

Even though SCGs contain cellulose and hemicellulose, which can be carbonized to create a porous structure with a large surface area and high adsorption capacity [80,81], Chen and co-workers confirmed the initial reports that SCGs possess photothermal properties under NIR irradiation without the need for any pre-processing such as carbonization [40]. Furthermore, in their study, it was found that SCGs exhibit a useful photothermal conversion efficiency of 24.8%. Authors also attempted to incorporate SCGs into photoresponsive poly(*N*-isopropyl acrylamide) (PNIPAM) hydrogels to assess their utility as photothermal actuators capable of converting environmental stimuli into mechanical work. PNIPAM hydrogels containing SCGs showed thermal shrinkage and bending properties under NIR radiation. When more SCGs were added, the hydrogel crosslinking density became low, and the degree of shrinkage and bending was high. Additionally, after alternating NIR irradiation and cooling, hydrogels containing SCGs exhibited precise reversibility [40].

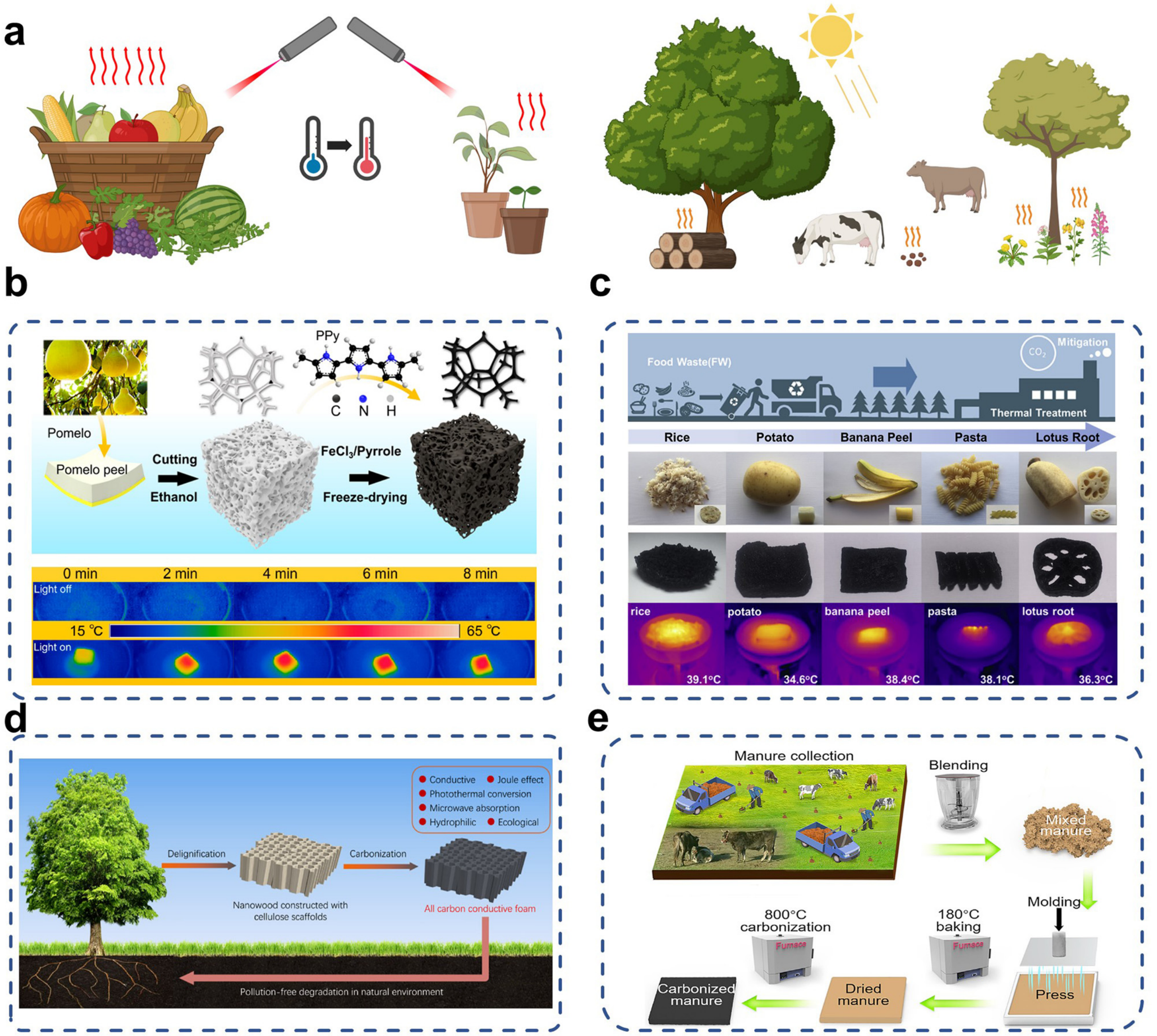

**Figure 3:** Plant-derived and animal-derived materials and (a) their potential to be used as photothermal platforms. (b) Visual representation of the fabrication process of pomelo peel functionalized with PPy for photothermal solar absorber application. The naturally existing interconnected porous framework of pomelo peel can act as a sponge-like template with photothermal properties attributed to the presence of PPy. Reproduced with permission from Zhang *et al.* [83], Copyright 2020, American Chemical Society. (c) Converting food wastes into carbonized materials with photothermal properties for use as solar evaporators. The carbonaceous food wastes have the capacity to trap solar heat, primarily owing to their broad optical absorption in the entire solar radiation spectrum. Reproduced with permission from Zhang *et al.* [84], Copyright 2019 Elsevier Ltd. (d) Schematic illustration of the preparation and characteristics of wood-derived ACCF. Natural wood owes its remarkable photothermal conversion ability and unique Joule-heating effect to delignification and carbonization. Reproduced with permission from Wang *et al.* [46], Copyright 2023, Elsevier Ltd. (e) Scheme showing the preparation of carbonized manure for solar evaporator application. Microchannels in carbonized manure trap the incoming light, low thermal conductivity permits heat localization and randomly arranged black carbon fibers create microchannels that pump the seawater, allowing salt dissipation. Reproduced under CC BY-NC-ND 4.0 license [101], Copyright 2021, The Authors.

About 50% of the SCGs are in the form of hemicellulose, which is high in carbon. As already known, carbon quantum dots (CQDs) can be synthesized from any carbon-containing starting materials. What is additionally noteworthy is that only about 33% of the proteins are extracted during the coffee extraction process, and the rest remains insoluble due to denaturation. Therefore, SCGs have a high amino acid content, and the proportions of sulfur-containing amino acids in SCGs are very low. Consequently, CQDs synthesized in this way are expected to have relatively constant properties and exhibit excellent visible-light-driven antimicrobial activity [82]. Kang *et al.* used SCGs to synthesize CQDs *via* microwave treatment. The scientists confirmed the antimicrobial effect of SCGs-derived CQDs on *Staphylococcus aureus* (Gram-positive bacteria) and *Escherichia coli* O157:H7 (Gram-negative bacteria) under visible light irradiation, which increases with decreasing pH due to the enhanced interaction between CQDs and pathogens [82].

### 2.2.2 Fruits and vegetables

Another organic waste material is pomelo peel. As a typical by-product of food, it possesses a naturally occurring, interconnected porous structure that can serve as a sponge-like template [83]. Pomelo peel can be used as a biocompatible and cost-effective 3D porous substrate for water transport.

However, its high reflection and low absorption of sunlight hinder the conversion of solar energy into thermal energy. Zhang *et al.* developed a multifunctional photothermal sponge composed of polypyrrole (PPy) and pomelo peel waste in a gentle, low-energy, and environmentally friendly manner, using an *in situ* wet decoration method (Figure 3b) [83]. Their research has revealed that pomelo peel-based waste materials are equipped with numerous capillary pores that enable continuous water pumping and/or organic substance absorption, and when modified with PPy, pomelo peel can act as a photothermal sponge with >95% solar light absorption. Furthermore, it is important to note that other peel wastes from fruits or vegetables, particularly those with thin inner skins, are not conducive to *in situ* chemical modification. As an alternative, they undergo carbonization to produce powders, which are subsequently processed into films for photothermal applications [83].

Carbonization is an effective method to tackle food waste. Approximately 1.3 billion tons of food waste are generated each year, which accounts for one-third of the total food intended for human consumption [82,84]. Zhang and co-workers presented a sustainable approach for utilizing food waste, which not only reduces carbon dioxide emissions but also transforms food waste into highly porous carbon-based photothermal materials for inexpensive solar desalination and thermoelectric generation [84]. In their study, rice, potatoes, pasta, banana peels, and lotus roots underwent thermal treatment to achieve desired characteristics such as resistance to natural degradation, porous structure, and broad-spectrum light absorption (Figure 3c). The carbon-based device derived from food waste exhibited exceptional steam generation capacity and was "wave-resistant," ensuring stable operation on the actual sea surface. The concept presented in their article not only transforms waste into useful materials and devices but also offers a sustainable solution to global issues such as water scarcity and managing food waste that contributes to soil and air pollution, as well as massive greenhouse gas emissions. It is worth noting that single-day potato waste in the UK amounts to as much as 5.8 million tons. Recycling them using carbonization can generate about 400 tons less $CO_2$ than incineration, and the clean water produced from potatoes in a single day will be sufficient to meet the daily drinking water needs of 250,000 people.[84]

Liu *et al.*, also using one of the biomass resources – corn cob – and the carbonization process, prepared a superhydrophobic, ice-phobic biocarbon coating containing iron(II,III) oxide ($Fe_3O_4$) with a photothermal conversion effect [85]. Biomass raw materials are characterized by abundant functional groups surrounded by cellulose, (hemi)cellulose, and lignin. The employment of activators serves to open the structure of lignocellulose, resulting in the production of biochar with complex pores and a wealth of functional groups. These features create sites suitable for the attachment of groups, such as those imparting hydrophobic properties [85]. Biochar produced at high temperatures is typically black, non-reflective, and has certain optical absorption properties [86]. It absorbs optical energy and generates heat, providing a high absorption capacity across a broad range of wavelengths [87]. In the study by Liu *et al.*, reducing the oxygen-to-carbon ratio in the carbon material decreased the surface energy, and its synergistic effect with a rough structure contributed to the superhydrophobicity of the coating [85]. The absorption of optical energy and the generation of vibrational heat in $Fe_3O_4$ resulted in an increase in coating temperature to 55.9°C.

### 2.2.3 Plant oils, seeds, and nuts

Plant oils are one of the most important renewable resources for the chemical industry. Among them, epoxidized soybean oil, as one of the most common and cost-effective plant oils in the world, is widely used for producing epoxy bioresin [88,89]. Furfural, on the other hand, is one of the chemicals with the highest added value obtained from agricultural waste [89,90]. Lu *et al.* presented a method for converting soybean oil, furfural, cardanol (derived from cashew nut shells), and turpentine into multifunctional thermosetting materials with photothermal conversion properties [89]. Soybean epoxidized oil was first transformed into an epoxy resin epoxidized soybean oil methyl ester (ESOM). Furfural, cardanol, and 1,8-*p*-mentanediamine (CFMA) (derived from turpentine) were used to synthesize a new bio-based curing agent. A strongly conjugated π bond of furfural gave the materials excellent photoabsorption ability, the unsaturated hydrocarbon chain of C15 cardanol improved strength, and the unique rigidity and chemical stability of turpentine enhanced thermal stability and mechanical strength. In order to combine the unique properties of each biomass resource, a dual-curing reaction of ESOM and CFMA was carried out, resulting in intelligent thermosetting epoxy resins with a photothermal conversion efficiency of 45.0%. Importantly, the biomass content in the thermosetting material exceeded 89.0%, and its properties could be fine-tuned by adjusting the mass ratio of CFMA/ESOM or the curing time [89].

*Camellia oleifera* is an oil-bearing plant rich in oil and unsaturated fatty acids. Importantly, it is one of the four main oil trees in the world [91]. China is the world's largest producer of *Camellia oleifera*, and in 2019, produced 2.85 million tons of camellia seeds and 0.755 million tons of oil. Traditionally, the residual camellia seed cake was often discarded as waste or used as fertilizer. However, it is worth noting that they contain tea saponin (TS) rich in –OH and –COOH groups which is also easily extractable using simple water/alcohol extraction methods [92]. Yang *et al.* used TS as a carbon precursor to design a porous, high-efficiency catalyst for the cycloaddition of $CO_2$ with epoxides. The study found that carbonized TS inherits numerous –OH and –COOH groups, enabling it to drive the $CO_2$ cycloaddition reaction under mild conditions due to its strong Lewis acidity. Additionally, the yellow color of TS changed to black as a result of pyrolysis, suggesting an increased light absorption capacity and a corresponding potential photothermal effect. Researchers confirmed that TS could catalyze the coupling of $CO_2$ and epoxide under light irradiation (UV-Vis light with intensity of 350 m W $cm^{-2}$), showing similar catalytic ability compared to thermally driven catalysis (80°C, 0.1 MPa $CO_2$).

Another material worth attention is peanut shells, which contain numerous meso- and micropores. Although they are an excellent source of protein, fat, and fiber, they constitute agricultural waste and are usually discarded after consumption. However, peanut shell powder (PSP) has attracted attention as a low-cost, sustainable material. Carbonized PSP (CPS) exhibits excellent adsorption properties and can be used as an effective adsorbent of heavy metals and other pollutants in wastewater treatment [93]. Arunkumar *et al.* were the first to use peanut shells to prepare a photothermal evaporator for solar steam generation. In this work, waste peanut shells were carbonized to obtain CPS. The high temperatures caused decomposition of organic material, releasing volatiles, thereby producing biochar. PSP before additional treatment showed large pores, the diameters of which increased up to 25 μm after carbonization. The prepared CPS was then applied to polyvinyl alcohol sponge for solar evaporation purposes. After the system was hydrolyzed and cross-linked, a seawater desalination experiment was performed, which showed a stable evaporation rate with an efficiency of 90.4% after irradiation with 1 sun radiation [93].

### 2.2.4 Flowers

In relation to the topic at hand, another interesting plant is *Camellia japonica*. In Spain, approximately 2.5 million camellia bushes grow annually, most of which are ornamental *Camellia japonicas*, exported to all of Europe [94]. However, little effort has been made to characterize their properties so far [95]. Kim *et al.* prepared sulfur-doped carbon dots (S-CD) with strong NIR absorbance using *Camellia japonica* flowers as a carbon source [96]. Bioinspired carbon dots (CDs) represent a class of materials for PTT derived from natural resources, including various types of renewable biomass, such as plants. The plentiful availability of natural carbon sources in the environment enables the creation of CDs with excellent biocompatibility and biological functionalities using the "bottom-up" synthesis approach. CDs derived from diverse biomass sources with varying heteroatoms, including nitrogen, phosphorus, and sulfur, display distinct surface functionalities and optical characteristics. However, most CDs produced from biomass waste exhibit limited absorption in the NIR region. Therefore, Kim *et al.* used an easy hydrothermal carbonization method to obtain a material with enhanced photothermal conversion efficiency from easily available, natural *Camellia japonica* flowers [96]. The developed system was highly compatible, and an optimally low dose of S-CD ($45\,\mu g\,ml^{-1}$) effectively led to efficient PTT with a photothermal conversion efficiency of 55.4% at moderate laser power (808 nm, $1.1\,W\,cm^{-2}$). As a result, S-CD achieved excellent phototherapeutic efficacy with complete tumor ablation without damaging nearby healthy tissue [96].

### 2.2.5 Wood

Another plant-derived material known for its rapid water transport and excellent heat localization is wood. As a component of trees, it is recognized for its ability to transport water and other nutrients from the soil to the leaves through complex mesostructures, such as numerous vertically oriented microchannels and indentations [97,98]. Furthermore, it is one of the most common renewable biomass resources and has many advantages, such as low cost, nontoxicity, biodegradability, high mechanical strength, and good workability [99,100]. Considering the capillary effect and low thermal conductivity, wood is of particular interest for applications in solar steam generation. However, light-colored wood exhibits low solar light absorption, leading to low efficiency in this process. Chen *et al.* made efforts to improve the solar energy absorption of wood-based solar steam generation devices [45]. Scientists have developed a simple brushing method for creating devices made of wood impregnated with aluminum phosphate (Wood@AlP). The aluminum phosphate compound deposited on the wood surface acts as a Lewis acid catalyst, accelerating the formation of a carbon layer. It also creates a hierarchically porous structure, which is beneficial for broad solar light absorption and steam escape. Leveraging the natural properties of wood, the resulting Wood@AlP system can float on seawater and achieve high solar-thermal conversion efficiency, reaching 90.8%. The system solar light absorption capability was determined to be 98% [45].

Wang *et al.* fabricated a wood-derived, all-carbon conductive foam (ACCF) in a simple two-step process [46]. Scientists removed lignin and most of the hemicellulose from natural wood, then subjected it to carbonization in an argon atmosphere (Figure 3d). The resulting monolithic photoelectrothermal evaporator exhibited a high thermal conversion capability, with a light absorption capacity of over 94.5%. Furthermore, it reached a very high temperature of 145.2°C at an input voltage of 2 V in a dry state. The electrical conductivity of the system resulted from the rearrangement of carbon atoms and the formation of graphite carbon during the carbonization process. Its other advantages are the 3D cross-linked bimodal pores and micro-mesoporous structure. Furthermore, following the low-emission ecological concept, ACCF can degrade in the natural environment, providing nutrients to the soil without causing secondary water pollution [46].

## 2.3 Animal-derived materials

As we have explored the potential of plant-derived materials for photothermal applications, it is also important to consider the significant contributions of animal-derived materials in this field. This section covers the materials derived from animals, with noteworthy examples including eggshells and bones, manure, and silk fibroin (SF).

### 2.3.1 Eggshells and bones

Eggshells are common biologically derived municipal waste, consisting mainly of the hard shell (calcium carbonate) and the soft eggshell membrane (fibrous proteins). The eggshell membrane, being a natural semi-permeable membrane, has a uniform porous structure that promotes steam transport and heat localization [102]. Furthermore, the eggshell membrane is organic biomass and, after thermal treatment, can be transformed into a completely carbonaceous material, allowing for broadband light absorption while maintaining exceptional stability even when exposed to high-salt seawater and contaminated wastewater.

Han *et al.* proposed a bio-derived, free-standing ultrathin membrane from eggshell membrane waste as a solar-powered water purification with ultrahigh energy efficiency [103]. In this work, researchers used protein networks of eggshell membranes, rich in numerous functional groups, as frameworks to anchor graphene or carbon nanotubes. The eggshell membranes functionalized in this way were further carbonized, resulting in the formation of hybrid structures. Carbon-based materials, such as graphene, carbon nanotubes, or carbon nanofibers, are widely used as components of porous materials for solar steam generation due to their broad light absorption, good stability, and large surface area [104,105]. The scanning electron microscopy analysis confirmed that the carbonized eggshell membrane had a uniform porous microstructure. Functionalization with graphene resulted in a similar morphology but with a rougher surface, reduced pore size, and slightly increased thickness. The growth of carbon nanotubes on the porous structure of the eggshell membrane generated a hierarchical pore size distribution. Furthermore, the membrane exhibited >99% light absorption in the UV-Vis-NIR range. The designed biogeneration cycle combines household waste recycling, the utilization of renewable solar energy, and photothermal water purification, making it an environmentally friendly solution to a global problem [103]. However, functionalization complicates the entire process, adds additional costs, and involves the use of harmful chemicals.

Other noteworthy animal-derived materials include bones, which exhibit fundamental characteristics suitable for applications related to photothermal water evaporation. These characteristics include a highly porous, interconnected structure, structural integrity, and appropriate hydrophilicity.

It is worth noting that animal bones are among the most common types of organic waste. According to 2020 data, the global meat industry produces 130 billion kilograms of animal bones annually, with over 10% originating from the European Union [106]. Zafar *et al.* were the first to introduce an alternative based on bone waste for photothermal water purification [107]. Natural bone exhibits only an internal porous structure, and because the pores are filled with organic compounds and trapped water, it has a dense form [108]. After carbonization, a porous structure was revealed, consisting of a fibrous texture and strongly interconnected longitudinal and transverse microchannels. The carbonized bone also exhibited broad-spectrum light absorption, photothermal conversion, and reduced enthalpy of vaporization due to special interactions with water. Such performance, combined with wide availability, ease of production, and stability, makes this material another promising system for freshwater production. The effective utilization of bone waste in valuable photothermal devices addresses various issues in line with the United Nations' sustainable development goals. It significantly contributes to achieving the goal of "clean water for all" and presents an innovative and sustainable approach for food waste management [107].

### 2.3.2 Manure

The abundance of raw materials provides a desirable and efficient approach to convert agricultural waste into energy, making it particularly well-suited for developing regions. Tian *et al.* proposed a photothermal evaporator based on carbonized cattle manure with hierarchically bimodal pores [101,109]. Through the carbonization process of cellulose fibers in manure, this material proved to be an excellent photothermal material with a solar light absorption of 0.98. The photo responsiveness is attributed to the soot present in carbonized manure since carbon has a high extinction coefficient compared to the negligible extinction coefficient of cellulose. Furthermore, the porous carbon foam based on manure had a hierarchical structure consisting of microchannels with diameters ranging from 5 to 30 μm, divided by nano-sized channels. The nano-channels allowed the capture of sunlight through multiple reflections and scattering on the walls of carbon fibers forming the network. Conversely, the microstructure provided pathways for water transport and salt removal (Figure 3e). The system was highly hydrophilic and capable of rapidly absorbing water. Additionally, the porous structure of the carbonized manure resulted in low thermal conductivity even after water absorption and effectively localized heat in a small evaporation area, enabling solar interfacial evaporation [101,109]. However, it seems that the nano-channels are not adapted for salt rejection, and the micro-sized channels could potentially reduce the heat localization ability. Therefore, balancing the quantity of nano- and micro-channels is crucial for the system to function as efficiently as possible.

### 2.3.3 SF

Another noteworthy animal-derived material is SF – a natural protein. Due to its softness, excellent biocompatibility, minimal inflammatory response, remarkable mechanical strength, and controlled biodegradation, SF exhibits promising properties in biomedical applications. Meanwhile, SF hydrogels have the ability to stabilize drugs. He *et al.* developed an injectable hybrid hydrogel system composed of SF nanofibers and upconversion NPs ($NaLuF_4$:$Er^{3+}$, $Yb^{3+}$) complexed with a nano-graphene oxide composite (SF/UCNP@NGO) for upconversion luminescence imaging and PTT [110]. They directly obtained SF from raw *Bombyx mori* cocoons and functionalized it with graphene oxide, which allowed the absorption of NIR radiation and consequent conversion into heat energy, thereby imparting photothermal properties to the system.

In another study, Xu and co-workers constructed a therapeutic nanoplatform based on SF for PTT of glioblastoma multiforme [111]. SF was first extracted from the cocoons of *Bombyx mori* silkworms, and then SF nanoparticles (SFNPs) were prepared for indocyanine green (ICG) staining. SF has a strong affinity for many dyes because the side chains of its amino acid residues can interact with pigments. The therapeutic nanoplatform ICG-SFNPs had a spherical morphology and a negative zeta potential, showing good stability in a physiological environment. ICG-SFNPs exhibited a more stable photothermal effect than free ICG after exposure to NIR radiation, effectively accumulated at the site of mouse tumors after intravenous injection, and showed strong red ICG fluorescence in the cytoplasm. Most importantly, the temperature at the tumor site quickly increased, leading to the death of cancer cells after local irradiation [111].

Yan *et al.* took a different approach to give SF photothermal properties [112]. Researchers developed a strategy to impart unique physical and chemical properties to silk textiles by feeding silkworms with functional nanomaterials. They synthesized reduced graphene oxide/bismuth sulfide nanocomposites, which were then sprayed onto fresh mulberry leaves and fed to the silkworms as food. The resulting silk textile could quickly and effectively convert light energy into thermal energy. Indeed, this technology has the potential to maximize the function of clothing, such as cold insulation, by retaining heat through photothermal effects when certain key parameters like photothermal conversion efficiency, excitation wavelength range, and the number of loaded nanocomposites are improved to an appropriate level [112].

### 2.3.4 Ethics and sustainability in animal-derived materials

Despite its enormous potential, the use of animal-derived materials in various applications brings some ethical and sustainability concerns. From an ethical point of view, animal welfare and the environmental impact of extracting and processing materials must be taken into account. For instance, manure often comes from farms, which may be related to animal welfare issues and the ethics of intensive farming practices. Similarly, the collection of eggshells and bones usually comes after the consumption of poultry and meat, which raises ethical debates about animal slaughter and farming conditions. SF extraction is a process traditionally involving the killing of silkworms, thus posing ethical dilemmas regarding cruelty toward animals. To address these concerns, it is crucial to implement humane and sustainable practices, such as sourcing materials from farms with high standards or using alternative methods that do not harm animals.

Sustainability is another important aspect of the use of animal-derived materials. For example, manure is a valuable resource improving soil health and reducing the need for chemical fertilizers. However, the environmental sustainability of manure depends on managing it in a way that prevents pollution and greenhouse gas emissions. Eggshells and bones, rich in calcium and phosphorus, can be recycled into fertilizers or used to produce biocomposites, thus minimizing waste. SF, which is biocompatible and possess good mechanical properties, finds applications in biomedical fields and sustainable textiles. However, the production of these materials must ensure minimal impact on the environment, *e.g.*, by implementing sustainable agricultural practices and reducing energy consumption during processing. In summary, addressing ethical issues and ensuring sustainability can lead to more responsible and environmentally friendly uses of animal-derived materials across industries.

# 3 Photothermal properties of the organic waste-derived and bioderived materials

With a comprehensive understanding of the various types of organic waste-derived and bioderived materials, this section investigates their photothermal properties and how these properties are influenced by their structural and chemical characteristics. This section will provide an overview of the composition and optical properties of photothermal materials produced from biological sources. Specifically, we will explore photothermal organic waste-derived and bioderived materials characterized by their origin from organic waste or biological sources and their intrinsic or process-enhanced ability to convert light into heat.

## 3.1 Underlying principles and mechanisms and factors contributing to photothermal behavior

Photothermal-based materials are stimuli-responsive materials that efficiently interact with light, leading to heat generation under a suitable electromagnetic excitation [113]. The capability to generate photothermal heating is crucial in different research fields, including physics, chemistry, biology, and medicine. Understanding the underlying principles, mechanisms, and factors contributing to the photothermal properties of tailored materials is essential for harnessing this phenomenon for diverse applications. The main aspects that regulate the capabilities of specific materials to convert light to heat are absorption of light, energy conversion, transfer and relaxation, and thermal diffusion. Photothermal conversion begins when the material absorbs external radiation. Indeed, when photons from the incident light interact with the material structure, they can be absorbed by the outer electrons displaced in the material atoms. Consequently, converting the light into a heating process starts because the absorbed energy is subject to various mechanisms, such as electronic transitions and vibrational excitations, that affect the light-to-heat conversion, depending on the specific material properties. Once the absorbed energy is stored in the material's atomic structure, the energy is transferred by exploiting different modes, such as the redistribution of energy among the electrons and phonons. Consequently, the generated heat increases in the material structure with a subsequent thermal diffusion that spreads the heat from the local site to the surrounding regions. It is worth pointing out that several physical mechanisms can efficiently contribute to the photothermal properties of specific photo-converter materials. In some materials, light absorption creates electronic transitions that form electron–hole pairs. The consequent recombination of these pairs could release energy in the form of heat (this is called an electronic mechanism). In other materials, light absorption causes vibrational excitations (phonons) that produce heat as they dissipate (the vibrational mechanism). Other materials, such as plasmonic NPs (*e.g.*, gold and silver), exhibit enhanced absorption due to their localized plasmonic resonance phenomenon, oscillating the bulk-free electrons at the metallic/dielectric interface. This physical phenomenon produces a very high light-to-heat conversion, possibly achieving nanomaterials with almost a 100% photothermal efficiency. Several factors influence the photothermal behavior of specific materials, such as (1) material properties: the absorption coefficient, the electronic structure, and the thermal conductivity can predominantly affect the photothermal behavior; (2) wavelength of the impinging electromagnetic radiation: materials possess different absorption properties at different wavelengths; (3) size and shape: there are nanostructured particles made of specific materials (gold, silver, copper) with particular dimensions (10–40 nm) and shapes (rod, prisms, triangles) that exhibit enhanced absorption due to resonance effects; and (4) dielectric constant: the optical and thermal properties of the medium surrounding the materials play a crucial role in the photothermal heating generation, confinement, and propagation. It is essential to point out that environmental conditions can dramatically affect the photothermal capabilities of several materials. Indeed, factors like temperature, pressure, humidity, pH and ionic strength, oxygen and reactive species, surface coating, and functionalization can influence the light absorption, heat dissipation, and the final efficiency of the photothermal conversion process.

## 3.2 Intrinsically photothermal organic waste-derived and bioderived materials

As mentioned earlier, some organic waste-derived and bioderived materials possess the photothermal property as an intrinsic characteristic. The presence of specific components like lignin, melanin, or melanoidins often coincides with the emergence of the photothermal capability of these materials. This suggests a mechanistic link between the unique molecular structures of those components and the ability to efficiently convert light energy into heat. The following subsections will focus on the photothermal properties of organic waste-derived and bioderived materials.

### 3.2.1 Lignin and melanin

Lignin is an extraordinary example of intrinsically photothermal material. It is a biomass-derived organic polymer that has recently received much attention as a sustainable material for photothermal applications. It is one of the most abundant biomasses on the earth. It is primarily found in the cells' walls of vascular plants. The molecular structure of lignin includes numerous aromatic rings and conjugated functional groups. This structure enables strong conjugation and π–π interactions among lignin molecules, allowing robust sunlight absorption across the solar spectrum [31,114]. The mechanism of the photothermal effect in these structures can be traced back to π-bonded molecular orbitals and π anti-bonded molecular orbitals. Upon absorbing light energy, the π electrons on the bonded molecular orbitals transition to the π anti-bonding molecular orbitals, entering an excited state. Subsequently, the electrons release part of their energy in the form of heat, returning to the ground state and generating a photothermal effect. Consequently, lignin exhibits distinctive optical properties and considerable potential for sustainable photothermal conversion. For instance, Wen *et al.* synthesized lignin-based carbon nanospheres (average diameter 100 nm) with a photothermal efficiency of 83.8%, measured under 808 nm laser light irradiation [115]. Additionally, Gu *et al.* achieved a photothermal conversion efficiency of 91.7% under solar light irradiation by introducing lignin in a wood-based evaporator material [116].

Natural melanin, a set of dark polymeric pigments, is found in many living organisms, including plants, animals, fungi, and bacteria. Eumelanin and pheomelanin are found in humans and other mammals, allomelanin is found in plants, while fungi and bacteria exhibit neuromelanin and pyomelanin. Melanin's broad optical absorption and efficient non-radiative decay give it intrinsic photothermal properties. Melanin's complex chemical structure, composed of disordered indolic and phenolic units, enables it to absorb a wide range of wavelengths across the UV-Vis-NIR spectrum [117,118]. This broadband absorption provides a basis for melanin's ability to harness light energy across multiple therapeutic wavelengths. Indeed, the primary function of eumelanin is to provide photoprotection from UV radiation to deeper layers of the skin. Upon light absorption, the excited electrons within melanin rapidly relax back to their ground state. Crucially, this relaxation process occurs primarily through non-radiative pathways, where the absorbed energy is dissipated as heat rather than re-emitted as light (fluorescence) [119]. This inefficient fluorescence, combined with the broad absorption, results in highly effective photon-to-heat conversion. Due to its spectroscopic properties, melanin is widely applied in photothermal solar-energy conversion and PTT. Although the isolation of melanin from natural sources is a complex process, it also needs the use of harmful reactants or time-consuming enzyme digestion [26].

### 3.2.2 Melanin-like materials (MLM)

MLM, such as MNPs, are obtained by extraction procedures of natural melanin from cuttlefish's ink sac. An example of MLM are melanoidins, the Maillard-reaction products naturally occurring during food cooking. They can also be produced during thermal pretreatment of organic solid waste or sewage sludges, but their recovery and purification are still under investigation [120]. They are known for their characteristic brown pigmentation and exhibit a broad absorption spectrum extending from UV to NIR wavelengths [121]. This optical property signifies their potential for applications harnessing light-based therapies. Studies on melanoidins derived from diverse sources, including coffee, beer, and sweet wine, reveal that molecular weight influences their absorption characteristics [122]. Higher molecular weight melanoidins demonstrate enhanced light absorption and, consequently, stronger photoacoustic signals. The presence of aromatic rings within melanoidin structures suggests that a conjugation effect underpins their photothermal mechanism [123]. Upon light exposure, electrons within these aromatic systems transition to an excited $\pi^*$ orbital. As these excited electrons relax back to the ground state, a portion of the absorbed energy dissipates as heat. This non-radiative relaxation pathway contributes to the photothermal conversion property of melanoidins, making them intriguing candidates for photothermal applications. Also, MNPs can be regarded as an interesting bio-derived material for photothermal applications. Indeed, some studies demonstrate that MNPs can exhibit a photothermal conversion efficiency in the range from 29 to 49%, under NIR laser irradiation thus making MPS appealing for PTT applications [124,125].

## 3.3 Process-enhanced photothermal organic waste-derived and bioderived materials

Pyrolysis and calcination are two of the most employed strategies to convert natural feedstock into new functional materials [30]. The starting material is decomposed by a thermochemical process performed in an inert atmosphere (pyrolysis) or in air (calcination) under high temperatures. The resulting biochar can be surface-modified by acid or base treatment, chloride functionalized, loaded with functional modifiers, or doped. The surface area, crystallinity, and aggregation of biochar are also strongly influenced by the processing conditions. Carbon-based materials, such as graphite, carbon nanotubes, graphene, fullerene, and carbon black, are efficient photothermal materials that are able to convert the light of the whole solar spectrum into thermal energy [126]. Porous nanostructured carbon-based materials can reduce the reflection of the light, in addition to being almost insensitive to the incidence angle, and have been successfully employed as valuable materials for steam generation. Further examples, based on natural materials, can be carbonized wood, mushrooms, and many vegetables, displaying high light absorption due to the multi-scattering reflection of light in their microcavities and channels [127]. Moreover, carbonaceous derivatives of plant-derived nanospheres, CDs, hollow particles, and fibrillar structures have been used for their high surface area and the possibility of being coated over different materials when suspended in organic solutions.

Wood-based materials, with their low density, open microchannels, capillary-induced hydrophilicity, and high thermal insulation, have recently gained attention for ISSG systems. ISSG systems use photothermal materials, which are materials that convert light into heat, to harness solar energy for water evaporation. These systems are designed to float on water and heat the surface, causing the water to evaporate more efficiently. The most employed strategy to enhance the photothermal activity of wood materials in ISSG systems is bulk or surface carbonization, which transforms the natural material into a black body that captures photons.

In this context, carbonized sugarcane was dried and pyrolyzed up to 700°C inside a tube furnace under nitrogen ($N_2$) and used as the top layer in an ISSG made by expanded polyethylene and fiber paper [128]. Similarly, the torrefaction (a mild form of pyrolysis performed from 200 to 320°C under an inert gas) of bamboo slices gave them an improved light absorption ability in the full solar spectrum (94.7% under one sun illumination) and a high water-transport capacity, thanks to the presence of vascular microchannels in their structure [129]. In another study, surface-carbonization was applied to the defoliated bamboo stems, and the product was used as an efficient biobased material for solar steam generation since the structure of bamboo already contains all the elements of a solar evaporator [130]. Indeed, its microstructure shows many vertical channels particularly efficient for transporting water, with a hollow core in its internals, which is an ideal air chamber for thermal insulation, while the external surface notably increases the absorption of the solar spectrum after carbonization (from 40 to 97%). A robust and natural-based sponge evaporator has been proposed using chitosan as an excellent and biocompatible hydrophilic material, carbonized pomelo peels particles as light-absorbing layer, and bamboo fibers acting as the tough matrix to support the device [131]. Owing to the bridged structure of bamboo fibers interspersed in chitosan lamellae and the high photothermal activity of carbonized pomelo peels, the composite solar sponge showed an evaporation rate up to $2.32\,\mathrm{kg\,m^{-2}\,h^{-1}}$ with a conversion efficiency of 89.23% under one sun illumination and the obtained results were almost insensitive to harsh water conditions. Other bioderived materials can also effectively acquire photothermal properties. Cattails from Typhaceae plants at different lengths and diameters were carbonized under an inert atmosphere using an increasing temperature profile (from 100 to 800°C) in a tube furnace [132]. Carbonized cattails have been fixed using expanded polystyrene foam and put into an evaporation chamber floating on the water surface. Shiitake mushrooms were also carbonized by a simple thermal treatment (500°C under argon for 12 h) and placed on a polystyrene foam [133].

Camphor nanospheres were recently obtained by calcination of *Cinnamomum camphora* extract pellets [134]. The obtained black soot was dissolved in ethanol, and the solution was deposited on polyvinyl alcohol sponge disks. Carbonized natural materials have also been widely applied in photothermal energy conversion for cancer therapy. For example, okara, a product of tofu preparation, has been calcined to form spherically shaped hollow particles with an average diameter of 200 nm, which have shown high biocompatibility and ability to act as photothermal converters for the NIR-triggered cancer treatment [135]. S-CDs, obtained by hydrothermal carbonization of *Camellia japonica* flowers, have killed cancer cells without damaging nearby healthy tissues after 5 min of NIR laser irradiation [96].

Researchers have recently subjected natural materials to surface (or bulk) chemical modifications in order to improve their intrinsic properties. The treatment of wood with tannic acid (TA) followed by a second treatment in the presence of a ferric sulfate solution gives it excellent photothermal properties, achieving 90% photothermal conversion under one sun illumination and improving water evaporation rate from 1.34 to 1.85 kg $m^{-2}$ $h^{-1}$ [30]. Similarly, coconut husks were first immersed into a solution of TA for 8 h at room temperature and then in a solution of ferric chloride for 2 h, washed, and freeze-dried. The obtained photothermal material showed fast water transportation in capillaries, large water-storage capability, and an evaporation rate 4.15 times higher than bulk seawater [136]. Hydrogen can be produced in a clean and green way by the dry reforming of methane (DRM). The $SiO_2$, extracted from bagasse and subjected to surface modification by KOH activation, has been recently employed as a support for a Ni catalyst for the DRM process. Thanks to the interaction of the catalyst with UV light to generate hydrogen, the temperature of the process could be lowered to 300°C instead of 700°C usually reached to obtain satisfactory yields [137]. Wind turbine blades have been treated with a super-hydrophobic layer with a photothermal effect based on biochar obtained from corncob carbonization. The biochar was loaded with $Fe_3O_4$, added to a solution of polydimethylsiloxane (PDMS) in *n*-hexane and spray-coated on the surface of the turbine blades, showing a high deicing performance under the sun illumination [85]. Similarly, Wang *et al.* developed an anti-icing surface treatment based on commercially available biochar and plasmonic TiN NPs, which were added into a fluorinated triethoxysilane solution [138]. The treated glass-fiber-reinforced plastic of the turbine blades showed a significant reduction in the icing mass.

Aluminophosphate-treated wood (W@AlP) can be easily obtained by means of facile, cost-effective, and scalable surface treatment [45]. AlP, prepared by reacting $Al(OH)_3$ powder with an aqueous solution of phosphoric acid ($H_3PO_4$), was brushed on the top surfaces of wood blocks, and the obtained samples were then heated at 130°C for 30 min. A black surface was obtained where the wood was treated due to the easy carbonization promoted by the Lewis acid catalyst, giving a hierarchical porous structure particularly suitable for broad solar spectrum absorption and water escape. Treated woods can float on seawater and exhibit a solar thermal efficiency of 90.8% with an evaporation rate of 1.423 kg $m^{-2}$ $h^{-1}$ under one sun illumination.

Loofahs, the fibrous skeletons of loofah fruit, are mainly composed of hydrophilic cellulose and show good mechanical properties and hydrophilicity. Zhang *et al.* recently proposed a carbon nanofiber decorated carbonized loofah (CL) steam generator supported on hydrophobic polyethylene-vinyl acetate foam as a thermal insulator [139]. CL sheets were first treated with a dopamine solution and heated up to 800°C in a nitrogen atmosphere for 2 h. PDA-coated CL was treated with an aqueous solution of nickel nitrate ($Ni(NO_3)_2$) for 24 h. Sheets were then calcined, obtaining the vapor deposition of carbon nanofibers over the whole surface. The proposed CL/carbon nanofiber layer gave a sewage water evaporation rate of 1.65 kg $m^{-2}$ $h^{-1}$ under illumination when used in an ISSG experimental device. Loofahs decorated with titanium carbide MXene nanocrystals have also been profitably employed in an evaporator for solar steam water desalination. The device showed high stability under sunlight, prevented salt deposition, and reached an evaporation rate of 1.57 kg $m^{-2}$ $h^{-1}$ under one sun illumination, with a thermal conversion efficiency of 95.5% [140].

## 3.4 Advantages of materials with “intrinsic” photothermal properties

The exploration of organic waste-derived and bioderived materials with intrinsic photothermal properties presents a promising avenue in the development of sustainable photothermal applications. These materials, by virtue of their natural composition, offer several benefits that reduce the need for extensive post-processing, which is often resource-intensive and environmentally taxing [31,33,35,40].

First, the intrinsic photothermal characteristics of these materials eliminate the necessity for additional chemical modifications or coatings that are typically required to enhance the photothermal response in synthetic materials [31,35]. This not only simplifies the production process but also minimizes the use of potentially hazardous chemicals, aligning with the principles of green chemistry. Second, materials with natural photothermal properties often exhibit a broad absorption spectrum, enabling efficient light-to-heat conversion across a wide range of wavelengths [33,35,41,141]. This broad-spectrum responsiveness is particularly advantageous in applications such as solar steam generation and PTT, where the utilization of the full spectrum of solar radiation or the flexibility in choosing an irradiation source can significantly improve performance. Finally, the integration of intrinsically photothermal bioderived materials with non-photothermal organic waste-derived counterparts yields a synergistic effect that significantly enhances the overall performance of photothermal applications [35,42,141]. This combination leverages the unique properties of each material, bringing together the best of both worlds to create a more efficient and sustainable solution.

For instance, natural melanin, found in abundance in squid ink and cuttlefish ink, exhibits intrinsic photothermal properties [142]. When used in conjunction with non-photothermal materials such as starch or chitosan in hydrogel form, they constitute a composite that not only retains the excellent photothermal properties of melanin but also benefits from the structural advantages of bioderived materials [35,141]. Starch and chitosan hydrogels provide a supportive matrix that facilitates water transport and retention, crucial for applications like solar steam generation. Therefore, cuttlefish ink-based solar absorbers use the natural pigments found in cuttlefish ink, such as melanin, to enhance light absorption. As mentioned, melanin is known for its broad-spectrum light absorption properties, which make it an effective material for converting solar energy into heat. Another compelling example of utilizing intrinsic photothermal properties is found in plants containing lignin [31,114,143]. Lignin, a complex organic polymer, forms a significant part of the cell walls in vascular plants, making it one of the most abundant biomasses on Earth. Its molecular structure is characterized by strong $\pi-\pi$ stacking interactions, which not only facilitate self-assembly but also enhance photothermal conversion [144]. This unique feature of lignin allows it to act as a natural photothermal agent within the plant matrix. Separately, the integration of PDA and wood offers a unique approach inspired by natural processes [42]. PDA, known for its broad light absorption across the UV, Vis, and NIR regions, enhances the photothermal properties of the materials it coats [145,146]. By applying a PDA coating to wood, a natural superhydrophilic scaffold, the efficiency of solar evaporation systems can be significantly improved [42]. Mimicking the transpiration mechanism in plants, where water is translocated from roots to leaves, coated wood can float and create a thin water layer on its surface, making it an ideal candidate for such applications. SCGs present another case. They intrinsically contain melanoidins, which are responsible for their photothermal properties [123,147]. These high-molecular-weight polymers, formed during the roasting process of coffee beans, exhibit significant light absorption capabilities. Given their powdery nature, SCGs should ideally be embedded in a structurally stable platform for practical applications [40]. However, the development of such platforms from organic waste-derived or bioderived materials has not been widely explored, indicating a promising area for future research.

These examples highlight the potential of combining intrinsically photothermal materials with those that are not, where each component brings distinct advantages to the table. It enhances the photothermal performance and simplifies the manufacturing process. Moreover, the use of such composites in photothermal applications serves as a model for circular economy practices. By valorizing waste products and utilizing renewable bio-resources, these materials minimize environmental impact and offer a pathway to resource recovery and waste reduction.

## 4 Applications of the photothermal organic waste-derived and bioderived materials

This section showcases the potential of photothermal organic waste-derived and bioderived materials across diverse applications. From water technologies aided with photothermal platforms to medical treatments, deicing strategies, and far-reaching environmental remediation solutions, these sustainable materials show alternatives to conventional approaches.

### 4.1 Solar-driven water technologies

Solar-driven water technology provides a promising avenue in freshwater production, which depends on light-to-thermal conversion and distillation processes [148,149]. Additionally, the solar-driven water evaporation process is accompanied by mineral production [150], power generation [151], seawater desalination [152], and other applications [153,154]. Currently, the research on solar-driven water technologies depending on light-thermal conversion behavior mainly focuses on photothermal material development and optimal structural design [155]. Photothermal materials are regarded as ideal materials for water treatment due to their broad solar absorption and high conversion efficiency [156]. To date, a variety of unique topologies and structures have been developed to endow solar evaporators with outstanding light harvesting, water absorption, and photothermal conversion capabilities [157]. However, it still faces challenges in developing eco-friendly and cost-effective materials. In recent years, bioderived and organic waste-derived materials, as inexhaustible renewable energy sources, have attracted extensive attention because of their low cost and environmental friendliness [27]. This section reviews the development of green photothermal materials and their applications in seawater desalination, water purification, and energy production.

The mechanism of water storage and evaporation in solar-driven water technologies involves several key processes [158,159]. First, water absorption and storage play a crucial role. Natural materials, particularly those derived from plants, often possess intrinsic capillary channels and vertically oriented porous structures designed for transpiration. These structures facilitate efficient water absorption and storage, as the water is absorbed through capillary action into the microchannels and pores. The hierarchical porous structure, from macro to micro scale, ensures a continuous supply of water to the evaporation surface. Solar absorption and photothermal conversion are the next critical steps. The photothermal material, often carbonized or modified to enhance solar absorption, captures sunlight across a broad spectrum, converting absorbed light into thermal energy, which significantly increases the temperature of the material. This heat is then localized on the surface of the photothermal material, where it heats the absorbed water. Due to the low thermal conductivity of these materials, heat is effectively confined to the evaporation zone, minimizing thermal losses. The localized heating increases the temperature of the water, causing it to evaporate. Finally, the produced water vapor rises and is subsequently collected and condensed into clean water. This process is facilitated by the porous structure of the material, allowing efficient vapor transport. In practical applications, the condensed vapor is collected using condensation systems designed to maximize the yield of purified water.

A wide variety of plant fruits have been used as starting materials for the production of solar evaporation devices. The carbonization approach provides a simple and robust route to improve the photothermal conversion capacity while maintaining the distinctive natural structures of plant fruits [160]. The natural materials with intricate architecture [161], possessing large specific surface areas and multilevel pores, are beneficial for solar absorbers. As an example, a solar evaporator with a 3D photothermal structure was fabricated *via* carbonization of durian skin at 700°C, which exhibited a macro-scaled 3D pyramid and micro-scaled porous petal-like architecture [162]. Benefiting from the multiple reflections and scattering on the unique hierarchical structure, carbonized durian skin exhibited better light trapping (99%). Beyond that, the outstanding capillary effect of the internal porous microchannels ensured adequate water transportation for evaporation. Subsequently, an evaporation rate of $2.22\ \mathrm{kg\ m^{-2}\ h^{-1}}$ with 93.9% energy efficiency was achieved upon one sunlight illumination. Furthermore, a carbonized durian-based outdoor device was built to demonstrate the practical application, and it was found that the daily collected purified water was able to meet the needs of more than 26 adults. Pomelo peel, a waste from pomelo, is lightweight with an interconnected foam-like structure and rich microscale pores. Inspired by the fractal structure in nature, Geng *et al.* developed fractal carbonized pomelo peel (FCPP) *via* direct graphitization followed by modification with macroscopic hole patterns by punching method and nanoscopic porosity by surface deposition of PPy nanowires [163]. The intricate fractal structure with macroscaled hole patterns and microscaled interconnected porous structure originated from the pomelo peel, and the nanoscaled porosity from the nanowire cluster benefited solar utilization significantly. As a result, the FCPP systems with 98% solar spectrum absorption were obtained. The evaporation rate and solar thermal conversion efficiency were $1.95\ \mathrm{kg\ m^{-2}\ h^{-1}}$ and 92.4%, respectively, showing a potential for seawater desalination. Furthermore, to meet the synchronous demands of fresh water and electricity, the discarded pomelo peel was converted into 3D porous carbon foams through freeze-drying and carbonization [164]. Owing to the superhydrophilic multichannel waterways, the carbonized pomelo peels showed a powerful water supply ability to avoid salt deposition. Then, the carbonized pomelo peel with solar-driven evaporation capability was integrated with a commercial thermoelectric generator. It was found that the as-prepared device could generate steam ($1.39\ \mathrm{kg\ m^{-2}\ h^{-1}}$) as well as electricity ($0.5\ \mathrm{Wm^{-2}}$) under one sun irradiation. Alternatively, chemical treatment provides another simple approach for developing photothermal materials. For example, the coconut husk-based photothermal materials was fabricated by immersion of coconut husk into a solution containing TA and $Fe^{3+}$ [136]. The structural feature in combination with surface chemical composition decreased water enthalpy, leading to enhanced evaporation efficiency. The seawater evaporation rate of the resulting system reached 1.83 kg $m^{-2}$ $h^{-1}$. Another study reported a scale-producible SCGs-based photothermal material with the aid of *in situ* polymerization of PPy NPs on the delignified SCGs (PPy@D-SCG) [165]. The modification of PPy NPs on the porous D-SCG enhanced the light absorption sites and water evaporation area. A 3 kg of photothermal PPy@D-SCG was fabricated, demonstrating the scale-up production capacity. The PPy@D-SCG displayed a water evaporation performance under one sun illumination with a rate of 1.54 kg $m^{-2}$ $h^{-1}$. Moreover, a 3D solar evaporator was developed by 3D printing of polylactic acid and PPy@D-SCG composite, enabling the removal of organic dyes and heavy metal ions from wastewater to produce fresh water.

Vegetable-originated materials with exquisite structures have been widely applied in solar absorption systems. Since the porous structure is of importance for water transportation and thermal management, loofah, a sponge-like plant with hierarchical macroporous and microchannel structures, has been a favorable choice. Lu *et al.* proposed a Janus solar evaporator consisting of an alkalized and CL sponge, serving as a porous supporter and light absorber, respectively [166]. The Janus structure combining the solar evaporation and surface biosorption property imparted the photothermal evaporator with freshwater generation and heavy-metal ion recycling capacity. Accordingly, evaporation (1.36 kg $m^{-2}$ $h^{-1}$) and energy conversion performance (83.7%) were obtained at one sun illumination, along with self-desalting capability. In another work, a multi-layered evaporator composed of loofah and MXene nanosheets was prepared [140]. The upper hydrophobic loofah with fluorinated alkyl silane and MXene coating enhanced the light absorption performance. Meanwhile, the bottom superhydrophilic loofah with large holes and microchannels enabled the pumping of water to the top layer and prevented salt accumulation. The loofah/MXene-based evaporator exhibited not only a high evaporation rate and solar-thermal conversion efficiency but also superior self-desalination capability.

A wood-based evaporator provides a feasible strategy owing to the aligned hierarchical porous structure, excellent mechanical stability, and low thermal conductivity [167]. In order to improve the evaporation rate and interfacial binding strength, Sheng *et al.* proposed an *in situ* synthesis method to assemble coordination polymers of Ni-dithiooxamidato (Ni-DTA) to the balsawood [168]. The Ni-DTA with both nanofiber and NP morphologies was grown on the wood walls, and 1D-nanofibers and 0D-NPs were formed by controlling methanol and dimethylformamide ratios (Figure 4a). The introduction of Ni-DTA with powerful hydration capacity to vertical channels of wood facilitated water supply and salt exchange. Notably, the presence of Ni-DTA was able to decrease evaporation enthalpy, leading to a higher water evaporation rate (2.75 kg $m^{-2}$ $h^{-1}$). Furthermore, the mechanism of reduced evaporation enthalpy was demonstrated by molecular dynamics simulations (Figure 4b). The molecular dynamics models of wood and wood-NiDTA evaporators were established to assess H-bonding density during the evaporation process. The escaped water molecules from the wood–NiDTA–water system are much larger than those from the wood–water system at 288 ps. The reason could be that the strong molecule interaction originating from Ni-DTA and $H_2O$ reduces the H-bonding density between water molecules, thereby decreasing the vaporization enthalpy of the adjacent water molecules along with increased evaporation rate. As another example, copper-based MOF (Cu-CAT), which is an electronically conductive material with broadband light absorption capability, was integrated with the wood sheets for the preparation of the solar evaporator [169]. Unlike the conventional bi-layered structure, the Cu-CAT was *in situ* grown on the top and bottom sides of wood sheets without any binder. The upper and bottom Cu-CAT layers provided light adsorption and anti-oil-fouling performances, respectively. Benefiting from the Cu-CAT coating, the evaporator could produce drinkable water from a variety of contaminated waters. Importantly, electricity could be generated along with the solar vaporization process.

The plant stems, which transport water from the ground to the leaves, possess a large amount of cellulose and a connected porous structure [170]. The luffa vine-based evaporator is an innovative example of using natural materials for efficient solar water evaporation. Figure 5a displays the internal porous structure of the natural luffa vine, highlighting its xylem vessels and piths, which are crucial for water transport. Figure 5b presents a schematic that illustrates the water and salt exchange process during solar water evaporation. Mentioned solar evaporator have been fabricated using surface carbonization followed by KOH-freeze-drying [171]. The lucerne vine possesses vascular bundles with multiple large vessels inside, and abundant pits exist on the wall of vertical hollow vessels. The small-diameter vessels, high capillary pressure difference, and abundant pits on the cell walls contributed to rapid and excellent water absorption and transfer performances (Figure 5a). The water vapor generation rate reached 3.26 kg $m^{-2}$ $h^{-1}$, and the evaporation efficiency was 118%. Furthermore, a

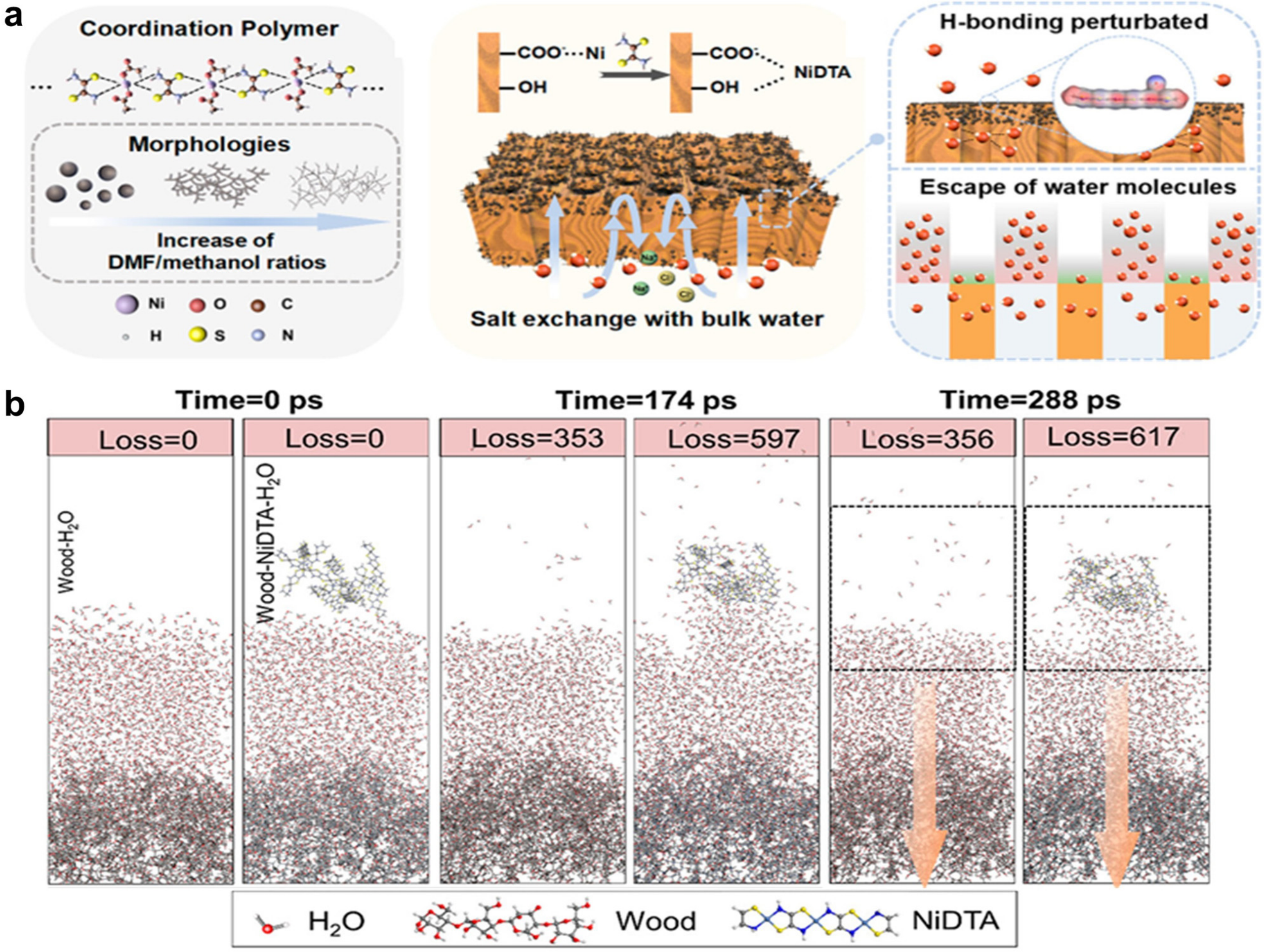

**Figure 4:** Wood-based evaporator. (a) Schematic illustration of morphological structures of Ni-DTA on the wood channels, as well as improved salt exchange and accelerated water evaporation attributed to the presence of Ni-DTA. (b) Molecular dynamics simulation of wood–water and wood–NiDTA–water evaporators at different times. Reproduced with permission from Sheng *et al.* [168], Copyright 2023, American Chemical Society.

spontaneous salt backflowing system was formed owing to the hierarchical architecture consisting of vessels and pits of different sizes (Figure 5b). During solar evaporation, a salt concentration gradient was formed in the lucerne vine evaporators since a larger salt concentration was reached in cell channels than in vessel channels. Furthermore, an enhanced salt concentration gradient was achieved in the upper layer of the vessels with quick evaporation of the surface water. Next benefitting from capillary pressure, the seawater continues to flow upward in the cell channels, accelerating the salt backflow process from the vessels into the water body. The salt backflowing behavior could reduce the surface salt crystallization and increase the lifespan. This setup demonstrates how the natural architecture of the luffa vine can be leveraged to enhance water evaporation rates while simultaneously managing salt accumulation.

Sunflower stalk (SS) consists of pith, vascular, and dermal tissue, which guarantee storage, transport, and protection of internal tissues, respectively. The effect of storage issue stem pith on evaporation behavior was investigated by Feng *et al.* [172] In their work, carbonized sunflower stalk (CSS), centerless carbonized sunflower stalk (C-CSS) with partial removal of piths inside the stalk, and hollow carbonized unflower stalk (H-CSS) with full removal of piths were prepared. Attributed to the water storage function of carbonized stem pith, the CSS showed a better water evaporation rate under one solar irradiation, which was 1.82-fold and 1.34-fold higher than those of C-CSS and H-CSS, respectively. In addition, the influence of carbonization temperature and height on the evaporation capability was studied. With a high energy conversion efficiency of 344.69%, the optimized CSS exhibited a water evaporation rate of 11.62 kg $m^{-2}$ $h^{-1}$ at one solar irradiation. The corn straw was

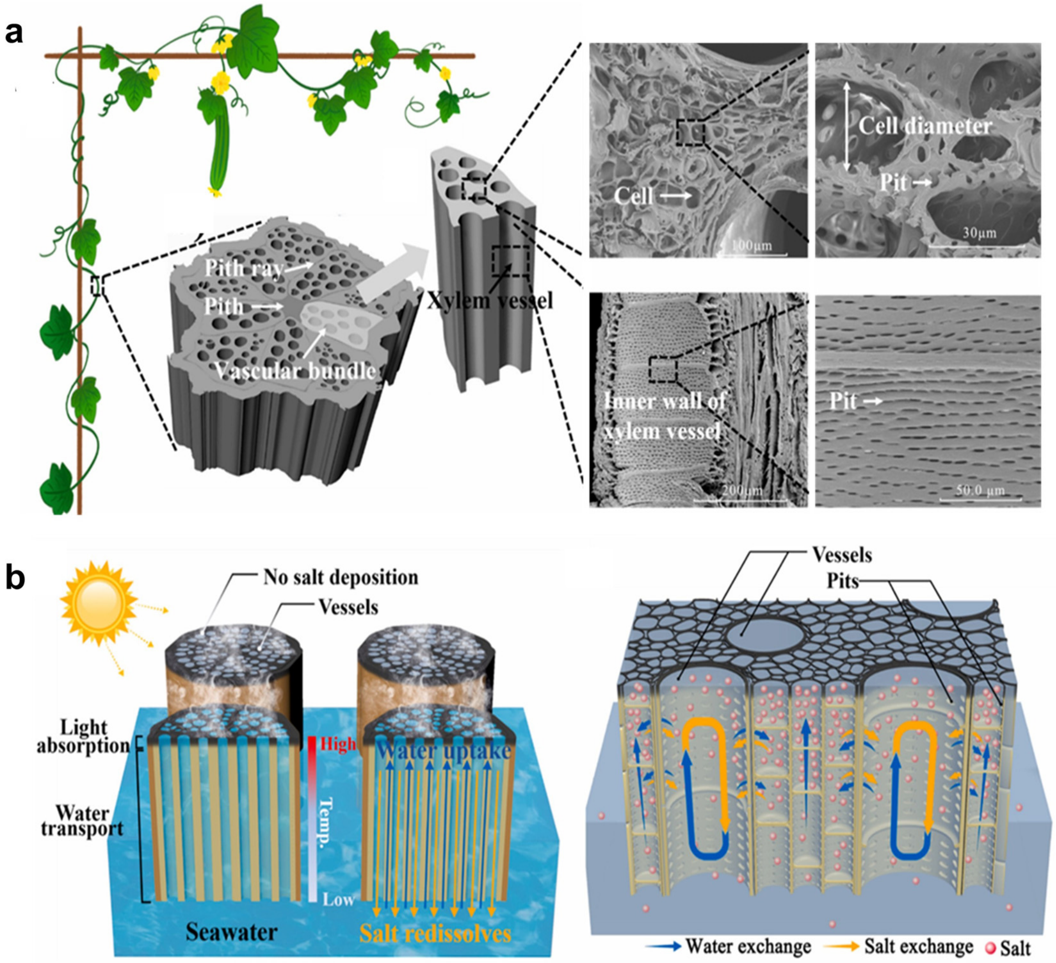

**Figure 5:** Luffa vine-based evaporator. (a) The internal porous structure of natural luffa vine with xylem vessels and piths. (b) Schematic showing water and salt exchange during solar water evaporation. Reproduced with permission from Lv *et al.* [171], Copyright 2023, Elsevier Ltd.

able to quickly supply and diffuse water owing to the special structure of vascular bundles and abundant closed tracheid. Therefore, the corn straw has been another choice for evaporator fabrication. For instance, Zhang *et al.* prepared a double-layered solar vapor generation device *via* carbonization of the top surface of corn straw [173]. It was found that the resultant bilayered corn straw-based structure was capable of diffusing water, evaporating water, and converting solar energy into thermal energy, holding great promise for solar vapor generation.

Besides plant-derived materials, the utilization of animal-derived materials and their derivatives has attracted substantial interest in the solar-driven water evaporation systems. Natural melanin, as extensively mentioned in Section 2.1, with excellent broadband light absorption ability has been extensively used to improve the photothermal conversion efficiency for the development of solar-steam generators [26]. Notably, natural melanin exists in many animal tissues, especially the ink sacs of some marine animals. Instead of using biomass in its raw state, the carbonization of animal-derived biomass into biochar offers another type of photothermal materials.

As a kind of black liquid, squid ink has the advantage of absorbing broadband light; however, its application is limited due to the lack of freestanding structure. A biomass hydrogel evaporator was prepared by using squid ink as photothermal material and starch as hydrogel skeleton material [141]. Under the light irradiation, a rapid increase in temperature was observed on the hybrid hydrogel compared with the pure hydrogel. Benefitting from the microporous structure of the starch hydrogel and the light absorption ability of the squid ink, the water evaporation rate and energy efficiency of squid ink-starch hydrogel were 2.07 $kg\ m^{-2}\ h^{-1}$ and 93.7%, respectively, under one sun irradiation. In addition, its seawater desalination capability was proved, in which a declined salinity of $<1\ mg\ L^{-1}$ was achieved. Excessive water transport is prone to the loss of unnecessary heat, which reduces conversion efficiency. Li *et al.* developed a cuttlefish juice-based solar absorber in which hydrophobic $SiO_2$ NPs were introduced to regulate water transportation [174]. The optimized absorber was able to block excessive water penetration, leading to reduced heat loss. The solar absorber yielded an evaporation efficiency of 85.8% under one sun irradiation, which is higher than the theoretical value (81%).

Animal bones are another type of easily accessible and low-cost biomass material, and their special hierarchical porous structure plays a valuable role in solar-driven evaporation. Carbonized cattle bone, which is cattle bone that has been heated to high temperatures in the absence of oxygen to convert it into a carbon-rich material, has shown great potential as a solar absorber. This process creates a unique porous structure with a high surface area, which enhances its ability to absorb solar energy. As an example, carbonized cattle bone was fabricated after treatment at 600°C, which showed interlinked microchannels and fibrous mesoporous structure [107]. Owing to efficient water transportation, reduced vaporization enthalpy, broadband light absorption, and excellent photothermal performance, the outstanding solar steam generation capability was proved. Furthermore, the ions removal efficiency of the collected freshwater reached 99.99%. The salt fouling, which causes evaporation rate degradation, remains a huge challenge for interfacial solar-vapor generation. Li *et al.* developed a salt-resistant cuttlebone-based solar evaporator, modified with PDA, reducing graphene oxide and PPy [175]. The superhydrophilic 3D directional channels are conducive to rapid water transport, which allows an adequate water supply, rapid automatic salt exchange, and a decrease in the salt concentration gradient. As a result, after 10 h of exposure to natural sunlight, the modified cuttlebone collected 8.32 kg $m^{-2}$ of fresh water, which could meet the needs of several people.

Overall, the biomass and waste-derived materials provide a promising platform for solar-driven water evaporation. Significant achievement has been made in the development of solar evaporators with favorable thermal conversion efficiency and water evaporation rate (Figure 6). Although a variety of eco-friendly and cost-effective materials have been developed, the complicated manufacturing process and poor durability are critical issues for their real-world application. Most of the photothermal conversion materials for solar-driven water systems require complex processing or introduce fictitious materials. Further research is still needed to simplify the treatment process without reduction in the required properties. Furthermore, the practical application of solar-driven water devices is largely overshadowed due to instability. Few bioderived photothermal materials reported the previously mentioned service lifespan. Future studies should pay more attention to the improvement of material stability in the actual harsh environments. The development of sustainable organic waste-derived or bioderived solar-evaporators with low cost, simple preparation process, and long service life will boost their practical applications.

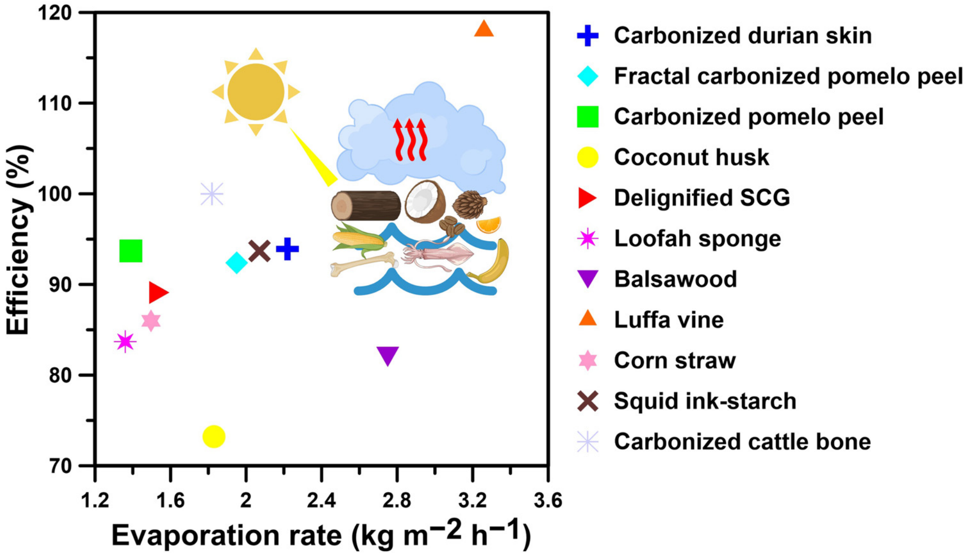

**Figure 6:** Comparative analysis of evaporation rates and efficiencies for photothermal materials derived from organic waste and bioderived sources. The materials included are as follows: Carbonized durian skin [162], FCPP [163], carbonized pomelo peel [164], coconut husk [136], delignified SCG [165], loofah sponge [166], balsawood [168], luffa vine [171], corn straw [173], squid ink-starch [141], and carbonized cattle bone [107].

## 4.2 Biomedical applications

Photothermal waste- and bioderived materials hold immense promise in revolutionizing healthcare through their unique ability to convert light energy into heat. Their biocompatibility, sustainability, and photothermal properties make them versatile candidates for a wide range of applications in the biomedical field. These materials offer environmentally friendly alternatives to conventional resources, contributing to the development of greener technologies in healthcare.

A prime example of developing eco-friendly, budget-friendly, and easily synthesized photothermal materials entails utilizing leftover coffee grounds. The photothermal characteristics of this material have demonstrated notable efficacy in eradicating planktonic bacteria and eliminating biofilms [176]. An excellent example of an antimicrobial bioproduct is rice husk biochar-mediated red phosphorus. The designed product generates $^{\cdot}$OH and $^{\cdot}O_2$ free radicals that cause damage to cellular structures, including membranes, proteins, and enzymes. Additionally, bioproduct photothermal properties enhance cell membrane permeability, allowing more free radicals to enter the cell. The combined action of these two factors accelerates cell death, ultimately achieving highly efficient bacteria elimination [177].

The interest in utilizing materials derived from marine organisms or resources in biomedical applications is steadily increasing. Cuttlefish ink natural nanoparticles (CINPs), a subcategory of MNPs, have garnered researchers' interest due to their ease of extraction by simply washing the ink, nearly zero cost, and avoidance of complex processing as opposed to artificial nanomaterials. CINPs possess remarkable affinity and coupling efficiency for proteins without additional chemical modification and have photothermal conversion capabilities, attributed to the high concentration of eumelanin pigments [33]. Drawing inspiration from the adhesive properties found in mussel proteins, PDA has become a prevalent technique for enhancing the photothermal functionality of material surfaces. Implementation of PDA opens up opportunities for improving medical devices and implants [178–181]. Leveraging the outstanding ability of PDANP-PEI-rPEG to convert light into heat within living organisms, the combined approach of gene and PTT presents a compelling strategy for treating cancer [178].

In recent decades, a significant focus has been on precisely detecting biological molecules, drugs, and pesticides. Harmful molecules are commonly found in hospital waste, sewage water, and groundwater, posing severe risks to aquatic and human life. A cutting-edge approach to detecting such molecules involves utilizing the highly fluorescent and water-soluble nature of C-dots. Vijeata *et al.* have used leaves from the traditionally medicinal *Ocimum sanctum* plant to create stable C-dots capable of swiftly detecting ciprofloxacin [182]. Thakur *et al.* harnessed recycled carbon from *Citrus limetta* organic waste for photo-electrocatalytic, sensing, and biomedical applications [183]. Another sensing application was producing adsorptive materials to eliminate hazardous substances commonly found in the environment, such as mercury. Mercury, when absorbed by the body, harms the digestive tract, kidneys, capillaries, and the nervous system. The group led by Liu *et al.* has developed an effective and rapid removal of Hg(II) from aqueous solutions by synthesizing a highly efficient adsorbent using activated carbon from corn cob by KOH activation [184].

One of the critical issues in biomedical applications lies in developing an efficient delivery platform capable of facilitating the passage of drugs through the highly selective blood–brain barrier (BBB). This barrier, composed of specialized endothelial cells, restricts the entry of most substances into the brain, presenting a significant hurdle for effectively treating neurological disorders and diseases. PTT, due to its notable advantages, including high efficacy, easy application, and minimal invasiveness, has become an effective strategy to improve BBB penetration *via* photothermal agents. An interesting solution presented by Zhang *et al.* involves utilizing NPs extracted from the beard hair of young Asian males, which are primarily composed of keratin and melanin that possess remarkable photothermal conversion capacity (Figure 7a). The results show that the negatively charged surface of extracted NPs attracts positively charged fluoxetine, which enhances BBB permeability under NIR irradiation and exhibits a strong antioxidant effect [185]. This innovative approach shows promise for improving the treatment of depression. Another waste- and bioderived material application is transdermal drug delivery systems (TDDS), which present an appealing alternative for administering drugs and bioactive compounds through the skin. Compared to oral drug delivery, TDDS provide the advantages of bypassing first-pass metabolism, enhancing drug bioavailability, and reducing the likelihood of gastrointestinal disorders. Due to the protective barrier of the stratum corneum, the percutaneous penetration of low molecular weight (<500 Da) and lipophilic drugs through passive diffusion is limited. However, photothermally controlled drug release of naproxen incorporated mainly into mungbean starch-containing MNPs overcomes these challenges [186].

The ongoing challenge that stands prominently before humanity is finding a reliable method to eradicate solid tumors while simultaneously preventing cancer from recurring. Over the years, a diverse range of agents has been developed for PTT, encompassing noble metal nanomaterials,

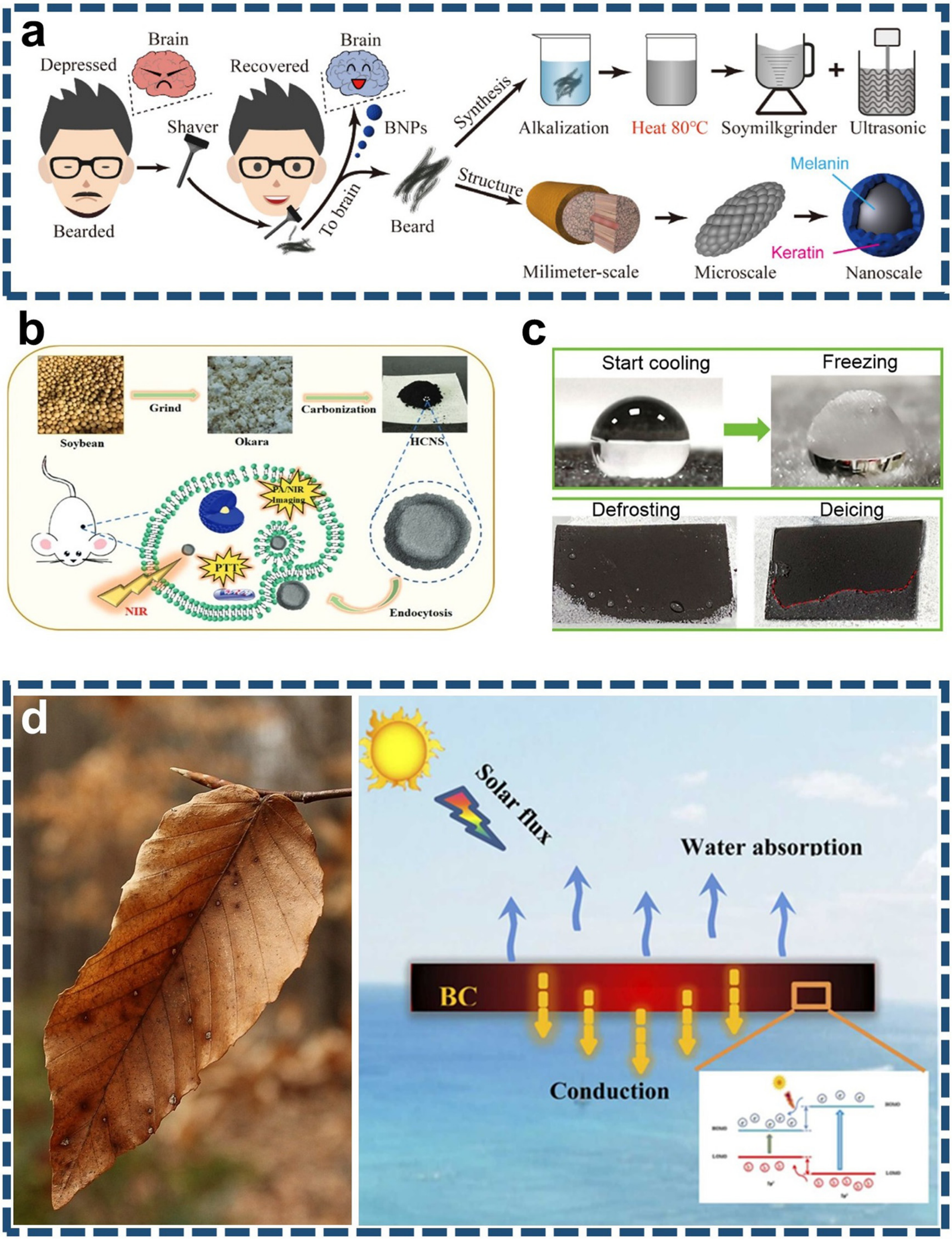

**Figure 7:** Biomedical, deicing, anti-icing, and environmental applications of photothermal organic waste-derived and bioderived materials. (a) A human beard-derived photothermal drug delivery platform for depression therapy. Reproduced with permission from Zhang *et al.* [185], Copyright 2020, Elsevier Ltd. (b) Hollow carbon nanospheres derived from biomass by-product okara for imaging-guided photothermal treatment of cancers. Reproduced with permission from Weng *et al.* [135], Copyright 2019, The Royal Society of Chemistry. (c) Anti-icing/deicing performance of modified biochar coating, representing the freezing and defrosting process of water droplets. Reproduced with permission from Wang *et al.* [138], Copyright 2022, Elsevier Ltd. (d) Heat transfer diagram of leaves-derived leaf biochar during the solar-driven interfacial evaporation process tested for seawater desalination and sewage treatment. Reproduced with permission from Wang *et al.* [189], Copyright 2022, Elsevier B.V.

organic reagents, and materials like black phosphorus and carbon-based compounds. Considering biomass's sustainability, affordability, and abundant availability, there has been a recent surge in innovative approaches to transform diverse biomass sources into valuable functional materials based on carbon. A noteworthy study led by Weng *et al.* employed dried okara, a residual product of soybean food production (Figure 7b). The results demonstrate that the carbonized okara forms sphere-shaped hollow particles with an average diameter of 200 nm, exhibiting an excellent photothermal conversion efficiency. The distinctive structure of the carbon particles imparts them with superior efficiency in converting light into thermal energy, resulting in a robust photoacoustic response and serving as an imaging-guided agent for PTT in cancer treatment [135]. Another work was presented by Kim *et al.*, who engineered bioinspired *Camellia japonica* CDs with NIR solid absorbance for effective photothermal cancer therapy [96]. Lung cancer was the challenge of Wang *et al.*, who employed photothermal treatment by utilizing graphene sheets functionalized with plant extract polyphenols [187]. In discussions about PTT, it is crucial to underscore a critical point. This technique can still adversely affect neighboring tissues, highlighting the importance of limiting exposure to healthy areas. One effective strategy to address this concern is using materials with the capacity to attenuate both radiation and generated heat. Aerogels hold promise for this application due to their insulating properties. The study conducted by Ferreira-Gonçalves *et al.* successfully engineered silica ($SiO_2$) and pectin-based aerogels to serve as optical and thermal insulators, acting as constraints in PTT applications. In detail, the fabrication of organic and inorganic aerogels involved combining pectin and $SiO_2$, with cotton fibers added for reinforcement. The aerogels were formed through ethanol- and thermal-induced gelation, followed by supercritical drying for the organic aerogels and a two-step catalyzed sol–gel process with subsequent oven drying for the inorganic ones. The safety of both types of aerogels confirms their suitability as controllers of light and heat and as insulators in the context of PTT systems [188].

Photothermal materials from waste and biological sources show promise in healthcare but face some challenges. Ensuring material consistency and purity is vital for reliable photothermal properties. Scaling production to meet demand must be cost-effective and efficient. Biocompatibility and toxicity testing are essential due to potential new toxic or immunogenic compounds. Targeting diseased tissue without harming healthy tissue is a key challenge, especially in cancer therapy. Controlling heat distribution to prevent damage is difficult. Regulatory approval necessitates rigorous testing, which is time-consuming and expensive. Material stability over time, particularly in biological environments, is a concern. Integration with current medical technologies may require further development. The cost-effectiveness of the overall production process is crucial for competitiveness. Environmental considerations are important in the extraction and processing of these materials. Interdisciplinary research is needed to overcome these challenges and safely apply these materials in healthcare.

## 4.3 Deicing and anti-icing solutions

Icing is a commonly observed natural phenomenon that can lead to significant challenges and risks in various sectors, including powerlines, buildings, highways, railways, aircraft, and wind turbines [190]. The accumulation of ice over large areas, whether in the form of sizeable masses or minute crystals like freezing rain, damaging frosts, and heavy snow, presents significant challenges to infrastructure, transportation, and crops, leading to substantial economic losses and posing threats to human life [191,192]. Conventional methods for ice removal, encompassing mechanical, electric heating, or chemicals to eliminate ice accretion persist as widely used practical solutions [193,194]. Unfortunately, these approaches often come with drawbacks such as high energy consumption and difficulties in designing environmentally and economically friendly equipment and systems or contributing to environmental pollution [195]. Hence, there is a pressing need for cost-effective alternative materials and simpler fabrication methods. In response to these challenges, a variety of innovative techniques have emerged to mitigate ice growth and accumulation [196]. In recent times, there has been growing interest in passive anti-icing and deicing approaches driven by superhydrophobic coatings with a photothermal effect. Unlike traditional methods, this approach efficiently converts absorbed light into heat, rapidly accelerating the melting of ice. The superhydrophobic nature of the coating facilitates the quick-rolling off of melted droplets, leaving the surface dry [197]. These coatings encompass superhydrophobic coatings/surfaces, ice phobic materials with low-interfacial toughness, slippery liquid-infused porous surfaces, phase transformation materials, and photothermal trap structures [198]. Furthermore, photothermal materials can keep the surface temperature above freezing, avoiding the production and deposition of ice. Continuous surface warming is especially advantageous in minimizing the frequency and intensity of deicing treatments [199,200]. Among them, the use of organic waste-derived and bioderived materials has the intrinsic advantage of being environmentally friendly. For instance, researchers recently introduced an innovative solution – a scalable flexible bilayer bamboo (BLB) for deicing purposes [194,201]. Crafted through a process involving homogeneous carbonization and hydrogel coating of bamboo veneer, this biomaterial possesses necessary attributes essential for efficient anti-icing surfaces. These qualities include strong photothermal trapping capability, an ion reservoir effect, and exceptionally low ice adhesion strength. By leveraging established manufacturing techniques alongside the abundant concave parenchymal cell lumina microstructure intrinsic in bamboo veneer, this method integrates a dual-action mechanism and can combat ice formation through both photothermal heat generation and nucleation-inhibition processes [202,203]. In other studies, the BLB has been highlighted for not only demonstrating its effectiveness in removing ice blocks, frozen condensate drops, and large amounts of snow but also for establishing itself as a versatile and long-lasting anti-icing solution suitable for various surfaces, including challenging curved ones commonly found on buildings and communal facilities. Additionally, the use of bamboo veneer shows a commitment to sustainability, as bamboo is a rapidly renewable resource that aligns with modern eco-conscious sensibilities. With its benefits and eco-friendly profile, the BLB represents an advancement in anti-icing technology, a development supported by the findings of previous studies in the field [204].

Another example is biochar, which is derived from organic waste and bioderived materials and has emerged as a versatile player [85,205]. Derived from the pyrolysis of straw, rice husk, sawdust, and wood, its eco-friendly traits and remarkable photothermal characteristics have positioned it as a candidate for applications in water purification and soil enhancement [138]. Despite its intrinsic potential, the practical application of biochar has been hampered by challenges associated with its intricate composition, encompassing diverse functional groups (−OH, $-NH_2$, −COOH) and minerals (N, P, S, Si, Ca, Mg, and K). This complexity renders biochar intrinsically hydrophilic or weakly hydrophobic. In a quest to unlock the full potential of biochar, various methods, including acid modification, metal oxide modification, and metal salt modification, have been explored to enhance its hydrophobicity. Additionally, many reported hydrophobic biochars are self-synthesized through intricate and time-consuming processes, showing the need for commercially low-cost biochar to facilitate its widespread industrial application [201]. As an example, researchers presented a straightforward method to craft a superhydrophobic photothermal anti-icing/deicing coating utilizing readily available biochar and economically viable titanium nitride (TiN) NPs [138]. The synergistic integration of TiN NPs and biochar yields a coating that remarkably enhances water-repellency and photothermal conversion performance. Notably, when the TiN content surpasses 20 wt%, the coating achieves a superhydrophobic state, boasting an impressive contact angle of up to 156° and a roll-off angle of less than 5°. This achievement highlights the pivotal role played by the micro-nano structure combined with low surface energy in conferring superhydrophobicity upon the coating. Further elevating the performance of the coating, a thermal insulating layer is inserted between the superhydrophobic surface and substrate. In practical terms, with a temperature increase of up to 63.3°C under one sun's illumination in subzero conditions, the coating effectively melts, covering frost and ice without leaving water droplets on the surface (Figure 7c). Mechanical durability is substantiated through water droplet impact, sand abrasion, and bending tests. Notably, the scalability of the coating is demonstrated through the fabrication of a 900 $cm^2$ superhydrophobic photothermal coating. Therefore, photothermal coatings hold great promise for multifunctional applications, leveraging solar energy efficiently. However, a current challenge lies in identifying a readily prepared material with high photothermal performance. Drawing inspiration from mussel adhesion and lotus leaf surfaces, researchers have developed superhydrophobic photothermal coatings featuring a hierarchical structure. This is achieved through the sequential deposition of melanin-like PDA and dip-coating PDMS/hydrophobic fumed $SiO_2$. Additionally, the coatings offer UV protection, ensuring prolonged functionality under extended outdoor sunlight exposure [206].

## 4.4 Environmental remediation and beyond

Environmental remediation, the process of mitigating the impact of pollutants on ecosystems, has become a critical area of scientific research and innovation. The exploration of sustainable materials for this purpose has led to a growing field focusing on the applications of photothermal organic waste-derived and bioderived materials. This section explores the diverse applications of these materials in environmental remediation, highlighting their potential to address pollution challenges and contribute to a more sustainable future. In general, photothermal materials serve an important role in environmental remediation because of their ability to transform solar energy into heat, accelerating the destruction of contaminants in water, soil, and air *via* photodegradation processes [207,208]. Moreover, photothermal materials enhance photocatalytic reactions, by raising reaction rates. In disinfection, the heat produced by these materials can inactivate pathogenic germs in water by breaking cellular structures [209]. They aid in oil–water separation by lowering oil viscosity during heating and drive membrane distillation by providing vapor pressure gradients for water purification [210]. Heat enhances adsorption capacity by increasing the contaminant diffusion rates and widening adsorbent pores. Thermo-catalytic processes use localized heat to transform pollutants, such as turning $CO_2$ into fuels or breaking down complex organic molecules. This combines increased temperatures and catalytic activity for effective remediation [211].

Therefore, those organic waste-derived or bioderived materials that are intrinsically photothermal or acquired this property are promising candidates for environmental applications [212]. These materials, produced from renewable sources such as cellulose, lignin, chitosan, and agricultural by-products such as corn starch, excel in a variety of pollutant removal processes. Bioderived materials play an important part in sustainable pollutant removal solutions by utilizing physical adsorption, chemical binding, and biological processes, providing both efficiency and environmental compatibility [213]. Cellulose-based materials have a hierarchical porous structure rich in hydroxyl groups (–OH), allowing contaminants to bind to large surface areas through physical interactions. Modified cellulose nanofibers containing functional groups such as carboxyl (–COOH) improve their ability to selectively adsorb heavy metals and pollutants in water, greatly increasing removal efficiency [214,215]. Lignin, a complex aromatic polymer found in plant tissues, has strong adsorption properties for organic contaminants and colors due to its polyphenolic composition. Lignin NPs functionalized with amine groups ($–NH_2$) show greater effectiveness in removing dyes such as methylene blue, boosting environmental remediation efforts. They create strong π–π interactions and hydrogen bonds with aromatic contaminants [216,217]. Chitosan amino groups ($–NH_2$) allow the efficient chelation and binding of heavy metal ions *via* coordination chemistry. Chitosan beads and membranes are particularly successful for pollutant removal from aqueous solutions due to their positively charged surface, which allows for electrostatic interactions with negatively charged contaminants including anionic dyes and phosphates [218]. Modified corn starch compounds have amphiphilic characteristics, allowing them to produce biodegradable films that can capture oil and grease from water surfaces. These materials adsorb nonpolar contaminants through hydrophobic interactions and provide stability and adhesion through hydrophilic groups, making them suited for use in oil spill cleaning and water remediation [219]. Moreover, algae and microorganisms provide biological channels for pollutant removal in aquatic environments and polluted soil. Algae bioaccumulate toxins by active transport systems, concentrating them inside their biomass. Meanwhile, microorganisms such as bacteria and fungi breakdown complex organic contaminants through enzymatic processes, transforming harmful substances into simpler, less toxic forms and so contributing to long-term environmental cleanup efforts [220]. Another example is carbon-based bioderived materials that exhibit remarkable light absorption across a broad spectrum, possess a highly adaptable structure, and are cost-effective with abundant resources. Recently, they have become a focal point in solar energy research. Enhancing the photothermal conversion efficiency of carbon-based materials involves compounding carbon-based materials with other substances to form heterojunctions and altering surface functional groups. Adjusting the microstructure of carbon-based materials holds promise for advancing solar steam generation efficiency, though further research is needed. Wang *et al.* proposed the adjustment of $sp^2$ hybrid carbon content in leaf biochar derived from discarded leaves. Biochar demonstrates potential applications in seawater desalination and sewage treatment, effectively removing ions and pollutants from industrial wastewater (Figure 7d). The practical utility of biochar is evaluated by observing its evaporation rate under natural light conditions [189].

The use of organic wastes like compost, animal manure, and agricultural residues for soil remediation has also gained traction owing to their capacity to enhance soil structure, nutrient levels, and microbial activity. These materials play a pivotal role in promoting soil health, reducing erosion, and sequestering carbon dioxide, thereby aiding in climate change mitigation. Moreover, organic wastes serve as a rich source of essential nutrients for plant growth and microbial activity. Composts, for instance, are teeming with nitrogen, phosphorus, potassium, and various micronutrients crucial for plant health. When applied to the soil, these nutrients become readily available to plants, promoting robust growth and development [221]. Additionally, organic amendments stimulate microbial populations in the soil, fostering a dynamic ecosystem of beneficial microorganisms. These microbes play vital roles in nutrient cycling, decomposition of organic matter, and suppression of soil-borne pathogens, thereby contributing to overall soil health and productivity [222]. In a study conducted by Medyńska-Juraszek and Ćwieląg-Piasecka, the potential of wheat straw biochar for cobalt sorption in contaminated soil was investigated [223]. Their study revealed that the investigated material exhibited high sorption efficiency, effectively reducing the mobility and availability of $CO_2^+$ ions in soil. This mitigation of cobalt mobility is crucial for minimizing health risks associated with human exposure to contaminated soil environments. The primary sorption mechanisms were attributed to interactions between cobalt ions and functional groups such as carboxylic and hydroxyl groups present on the biochar surface. However, it was noted that the immobilization of cobalt is a multifaceted process, influenced by factors such as biochar oxidation and interactions with soil constituents [224,225].

## 5 Conclusion and perspectives

This review has highlighted the significant advancements and potential of organic waste-derived and bioderived photothermal materials in promoting sustainable technologies. In the introduction, we outlined the growing interest in sustainable photothermal materials due to their ability to efficiently convert light energy into heat for various applications such as water purification, medical therapies, and environmental remediation. We emphasized the limitations of conventional photothermal materials and the advantages of using organic waste-derived and bioderived materials as cost-effective and sustainable alternatives. The section on the types of organic waste-derived and bioderived materials detailed their origins from marine, plant, and animal sources. We explored the unique properties of these materials, such as the inherent photothermal properties of chitin and chitosan from crustacean shells, melanin from cephalopods ink, and the structural advantages of materials like wood. In discussing the photothermal properties of these materials, we examined the underlying principles and mechanisms that contribute to their ability to convert light into heat. We highlighted the intrinsic photothermal properties of materials like lignin and melanin and the enhanced properties achieved through processes like pyrolysis and calcination. The applications section showcased the diverse potential of these materials across various domains. Solar-driven water technologies, including seawater desalination and water purification, demonstrated the practical benefits of using these sustainable materials. We also explored their applications in medical treatments, deicing strategies, and environmental remediation.

The potential of organic waste-derived and bioderived photothermal materials in advancing sustainable technologies is immense. These materials offer a promising alternative to conventional photothermal agents owing to their inherent sustainability, biocompatibility, and potential for low-cost fabrication. While several obstacles need to be surmounted to fully realize the potential of these materials, their future is promising.

First and foremost, there is a need to unveil the full potential of these materials. The current repertoire of organic waste-derived and bioderived materials is relatively limited, as only a few have been thoroughly investigated. Expanding the search to a wider range of natural sources, including agricultural residues, food processing by-products, and industrial waste streams, it is crucial to uncover novel photothermal materials with enhanced properties and untapped potential.

Second, it is essential to strike a balance between photothermal effectiveness and environmental friendliness. While optimizing photothermal properties is paramount, it should not come at the expense of environmental sustainability. Innovations and thinking outside the box are needed to minimize the environmental impact of these materials throughout their lifecycle, from production to disposal. This includes exploring alternative processing routes that utilize renewable energy sources or employ eco-friendly solvents [226]. In particular, the focus of research should shift toward the development of innovative platforms that harness the intrinsic photothermal capabilities of naturally occurring pigments or pyrrolic compounds, thereby minimizing the need for external modifications and enhancing sustainability. Research on melanin-containing ocean-derived materials [227,228] and dark-colored products derived from mild-processing organic wastes, including melanoidins formed during Maillard reactions [41,121], demonstrate promising results. Another promising avenue is the development of hybrid platforms from these materials that combine photothermal properties with other functionalities, such as catalysis, luminescence, or sensing. By synergistically combining these properties, these platforms could enable novel applications in energy harvesting, biosensors, and targeted drug delivery.

It should be noted that the organic waste-derived and bioderived materials can be subjected to a variety of treatments to enhance their photothermal properties. These treatments can be broadly classified into physical, chemical, physicochemical, and biological methods. Each approach has its own advantages and limitations, and the choice of the most suitable method depends on factors such as energy consumption, industrial feasibility, and unit dimensions. Optimizing treatment processes is crucial for ensuring the industrial viability of the materials in the review focus. For instance, biological treatments, with their mild reaction conditions and low environmental impact, offer many advantages. However, their industrial viability is often hampered by long pre-treatment times. In contrast, physical and chemical treatments can be more efficient, but they may generate hazardous by-products or require high energy input.

Developing optimized treatment processes that balance photothermal enhancement with industrial feasibility and environmental sustainability is essential for commercializing these materials on a large scale.

Third is the complex mixture and the inherent heterogeneity of organic waste-derived and bioderived materials, which prompt further studies to clarify the underlying mechanisms of their photothermal conversion that are essential for rational design and optimization. In-depth studies on the energy transfer processes, charge carrier dynamics, and thermal management strategies will lead to the development of materials with enhanced performance and tailored properties. Furthermore, the lesson learned from enhancing the stability and durability of conventional photothermal materials should be implemented for organic waste-derived and bioderived materials. Strategies to mitigate photodegradation and degradation under harsh environmental conditions are crucial for ensuring the long-term effectiveness of these materials in various applications.

Finally, a collaborative approach is essential for the rapid advancement of these materials. Expertise from various disciplines, including materials science, chemistry, physics, biology, engineering, and medicine, must be brought together to accelerate progress. Fostering cross-disciplinary interactions will facilitate the translation of research findings into real-world applications and address the challenges outlined above. When examining the potential of these materials, it is imperative to thoroughly assess their environmental impact and biosafety considerations. Life cycle assessments can evaluate the environmental footprint of these materials from their production to their end-of-life stage. Thorough toxicity testing is essential to ensure the responsible and sustainable utilization of these materials in various applications without posing any health risks to humans and the environment.

It should be noted that the implementation of these materials in real-world applications could drive the development of decentralized and sustainable energy systems. For example, integrating organic waste-derived photothermal materials into solar panels or solar concentrators can increase the efficiency of solar energy conversion, making renewable energy sources more viable and cost-effective. The ability to utilize local waste resources also reduces the carbon footprint associated with material transportation and production, further enhancing the environmental benefits. In the context of environmental remediation, these materials offer innovative solutions for pollutant removal and management. Their high surface area and reactivity make them suitable for adsorbing and degrading contaminants in water and soil, contributing to cleaner and safer ecosystems. The practical applications of these materials are vast and varied, highlighting their potential to make substantial contributions to sustainable development goals by addressing critical issues such as clean water, affordable and clean energy, and good health and well-being.

The key findings of this study emphasize the sustainability and biocompatibility of organic waste-derived and bioderived materials, making them suitable for various applications including biomedical and environmental remediation. Notably, materials such as cuttlefish ink and SCGs exhibit high photothermal efficiency, demonstrating their potential in solar steam generation and other applications without extensive processing. Additionally, the versatility of these materials is highlighted by their promising performance across diverse fields such as solar-driven water technologies, PTT, and pollutant removal.

Looking ahead, future research should expand the range of natural sources to fully unveil the potential of these materials. Exploring agricultural residues, food processing by-products, and industrial waste streams can lead to the discovery of novel photothermal materials with enhanced properties. Balancing effectiveness and environmental friendliness is crucial, and future studies should focus on innovative processing routes that utilize renewable energy sources or eco-friendly solvents. The development of hybrid platforms that combine photothermal properties with other functionalities, such as catalysis, luminescence, or sensing, presents significant potential for novel applications in energy harvesting, biosensors, and targeted drug delivery. Enhancing the stability and durability of these materials under harsh environmental conditions is essential to ensure long-term effectiveness, necessitating strategies to mitigate photodegradation and improve material stability.

During the past few years, the subject of circular economy, without a doubt, has received enormous attention. The demand for developing sustainable platforms has brought organic waste-derived and bioderived materials with photothermal properties into the spotlight. The comprehensive realization of the full potential of these materials is an ongoing endeavor. A multi-pronged approach is essential – one that embraces innovative material discovery prioritizes sustainability, unravels fundamental mechanisms, and fosters cross-disciplinary collaboration. While several obstacles need to be surmounted to fully realize the potential of organic waste-derived and bioderived photothermal materials, their future is promising. Addressing these topics demands strategic research investments and a comprehensive life cycle perspective. The integration of sustainability, innovative material discovery, and cross-disciplinary collaboration will pave the way for the practical application of these materials in various domains.

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