



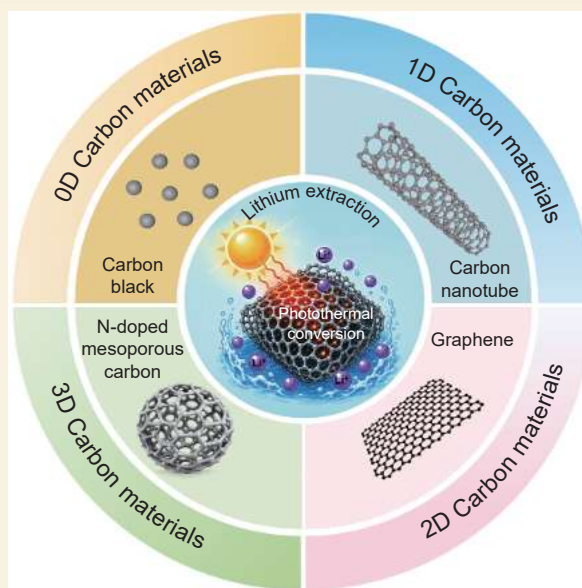
Research progress on carbon-based composite materials for photothermal lithium extraction

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Abstract: Carbon-based materials have emerged as a highly promising class of photothermal systems for solar-driven lithium extraction, because of their broad-spectrum light absorption, efficient photothermal conversion, tunable structural dimensions, and versatile interfacial engineering capabilities. Despite notable advances, comprehensive and insightful reviews on this subject remain scarce, and there is a clear need to consolidate the current developments in this field in a structured and critical manner. The roles of carbon materials in photothermal lithium extraction are summarized, focusing on their distinct heat-transfer behavior, ion-transport mechanisms, and structure-property relationships. Various carbon structures have notable capabilities in localized heating, directional thermal/ionic transport, interfacial heat diffusion, and thermal confinement. Recent advances in Li^+ enrichment, improving adsorption kinetics, anti-salt-fouling, and multifunctional integration are also discussed. Finally, future directions are outlined, focusing on multi-dimensional carbon hybrids, carbon-based composite systems with vertical channels, and scalable biomass carbon for efficient photothermal Li extraction.

Key words: Photothermal lithium extraction; Carbon materials; Photothermal conversion mechanisms; Graphene; Carbon nanotube



1 Introduction

With the rapid transition of the global energy structure toward electrification and low-carbon development^[1–2], lithium (Li) has become a critical strategic resource owing to its indispensable role in lithium-ion batteries^[3–4] for electric vehicles (EVs), portable electronics, and large-scale energy storage systems. Currently, lithium resources are mainly distributed in hard-rock ores^[5–7], salt-lake brines, and seawater. Compared with mineral resources, brines and seawater possess far larger lithium reserves^[8]. Particularly notable is seawater, whose total lithium content is estimated to be several thousand times greater than that of terrestrial resources^[6,9–10]. However, extraction of Li^+ from aqueous sources remains highly challenging or impractical due to the ultralow concentration,

high $\text{Mg}^{2+}/\text{Li}^+$ ratios, and the coexistence of abundant competing ions such as Na^+ , K^+ and Ca^{2+} ^[11].

To overcome these challenges, various lithium extraction technologies have been developed, including chemical precipitation, solvent extraction, lithium-ion sieve (LIS) adsorption, membrane separation, electrodialysis, and electrochemical adsorption. Among the currently available lithium extraction technologies, chemical precipitation is a mature and readily industrialized approach; however, it suffers from low selectivity, high reagent consumption, and signi-

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ficant lithium loss^[2]. Solvent extraction achieves selective lithium separation based on the difference in the distribution coefficients of lithium ions between the aqueous and organic phases, offering high separation efficiency and selectivity^[12]. Nevertheless, challenges such as organic solvent loss, potential environmental risks, and the high energy demand associated with solvent regeneration remain significant. Membrane-based separation technologies enrich lithium ions through mechanisms including size sieving and Donnan exclusion, enabling continuous operation and high Mg/Li separation performance. However, membrane fouling and inorganic scaling can substantially reduce lithium selectivity, particularly in highly saline brine systems^[13]. Electrodialysis-based lithium extraction is often constrained by ion leakage, membrane fouling, and excessive energy consumption, which limit its large-scale practical application^[14].

Among the aforementioned techniques, LIS adsorption exhibits high Li^+ selectivity but still suffers from slow ion-transport kinetics, high regeneration energy consumption, and performance degradation in complex brine^[15–16]. In recent years, solar interfacial evaporation (SIE) has emerged as a promising low-carbon strategy for lithium extraction^[17–18]. By localizing solar energy at the air-liquid interface, SIE enables efficient interfacial heating and continuous ion enrichment, while avoiding the high energy consumption associated with conventional bulk-heating processes^[19]. More importantly, when coupled with adsorption, membrane separation, or crystallization processes, evaporation-driven fluid flow and concentration gradients can effectively accelerate Li^+ migration and interfacial enrichment, thereby significantly enhancing lithium extraction kinetics^[17,20–21]. Consequently, photothermal lithium extraction has attracted extensive attention as a sustainable and energy-efficient lithium recovery technology^[22].

Carbon-based materials, on the other hand, have become one of the most promising candidates for photothermal lithium extraction for their broadband solar absorption, high photothermal conversion efficiency^[23], excellent chemical stability, and tunable

electronic structures. More importantly, the dimensional diversity of carbon materials family^[24–26], featuring zero-dimensional (0D) carbon black and carbon quantum dots (CQDs), one-dimensional (1D) carbon nanotubes and carbon fibers, two-dimensional (2D) graphene-based materials, and three-dimensional (3D) porous or biomass-derived carbons^[27], endows them with distinct heat-transfer and ion-transport capabilities^[28]. Specifically, 0D carbons favor localized heat accumulation, 1D carbons facilitate rapid thermal and ionic transport, 2D carbons enable uniform interfacial heating, while 3D carbons provide integrated functions of light harvesting, thermal localization, and directional mass transport^[29]. Therefore, carbon-based materials are no longer merely photothermal absorbers, but are evolving into multifunctional platforms integrating photothermal conversion, heat management, interfacial evaporation, and ion transport. Integrated functional systems have been constructed by combining carbon materials with LIS and hydrogel/membrane materials. These systems enable efficient photothermal extraction of Li^+ by utilizing the photothermal conversion capability of carbon materials and the specific adsorption performance of LISs^[30–32].

In this review, we start with a systematic overview of the research progress of carbon-based materials in photothermal lithium extraction. Rather than focusing solely on the improvements in evaporation efficiency, this review outlines the multifunctional roles of various carbon materials, including photothermal conversion, interfacial thermal regulation, enhanced mass transfer, adsorption promotion, and salt-resistant behavior. Particular emphasis is given to the contributions of carbon materials with different dimensional architectures and the mechanism through which these structures exhibit their respective photothermal behavior, heat and mass transport, and lithium extraction performance. This review aims to provide the first systematic carbon-material-centered perspective on low-carbon and sustainable photothermal lithium extraction technologies^[32]. Furthermore, the challenges and future opportunities of carbon-based photothermal systems are highlighted to provide guid-

ance for the rational design and practical application of efficient and sustainable photothermal lithium extraction technologies (Fig. 1).

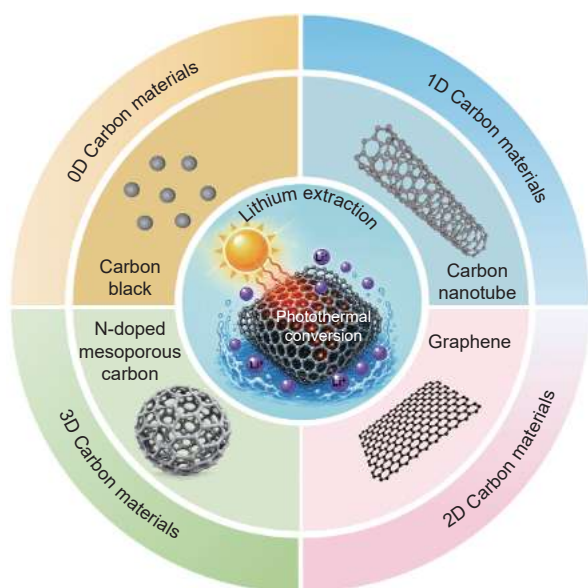


Fig. 1 Schematic summary of dimensionally different carbon-based materials for photothermal lithium extraction

2 Photothermal conversion materials and mechanisms

The essence of photothermal lithium extraction lies in the efficient conversion of solar energy into localized thermal energy, which is subsequently coupled with interfacial evaporation, ion migration, and selective separation processes^[33]. Therefore, the energy conversion mechanism of photothermal materials fundamentally determines the conversion efficiency, interfacial thermal management capability, and Li^+ transport behavior of the system^[34]. At present, photothermal materials employed in solar-driven interfacial evaporation for lithium extraction systems mainly include carbon-based materials, plasmonic materials, and semiconductors, whose photothermal conversion processes are primarily governed by localized surface plasmon resonance (LSPR), electron-hole generation/relaxation, molecular thermal vibration, respectively^[21,35].

As shown in Fig. 2, owing to their distinct photothermal conversion mechanisms, these three classes of photothermal materials exhibit different advantages and disadvantages.

Plasmonic materials demonstrate outstanding light-harvesting capability and photothermal conversion performance through the localized surface plasmon resonance (LSPR) effect; however, their practical application is constrained by high cost, lack of long-term stability, and challenges associated with large-scale deployment^[36–37]. Semiconductor-based materials possess desirable structural tunability and adjustable bandgap characteristics, but their utilization of the solar spectrum is inherently restricted by bandgap-dependent light absorption^[37–38]. In comparison, carbon-based materials, characterized by broad-spectrum light absorption, excellent chemical stability, low cost, and facile scalability, have emerged as the most widely employed photothermal materials. Nevertheless, their relatively high thermal conductivity may facilitate heat dissipation into the bulk phase, thereby reducing interfacial thermal localization efficiency^[37].

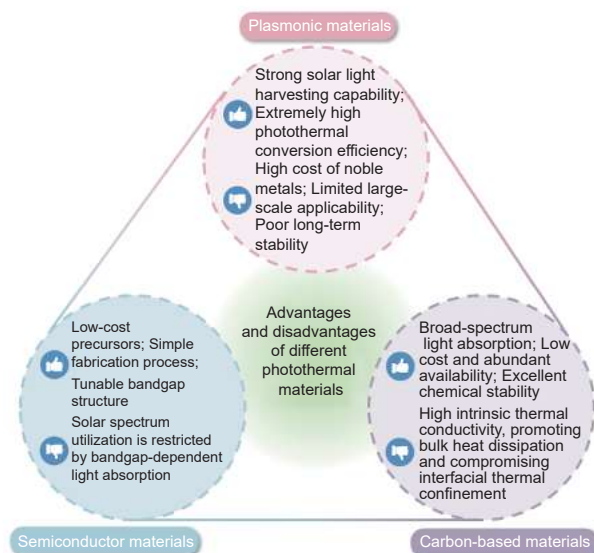


Fig. 2 Advantages and disadvantages of plasmonic materials, semiconductor materials and carbon-based materials

2.1 Plasmon-based materials

Plasmon-based materials (such as Au, Ag, TiN and Cu_2S_5) are capable of efficient photothermal conversion primarily through the localized surface plasmon resonance (LSPR) effect (Fig. 3a). The fundamental mechanism arises from the collective oscillation of free electrons on the metal surface upon excitation by the incident electro-magnetic field^[39–42].

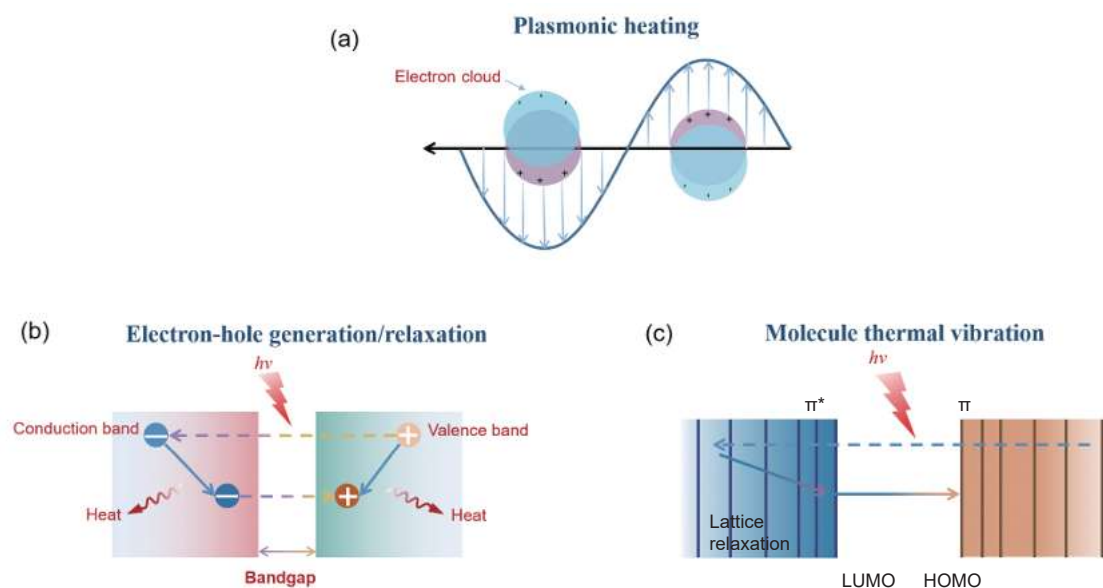


Fig. 3 Common photothermal mechanisms including molecular thermal vibration, plasmonic localized heating, and electron-hole generation/relaxation

When the frequency of incident light matches the intrinsic oscillation frequency of free electrons on the surface of metallic nanoparticles, localized surface plasmon resonance occurs at the metal-dielectric interface, generating strongly enhanced localized electromagnetic fields at the nanoscale^[42]. During this process, free electrons are excited into high-energy “hot electrons,” which subsequently undergo rapid energy redistribution through electron-electron scattering^[43–45]. The accumulated energy is then transferred to the lattice via electron-phonon coupling and ultimately dissipated into the surrounding environment in the form of heat.

2.2 Semiconductor-based materials

Semiconductor-based photothermal materials (such as MoS_2 , $\text{g-C}_3\text{N}_4$, Ti_2O_3 , CuS and MoO_3) primarily rely on the generation of electron-hole pairs and subsequent nonradiative thermalization processes for photothermal conversion^[46–47]. Semiconductor materials possess well-defined band structures, and only when the energy of incident photons exceeds the bandgap can electrons in the valence band be excited to the conduction band, thereby generating electron-hole pairs^[48–50].

In photothermal evaporation systems, the photo-excited carriers generally relax rapidly back to the band-edge states through nonradiative relaxation pro-

cesses, with excess energy being converted into localized thermal energy via phonon-mediated thermalization, thereby driving interfacial water evaporation^[51–52]. Consequently, the photothermal performance of semiconductor materials is closely associated with their bandgap structures. In general, narrow-bandgap semiconductors are capable of absorbing a broader range of the solar spectrum and therefore exhibit higher photothermal conversion efficiencies^[52]. In contrast, wide-bandgap semiconductors are more susceptible to radiative recombination, where part of the absorbed energy is re-emitted as photons, thereby reducing thermal energy utilization efficiency (Fig. 3b).

Several strategies such as elemental doping, defect engineering, and heterostructure construction are commonly employed to tailor their electronic band structures, thereby improving solar light absorption and suppressing carrier recombination, resulting in enhanced photothermal performance^[52–55].

As shown in Table 1, a variety of non-carbon-based photothermal materials have been applied in solar-driven lithium extraction systems and have achieved satisfactory lithium extraction performance, indicating the broad prospects of photothermal strategies in the field of lithium resource recovery. In recent years, among various photothermal materials,

Table 1 Performance comparison of different photothermal material systems excluding carbon-based materials

Photothermal material	Feed	Time/h	Lithium extraction performance	Evaporation rate (kg m ⁻² h ⁻¹)	Ref.
H _{1.6} Mn _{1.6} O ₄	40 mg·L ⁻¹ Li ⁺ solution	~ 6	520 mg·m ⁻²	1.15 (1 sun)	[56]
H _{1.33} Mn _{1.67} O ₄	Bohai Sea	60	34 mg·g ⁻¹	2.22 (1 sun)	[57]
H _{1.33} MnFe ₂ O ₄	100 mg·L ⁻¹ Li ⁺ solution	~ 10	879.4 mg·m ⁻²	2.93 (1 sun)	[58]
MoS ₂	20% sea-salt solution	~ 24	29.85 mg·g ⁻¹	2.13 (1 sun)	[59]
MoS ₂	~ 250 mg·L ⁻¹ Li ⁺ solution	60	53.4 mg·g ⁻¹	2.58 (1 sun)	[60]
MoS ₂	1000 mg·L ⁻¹ Li ⁺ solution	200 min	~ 190 mg·dm ⁻³	~ 170 (1 sun)	[61]
Fe ₃ O ₄	50 mg·L ⁻¹ Li ⁺ solution	1.5	34.5 ± 1.1 mg·g ⁻¹	/	[62]
PVDF/Fe ₃ O ₄	Seawater	10	0.05 mg·g ⁻¹	3.51 (1 sun)	[63]
Amine-capped aniline trimer (ACAT)	Brine/Wastewater	30	Mg ²⁺ /Li ⁺ mass concentration ratio decreased from 5.0:1 to 2.6:1	2.79–3.64 (1 sun)	[64]
Cu-MOF/PDA/ATP@Al photothermal sheet	200 mg·L ⁻¹ Li ⁺ solution	7	20.09 mg·g ⁻¹	1.51 (1 sun)	[65]
Polypyrrole (PPy)	Simulated brine (Mg ²⁺ /Li ⁺ = 10)	8	>600 mg·m ⁻² ·day ⁻¹	2.43 (1 sun)	[66]
Polypyrrole (PPy)	Synthetic brine (1000 mg·L ⁻¹ Li ⁺)	24	1353.5 mg·m ⁻²	2.98 (1 sun)	[67]
CC-PPy arrays	Seawater	9 batches	Li/Na mass ratio enrichment: by factors of 39 (salt lake brine) and 675 (seawater)	1.874 (1 sun)	[68]
PANI nanoarrays	Simulated salt lake brine (348.4 g L ⁻¹ , Mg ²⁺ /Li ⁺ = 19.8)	/	Mg ²⁺ /Li ⁺ decreased by a factor of 66	2.2–3.13 (3 sun)	[69]
Al NPs-decorated AAO	3 mg·L ⁻¹ brine	24 h	33.2 mg·m ⁻² ·day ⁻¹	1.28 (1 sun, outdoor)	[70]
PCN-134-2D nanosheets	LiCl solution (1.19 g·L ⁻¹)	20 h	Li concentration factor increased by 106.7%	36.43(L m ⁻² ·h ⁻¹)	[71]

carbon-based materials have gained growing attention from researchers due to their relatively lower cost, which is particularly favorable in industrial uses.

2.3 Carbon-based materials

Carbon-based materials have gradually emerged as the most representative core photothermal materials in photothermal lithium extraction systems. Compared with plasmon-based metallic materials, which generally suffer from high cost and instability, or semiconductor materials constrained by bandgap limitations and carrier recombination^[23,72–73], carbon-based materials feature broadband solar absorption, high photothermal conversion efficiency, excellent chemical stability, tunable micro/nanostructures, and low-cost scalable production (Fig. 3c).

The photothermal conversion capabilities of carbon-based materials fundamentally originates from the nonradiative electron relaxation process within their sp²-conjugated carbon networks^[74]. Typical carbon materials, including carbon black, graphene, carbon nanotubes, biomass-derived carbon, and porous carbon, possess abundant delocalized π -electron systems^[35,74–76]. Upon solar irradiation, π electrons absorb incident photons and are excited from low-energy states to high-energy excited states. Subsequently, the excited electrons relax back to the ground state rapidly through electron-phonon coupling,

releasing energy in the form of lattice vibrations (phonons), thereby enabling efficient conversion of light energy into thermal energy^[77–78]. Since this process is dominated by nonradiative energy dissipation, carbon-based materials generally exhibit outstanding solar-to-thermal conversion capability and broadband light absorption spanning from the ultraviolet to near-infrared regions^[78–80].

Compared with metallic materials which primarily rely on localized plasmonic effects, or semiconductor materials restricted by bandgap-dependent absorption, carbon-based materials demonstrate superior overall performance in solar-driven interfacial evaporation lithium extraction systems^[81]. In addition to enabling efficient and stable photothermal conversion, carbon-based materials can further regulate the heat distribution, water transport, and ion migration processes through dimensional structural engineering, thereby providing an important material foundation for the development of highly efficient, low-energy-consumption, and sustainable photothermal lithium extraction systems^[82]. As shown in Table 2, carbon-based photothermal materials with diverse structures and dimensionalities demonstrate excellent performance in enhancing photothermal lithium extraction efficiency.

Table 2 Performance comparison of different carbon-based photothermal material systems

Carbon materials	Feed	Time/h	Lithium extraction performance/($\text{mg} \cdot \text{g}^{-1}$)	Evaporation rate/($\text{kg} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$)	Refs.
rGO/CNT	50 $\text{mg} \cdot \text{L}^{-1}$ Li^+ solution	5	19.88	1.23 (1.5 sun)	[83]
Graphene	25% salt solution	5	10.77	3.18 (1 sun)	[84]
Laser-induced graphene	$\sim 1000 \text{ mg} \cdot \text{L}^{-1}$ Li^+ solution	25	1467 $\text{mg} \cdot \text{m}^{-2}$	2.26 (1 sun)	[85]
Graphite powder	seawater	21 day	15.71	1.60 (1 sun)	[86]
MWCNTs	$\sim 500 \text{ mg} \cdot \text{L}^{-1}$ Li^+ solution	~ 3	43.5	3.85 (1 sun)	[87]
CNT	100 $\text{mg} \cdot \text{g}^{-1}$ Li^+ solution	5	31.83	1.74 (1 sun)	[34]
Carbon black	200 $\text{mg} \cdot \text{L}^{-1}$ Li^+ solution	5	27.7	2.8–3.0 (1 sun)	[88]
Flamed wood	50 $\text{mg} \cdot \text{L}^{-1}$ Li^+ solution	~ 400 min	~ 16.6	2.82 (1 sun)	[89]
CNT	200 $\text{mg} \cdot \text{L}^{-1}$ Li^+ solution	5	50.1	2.33 (1 sun)	[90]
N-doped mesoporous carbon	100 $\text{mg} \cdot \text{L}^{-1}$ Li^+ solution	6	28.7	1.32 (1 sun)	[91]
Carbon black	200 $\text{mg} \cdot \text{L}^{-1}$ Li^+ solution	2	40.87 $\text{mg} \cdot \text{m}^{-2}$	1.42 (1 sun)	[92]

3 Different dimensional carbon-based materials toward enhanced photothermal lithium extraction

The structural diversity of carbon-based materials originates from the versatile hybridization modes of carbon atoms, including sp , sp^2 and sp^3 configurations. The various hybridized architectures further give rise to 0D, 1D, 2D and 3D carbon materials. Owing to the intrinsic differences in dimensional structures, these carbon materials exhibit distinct thermal transport behaviors, photothermal conversion modes, and interfacial mass transfer mechanisms. Specifically, 0D carbon materials (e.g., carbon black) primarily rely on localized heat accumulation to achieve rapid interfacial temperature elevation^[72], 1D carbon materials (e.g., carbon nanotubes and carbon fibers) construct fast pathways for heat and ion transport through continuous sp^2 -conjugated structures; 2D carbon materials (e.g., graphene and GO/rGO)^[93–94] enable efficient interfacial photothermal conversion and uniform thermal diffusion through their large-area layered architectures; while 3D carbon materials further realize enhanced light harvesting, thermal localization, and directional ion transport through hierarchical porous networks (Fig. 4).

3.1 0D carbon materials

0D carbon materials mainly include carbon black (CB), carbon quantum dots (CQDs)^[95], and fullerene (C_{60}), which are typically characterized by nanoparticulate morphologies and highly disordered sp^2 carbon networks^[95]. Due to the large interfacial thermal

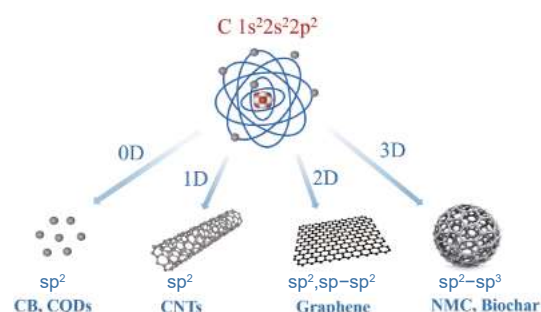


Fig. 4 Dimensionality-varied carbon frameworks based on different hybridization states of carbon atoms

resistance between adjacent nanoparticles, heat diffusion over long distances is substantially suppressed in 0D carbon materials, thereby facilitating localized heat accumulation at the evaporation interface. This “thermal localization” characteristic enables rapid interfacial temperature elevation under solar irradiation, thereby enhancing interfacial evaporation and promoting localized Li^+ enrichment, which constitutes one of the major advantages of 0D carbon materials in photothermal lithium extraction systems. In addition, materials such as carbon black are abundant, inexpensive, and readily scalable, making them highly promising for large-scale photothermal lithium extraction applications^[96–97].

The application of 0D carbon materials in photothermal lithium extraction is not without limitations. Owing to their intrinsically high surface energy, nanoparticles tend to aggregate within the composite systems^[92,98], leading to reduced effective photothermal active sites and declining interfacial light absorption efficiency. Meanwhile, the lack of continuous thermal conduction and ion transport pathways between particles makes it difficult to establish stable capillary

water transport networks and efficient Li^+ migration channels, thereby restricting long-range heat transfer and ion diffusion^[99]. In recent studies, it is increasingly common to incorporate 0D carbon materials into three-dimensional porous scaffolds, hydrogels, or interfacial evaporation architectures to synergistically optimize thermal localization and continuous mass transfer^[92]. In such systems, 0D carbon materials function as “localized photothermal centers,” whereas the porous framework is responsible for water transport, thermal management^[100], and ion migration, together constituting an important design strategy for efficient interfacial photothermal lithium extraction systems.

For example, Xing et al.^[92] integrated 0D photothermal nanoparticles with a 3D porous scaffold to construct a synergistic “0D photothermal center + 3D mass transfer scaffold” system. This system achieves both solar-driven lithium extraction and freshwater production through vertically alternating hydrophilic adsorption layers and superhydrophobic photothermal

layers simultaneously. The system consists of hydrophilic macroporous hydrogel layers (CCH) containing HTO lithium-ion sieves and superhydrophobic O-Sponge layers interconnected by hydrophilic cotton threads (Fig. 5a). In this architecture, 0D carbon black (CB), serving as the photothermal material, is dispersed within the CCH hydrogel. Benefiting from the embedded CB nanoparticles, the CCH hydrogel exhibits an outstanding solar absorption of approximately 97% across the entire solar spectrum (Fig. 5b). CB nanoparticles rapidly convert absorbed light into heat via nonradiative relaxation. Coupled with high interparticle thermal resistance, which limits heat dissipation into the bulk solution, this results in significant localized heat accumulation at the evaporation interface. Such highly localized interfacial heating efficiently elevates the interfacial temperature, enhances water evaporation, and continuously promotes Li^+ enrichment near the adsorption interface.

Importantly, the superior performance of mixed-

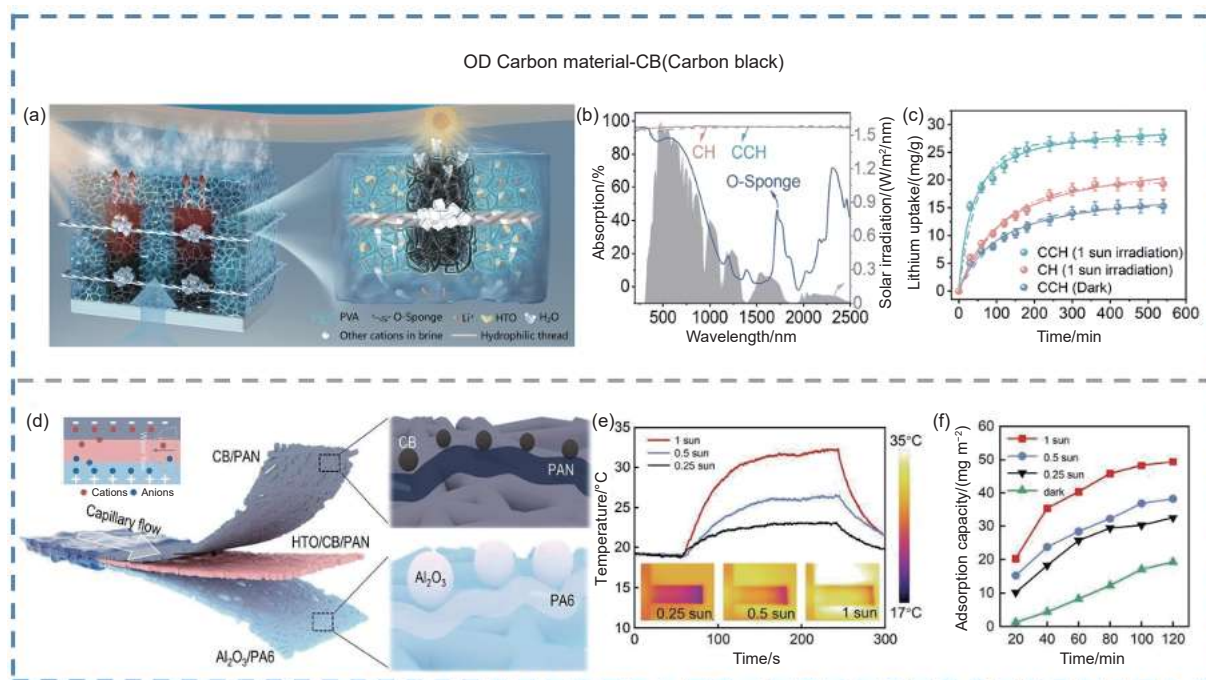


Fig. 5 Examples of 0D carbon materials applied in photothermal lithium extraction. (a) Schematic of a 3D evaporator for lithium extraction, assembled from hydrophilic CCH (with CB), a superhydrophobic O-sponge, and patterned hydrophilic threads. (b) Light absorbance performance of CCH, CH and the O-sponge. (c) Lithium adsorption kinetics of the 3D evaporators (200 mg·g⁻¹, pH=12). Error bars are the standard deviation of lithium uptake over three repetitions^[88]. Copyright 2025, Energy & Environmental Science. (d) Schematic of e-fabric evaporator structural design: Top layer is PAN-reinforced CB photothermal layer; Bottom layer is PA6-modified Al₂O₃ thermal insulation layer. (e) Surface temperature profiles of e-fabric under varying light intensities. Insets show corresponding infrared thermographic images. (f) Li⁺ adsorption capacity versus sunlight intensity in 200 mg·L⁻¹ solution^[92]. Copyright 2025, Advanced Materials

dimension carbon system relies on both the localized heat-generation capability of 0D carbon black, and the synergistic regulation of heat and mass transfer enabled by the 3D layered architecture. Unlike conventional homogeneous evaporation systems, the hydrophilic/hydrophobic wettability contrast allowed directional transport of heat, water, and ions within the system. As a result, under 1 sun irradiation, the system achieves a Li^+ adsorption capacity of $27.7 \pm 1.4 \text{ mg} \cdot \text{g}^{-1}$ within 300 min, significantly higher than that under dark conditions, demonstrating that localized photothermal heating and interfacial ion enrichment markedly enhanced Li^+ adsorption kinetics (Fig. 5c). Even in practical brine sourced from the Dongtai Jiner Salt Lake, the system maintained a Li^+ adsorption capacity of $24.7 \text{ mg} \cdot \text{g}^{-1}$ and a $\text{Li}^+/\text{Mg}^{2+}$ separation factor exceeding 400, while exhibiting excellent long-term stability over 40 adsorption–desorption cycles with Ti loss below 3%.

The superior performance of carbon materials goes beyond an isolated example. Lin et al.^[101] expanded the functional role of 0D carbon materials in photothermal lithium extraction systems by enabling them to function not only as localized heat sources but also as interfacial charge sources simultaneously, thereby advancing photothermal lithium extraction toward self-powered and multifunctionally integrated systems. Specifically, an evaporation-driven fabric composed of a CB-loaded PAN photothermal top layer, an intermediate HTO adsorption layer, and a hydrophilic PA6 layer loaded with Al_2O_3 at the bottom is constructed (Fig. 5d). In this system, carbon black is also responsible for the primary photothermal effect.

Notably, due to the negatively charged surface of the CB and the distinct surface polarity of the underlying $\text{Al}_2\text{O}_3/\text{PA6}$ layer, a charge gradient is established along the thickness direction. Cations, particularly Li^+ and Na^+ in the flowing liquid, preferentially migrate toward the negatively charged CB layer during solar-driven evaporation. This process enables directional ion separation and generates a streaming potential across the asymmetric interface. Therefore, the introduction of carbon black not only promotes evapora-

tion-driven lithium-ion transport but also converts interfacial ion migration into utilizable hydrovoltaic electricity (Fig. 5e). When increasing the irradiation intensity from 0.25 to 1 sun, the Li^+ adsorption capacity gradually increased from 16.51 to 40.87 mg m^{-2} , while the evaporation rate increased from 0.36 to $1.42 \text{ kg m}^{-2} \text{ h}^{-1}$ (Fig. 5f). Lithium recovery efficiency remained as high as 93.2% even after eight adsorption-desorption cycles. This photothermal-hydrovoltaic coupling mechanism enabled the evaporation-driven fabric to achieve efficient Li^+ extraction while powering low-energy sensors continuously, thereby realizing a synergistically integrated “ Li^+ extraction-freshwater generation-self-powered” system.

Overall, 0D carbon materials exhibit significant potential in photothermal lithium extraction systems owing to their nanoscale thermal confinement effect, low cost, and scalability. However, their inherently high surface energy often leads to particle aggregation, while the lack of continuous pathways for heat and mass transport between discrete nanoparticles limits their long-term operational stability, particularly in high-salinity environments. Future research should focus on the integration of 0D carbon materials with 3D porous frameworks, hydrogels, and functional membranes. By constructing continuous water transport and ion migration networks, it may be possible to preserve the advantages of localized thermal confinement while simultaneously enhancing overall mass transfer efficiency.

3.2 1D carbon materials

Unlike 0D carbon materials, which primarily rely on interparticle thermal resistance to achieve localized heat accumulation, the key advantage of 1D carbon materials in photothermal lithium extraction systems lies not merely in “light absorption and heat generation”^[102–103], but more importantly in their ability to construct continuous thermal and ionic transport networks. The sp^2 -conjugated framework found in 1D carbon materials has exceptionally high aspect ratios and axially continuous structures. Its presence gives these materials outstanding axial thermal conductivity and efficient heat diffusion characteristics by allow-

ing phonons to propagate through rapidly^[97,104–105].

Consequently, 1D carbon materials such as carbon nanotubes (CNTs) can distribute localized photo-thermal energy rapidly throughout the entire adsorption interface^[106], thereby avoiding local overheating and establishing a more uniform and stable temperature field^[98,106–107], which is of great significance for enhancing interfacial evaporation and improving photo-thermal utilization efficiency^[97–98,108]. Meanwhile, the interconnected nanofibrous network formed by CNTs can also provide continuous capillary transport channels and low-tortuosity ion diffusion pathways^[109]. Particularly in hydrogels, porous membranes, and fibrous textile systems, CNTs can form interpenetrating network structures with polymer chains^[110], enabling rapid Li^+ migration along nanoscale channels, thereby reducing ion diffusion resistance and enhancing interfacial mass transfer effectively^[95,111–113]. The advantages of 1D carbon materials, exemplified by CNTs, are primarily characterized by rapid axial

thermal transport.

These advantages were clearly demonstrated in a recent study by Zhou et al.^[90]. Through a simple dip-coating and crosslinking process, CNTs, LIS of $\text{H}_4\text{Ti}_5\text{O}_{12}$ (HTO), and gelatin were blended and coated onto weaved cotton to fabricate a flexible photothermal membrane termed CHG-10. In this system, CNTs formed an axially continuous thermal conduction network (Fig. 6a). Under 1 sun irradiation, the efficient photothermal conversion of CNTs rapidly increases the membrane surface temperature to $52.1\text{ }^\circ\text{C}$, driving a water evaporation rate of $2.33\text{ kg m}^{-2}\text{ h}^{-1}$ with an evaporation efficiency as high as 93.8%. More importantly, the CNT network simultaneously established capillary nanochannels to reduce the diffusion resistance of Li^+ from the bulk solution toward the HTO adsorption sites. Notably, under illumination, the thermo-osmotic ion pumping effect maintained the lithium concentration close to the inlet level, whereas under dark conditions, only 70% of the initial lithium

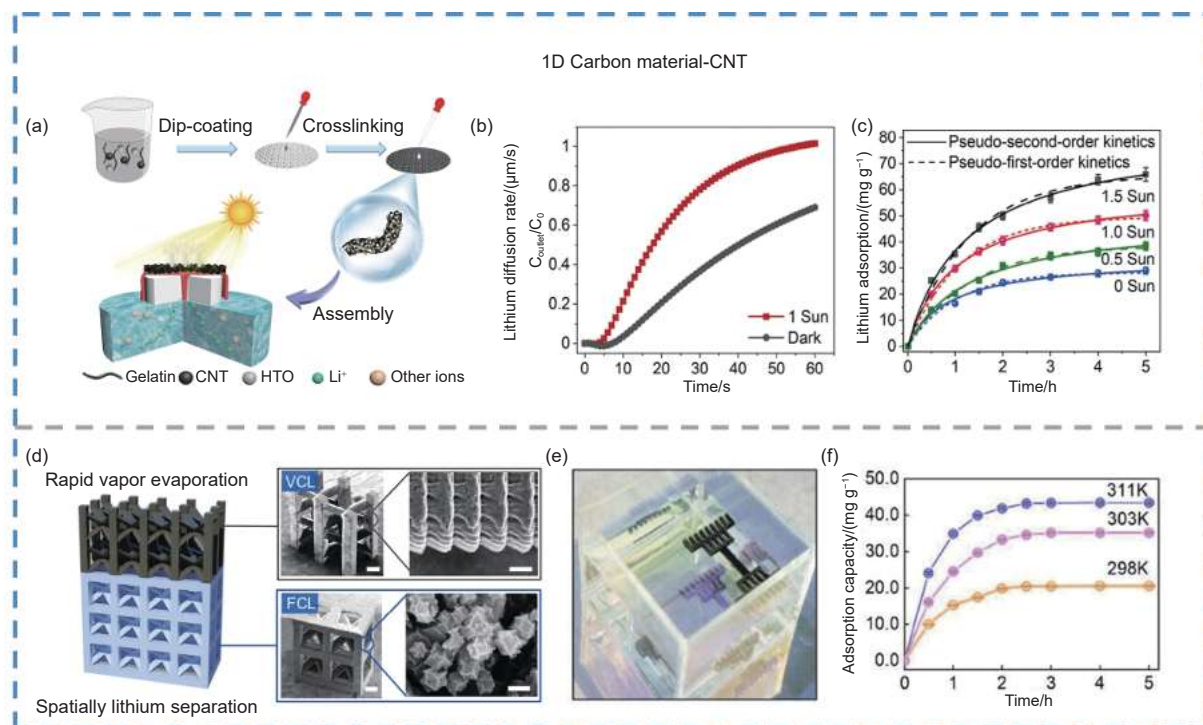


Fig. 6 Examples of 1D carbon materials applied in photothermal lithium extraction. (a) Scheme for the preparation of CHG-x for the water evaporation-enhanced lithium extraction from salt-lake brines. (b) Lithium enrichment factor (C_{outlet}/C_0) near to the surface of the evaporator under 1-sun and dark conditions. (c) Lithium adsorption of CHG-10 under solar irradiation of various intensities, and the quasi-first-order and quasi-second-order kinetic fittings ($\text{pH}=12$, lithium concentration= $200\text{ mg}\cdot\text{L}^{-1}$)^[90]. Copyright 2026, Journal of Materials Science & Technology. (d) Structural illustration of the JCSP device featuring a multi-branched Janus cellular architecture, where the upper and lower layers are connected via a central flipping lever (Scale bar: 10 mm). (e) the collector for lithium recovery. (f) Temperature-dependent Li^+ adsorption kinetics of the $\text{HTO}@C\text{-ZIF-8}$ nanocomposite^[87]. Copyright 2025, Advanced Materials

concentration within the CHG-10 layer could be retained (Fig. 6b). In $200 \text{ mg} \cdot \text{L}^{-1} \text{ Li}^+$ solution, the Li^+ adsorption capacity of CHG-10 reached $50.1 \pm 1.6 \text{ mg} \cdot \text{g}^{-1}$ within 5 h under illumination, which was substantially higher than the $29.0 \text{ mg} \cdot \text{g}^{-1}$ obtained under dark conditions (Fig. 6c). Furthermore, the system exhibits a $\text{Li}^+/\text{Mg}^{2+}$ selectivity factor of 177.9 and demonstrates excellent cycling stability in simulated salt-lake brine.

More recently, Wang et al.^[87] designed a bilayer Janus cellular-structured solar-powered platform (JC-SP) by 3D printing for simultaneous solar-driven lithium extraction and freshwater generation using Ti-based LISs as adsorbents. Specifically, the upper layer consists of a hydrophobic photothermal layer with a vertical cubic lattice (VCL) modified by multi-walled CNTs (MWCNTs). As shown in Fig. 6d, MWCNTs are embedded into the 3D-printed resin matrix resulting in broadband solar absorption efficiency as high as 95.9% together with excellent thermal localization. Meanwhile, the hydrophobicity of the resin matrix suppressed salt crystallization effectively. The lower layer, serving as a hydrophilic adsorption layer, is composed of a full cubic lattice (FCL) functionalized with $\text{HTO}@\text{C-ZIF-8}$ composite adsorbents. The nano-confined channels formed by MWCNTs and carbonized ZIF-8 cooperated with the LIS synergistically to provide rapid migration pathways for Li^+ . Such combination resulted in enhanced ion diffusion through structure-guided fluid transport. The photothermal layer induced interfacial Marangoni flow, while the adsorption layer enabled spatial enrichment and selective capture of Li^+ ions.

The aforementioned bilayer system incorporated a self-flipping mechanism in which evaporation-driven mass imbalance triggered autonomous self-cleaning behavior to prevent salt crystallization and pore blockage (Fig. 6e). Benefiting from the significantly accelerated Li^+ adsorption kinetics induced by the photothermal effect (Fig. 6f), the JCSP exhibits Li^+/Na^+ and $\text{Li}^+/\text{Mg}^{2+}$ separation factors of 112 and 268, respectively, in multicomponent high-salinity brine containing 20% total dissolved salts (Li^+ , Na^+ ,

Mg^{2+} , Ca^{2+} and K^+), while achieving a high adsorption capacity of $43.5 \text{ mg} \cdot \text{g}^{-1}$ and maintaining excellent stability over 30 adsorption–desorption cycles.

Another recent development by Gao et al.^[34] features a superhydrophilic photothermal adsorption hydrogel composed of acrylamide, chitosan, CNTs and LIS nanoparticles. By coupling solar-driven interfacial evaporation with photothermal-enhanced ion enrichment, their system elevated the local interfacial temperature and Li^+ concentration simultaneously, thereby achieving a high lithium adsorption capacity of $31.83 \text{ mg} \cdot \text{g}^{-1}$ in simulated seawater, alongside an excellent photothermal conversion efficiency of 97.61%.

Notably, carbon fibers have also been employed as supporting substrates and transport scaffolds for photothermal functional layers. For example, Liu et al.^[68] developed a carbon-cloth-supported polypyrrole nanoarray evaporator, in which the continuous fluid transport channels and robust structural integrity of the carbon-fiber framework facilitated efficient solar-driven evaporation and selective lithium-sodium separation.

One-dimensional carbon materials fully exploit their continuous axial structure to facilitate efficient transport processes within photothermal lithium extraction systems. Interconnected networks formed by materials such as carbon nanotubes can reduce ion diffusion resistance and promote interfacial mass transfer effectively, which improves lithium adsorption kinetics significantly. Nevertheless, some one-dimensional carbon materials suffer from poor dispersibility, and their intrinsically high thermal conductivity may weaken interfacial thermal localization. In addition, relatively high production costs remain a challenge for large-scale applications. Future developments should emphasize their role as transport scaffolds by constructing directionally aligned and hierarchically interconnected nanochannels. Such architectures are expected to enable the coordinated and directional transport of heat, water molecules, and lithium ions, further improving the overall efficiency of photothermal lithium extraction.

3.3 2D carbon materials

Compared with 0D and 1D carbon materials, 2D carbon materials have the capacity to reconstruct the entire evaporation interface of adsorption systems^[95,114]. Representative examples including graphene, graphene oxide (GO/rGO) are composed of continuous sp^2 -conjugated carbon nanosheets. Such highly extended layered structures not only enable efficient solar absorption, but more importantly facilitate the establishment of continuous and spatially uniform thermal fields over large interfacial areas^[79,111,115]. Consequently, 2D carbon materials no longer function merely as conventional “photothermal fillers within photothermal lithium extraction systems^[110,113,115], but rather serve as key structural units for constructing interfacial evaporation platforms^[109,116].

For instance, Zhu et al.^[84] fabricated a bilayer spherical micro-evaporators (SMEs) with a porous interior and dense outer shell by blending graphene with polyacrylonitrile (PAN) through a diffusion-driven

phase separation strategy, while simultaneously incorporating manganese-based LIS (HMO) particles (Fig. 7a). Within this spherical architecture, graphene nanosheets are uniformly dispersed throughout the polymer framework. Upon solar irradiation, the loosely delocalized π electrons of the graphene are photoexcited, converting absorbed light into thermal energy rapidly through non-radiative relaxation processes, enabling the HGPB surface temperature to increase by 3.2 °C relative to pure water under 1 sun, while a temperature rise of 26.3 °C was achieved under 1.5 sun.

More importantly, the spherical configuration endowed the system with a uniquely adaptive density-driven self-cleaning mechanism. Specifically, when salt crystals accumulated on the evaporator surface and increased the overall density beyond that of saturated brine, the microspheres automatically sank into the solution. During sedimentation, deposited salt particles detached due to hydrodynamic impact and dissolution effects, after which the microspheres re-

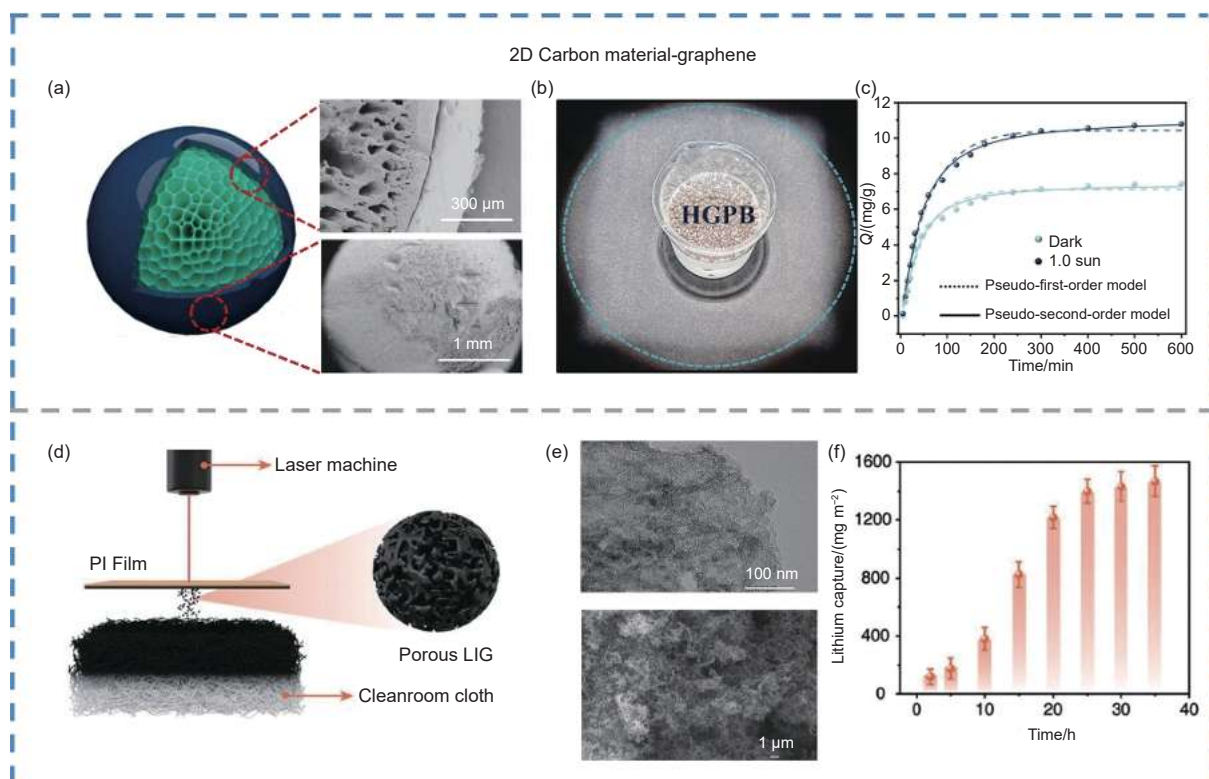


Fig. 7 Examples of 2D carbon materials applied in photothermal lithium extraction. (a) Schematic diagram of HGPB structure. (b) Photograph of actual evaporation unit. (c) Adsorption kinetics of HGPB^[84]. Copyright 2026, AIChE Journal. (d) Schematic preparation of LIG-cleanroom wipe. (e) HRTEM image of LIG and SEM image of LIG coated cleanroom wipe. (f) Lithium capture of the device changes over time under 1 solar illumination^[85].

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floated as their density decreased. Remarkably, the entire self-cleaning cycle is completed in only 4.02 s. This mechanism is highly effective in preventing the continuous salt accumulation commonly observed in conventional fixed evaporators (Fig. 7b). In terms of lithium extraction, the synergistic effects of photothermal-induced interfacial Li^+ enrichment and localized temperature elevation significantly enhanced the adsorption kinetics of HMO. Under 1 sun irradiation, the Li^+ adsorption capacity of HGPB increased by 45% compared with that under dark conditions, reaching $10.77 \text{ mg} \cdot \text{g}^{-1}$ (Fig. 7c), while retaining 91% of its initial adsorption capacity after six adsorption-desorption cycles.

Notably, owing to the abundant defects, oxygen-containing functional groups, and tunable micro/nano-scale roughness present on the surfaces of certain 2D carbon materials, their interfacial wettability can be readily manipulated from hydrophilic to superhydrophobic states^[116]. Since wettability characteristics directly influence interfacial water transport behavior and salt crystallization processes^[63], 2D carbon materials provide promising strategies to address the challenges in salt precipitation and fouling, the most critical bottlenecks in current photothermal evaporation-based lithium extraction systems^[65,117].

In a recent report, laser-induced graphene (LIG) with intrinsic micro/nano hierarchical roughness and low surface energy shows remarkable superhydrophobicity, with a water contact angle reaching 143° . Specifically, Zhong et al.^[85] integrated a metal-organic framework (MOF)-based membrane with LIG to construct a sandwich-structured solar interfacial evaporation-driven lithium extraction (SIEDL) system (Fig. 7d, e). LIG functioned as an efficient photothermal material, while also leveraging its intrinsic superhydrophobicity to suppress salt fouling during prolonged evaporation. Even with localized brine supersaturation causing trace salt crystallization, the LIG photothermal surface did not allow particles to adhere to it, instead rolling away with condensed droplets or being diverted to peripheral water-transport layers. As a result, the system eliminated the need for complica-

ated anti-salt engineering strategies commonly adopted in conventional evaporators, such as Janus architectures, self-flipping designs, or adaptive floating-sinking mechanisms. Benefiting from this unique anti-fouling behavior, the system achieved a maximum Li^+ extraction capacity of $1467 \text{ mg} \cdot \text{m}^{-2}$ under 1 sun irradiation, while the LIG layer retained 94.2% of its initial lithium extraction performance after 20 extraction-regeneration cycles (Fig. 7f). In addition, designing a bilayer sponge by integrating CNT and rGO is also seen to improve Li^+ adsorption efficiency^[83].

2D carbon materials, by virtue of their ultra-large specific surface area and continuous conjugated structure, establish a uniform and stable temperature field across large-scale evaporation interfaces while simultaneously integrating photothermal conversion and interfacial wettability regulation. Consequently, they are highly efficient photothermal materials while providing essential structural support in evaporation platforms. However, two-dimensional nanosheets are prone to interlayer restacking, which leads to a reduction in their effective specific surface area, while excessively dense layered structures may increase the transport resistance for water molecules and ions. Future research should focus on the interfacial engineering of 2D carbon materials. By modulating the interlayer structure, surface wettability, and micro/nano-scale roughness, enhanced light harvesting, optimized interfacial temperature fields, and improved salt resistance can be achieved, thereby further exploiting their advantages as core structural units of photothermal evaporation interfaces.

3.4 3D carbon materials

With the continuous development of photothermal lithium extraction technologies, the functional role of carbon materials has gradually evolved from simple photothermal conversion surface toward integrated interfacial regulation. Compared with 0D, 1D and 2D carbon materials, which mainly focus on localized heat generation, directional thermal conduction, or interfacial heat diffusion, 3D carbon materials feature the synergistic regulation of light harvesting, heat management, water transport and ion migration in one

package. Essentially, they can be regarded as interfacial microreactor systems with intrinsic multi-field coupling capabilities^[118–119].

3D carbon materials generally possess hierarchical porous architectures composed of interconnected micropores, mesopores, and macropores^[120]. Such complex pore networks significantly increase the specific surface area while also endowing the materials with unique volumetric light-harvesting capability. Unlike 2D materials that mainly rely on surface light absorption, 3D carbon materials utilize solar energy throughout their entire bulk volume for stable and efficient photothermal conversion performance^[121].

Beyond enhanced light capture, 3D porous carbon frameworks also play crucial roles in thermal management and interfacial mass transfer. Owing to the large amount of low-thermal-conductivity air confined within the pores, 3D carbon skeletons can generate pronounced thermal localization effects, suppressing heat dissipation into the bulk solution. The confinement of heat minimizes thermal loss while maintaining elevated temperatures at the evaporation interface, further promoting interfacial evaporation and Li^+ enrichment^[122]. Consequently, the porous architecture itself functions not only as a structural scaffold, but also as an essential component for interfacial thermal regulation. In addition, the interconnected macroporous and mesoporous networks provide continuous capillary-driven water transport, enabling stable brine delivery to the evaporation interface^[123–124]. The evaporation-induced directional fluid flow further facilitates Li^+ migration toward the adsorption sites, thereby enhancing interfacial mass transfer and adsorption kinetics.

For example, Xia et al.^[91] constructed an integrated solar micro-evaporator based on nitrogen-doped mesoporous carbon (NMC) nanospheres (Fig. 8a). The NMC framework features a hierarchical porous structure comprising micropores, mesopores, and macropores. The approximately 20 nm mesoporous channels induce multiple internal reflections and scattering of incident light, which significantly reduces optical reflection losses and achieves an overall light

absorption efficiency of up to 98%. Such a 3D porous structure endows the material with excellent volumetric light-harvesting capability, serving as the foundation for efficient photothermal conversion (Fig. 8b). Meanwhile, the low-thermal-conductivity microenvironment formed by the confined air within the pore channels further enhanced thermal localization and suppressed heat dissipation into the bulk solution. On this basis, HTO was grown in situ within the mesoporous cavities of the NMC, forming a typical yolk-shell structure.

In addition to its photothermal conversion capabilities, the hydrophilic 3D NMC skeleton with a water contact angle of $\sim 20^\circ$ enables continuous brine transport through its interconnected capillary network. It can sustain a stable liquid film at the evaporation interface while promoting Li^+ migration and enrichment within nanoconfined pores. Importantly, the hierarchical porous structure of NMC serves multiple purposes at once, including photothermal conversion, thermal localization, capillary water transport, and nanoconfined ion enrichment. As a result, the entire system functioned synergistically as a “photothermal engine-microfluidic pump-nanoreactor” integrated platform. Under 1 sun, the Li^+ adsorption capacity of the HTO@NMC composite increased to 28.7 $\text{mg} \cdot \text{g}^{-1}$, compared with 23.7 $\text{mg} \cdot \text{g}^{-1}$ under dark conditions, while the adsorption saturation time was shortened to 6 h, indicating that the synergistic interfacial heat and mass transfer processes significantly enhanced Li^+ adsorption kinetics (Fig. 8c).

In contrast to conventionally synthesized porous carbons, biomass-derived carbon offers distinct advantages due to its naturally hierarchical porosity and low-cost, one-step preparation. These inherent strengths translate into superior performance in integrated applications such as photothermal evaporation and resource recovery. For instance, Zhu et al.^[89] physically integrated flame-treated delignified wood (FW) (Fig. 8d) with HMO-loaded porous straw (HS) to construct a gradient-channel photothermal adsorbent (FW-HS) featuring an “upper-large/lower-small” pore architecture. Specifically, FW retained the natur-

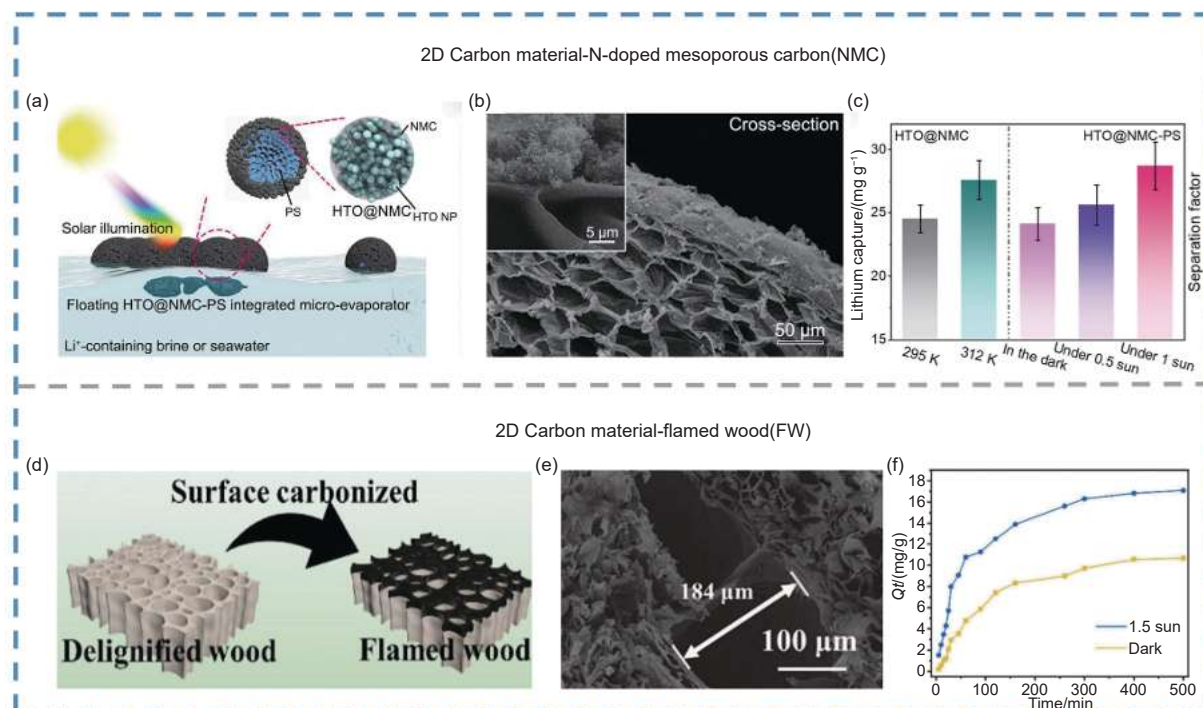


Fig. 8 Examples of 3D carbon materials applied in photothermal lithium extraction. (a) Design and characterization of LTO@NMC nanocomposites for the photothermal and nanoconfined lithium recovery. (b) Cross-section SEM images of the HTO@NMC-PS bead, respectively. The inset shows the enlarged morphology. (c) Li⁺ adsorption performance of the HTO@NMC-PS evaporator system in the dark and under solar irradiation in Li⁺ simulated brine (100 mg g⁻¹, pH 12)^[91]. Copyright 2024, Proceedings of the National Academy of Sciences. (d) Schematic diagram of the preparation process of FW. (e) SEM images of FW. (f) adsorption capacity^[89]. Copyright 2025, Chemical Engineering Science

al vertically aligned macropores of wood (130–200 μm) (Fig. 8e), while the carbonized surface exhibited significantly enhanced light absorption across the 200–2500 nm wavelength range. Under 1 sun irradiation, the surface temperature increased to 41.5 °C rapidly, driving an evaporation rate of 2.86 kg·m⁻²·h⁻¹. Meanwhile, the capillary channels within the lower straw layer (60–70 μm) provide continuous water supply, whereas the larger upper pores shortened ion migration pathways, enabling the complete dissolution and removal of 0.2 g NaCl from the surface within 15 min.

Benefiting from this synergistic structure, the FW-HS system exhibits an Li⁺ adsorption capacity enhancement of 6.84 mg·g⁻¹ under 1.5 sun irradiation compared with dark conditions, reaching a total adsorption capacity of 19.53 mg·g⁻¹ (Fig. 8f), while still retaining 91.9% of its initial adsorption capacity after five cycles. While its spectral absorption efficiency falls behind to that of NMC, particularly in the long-wavelength near-infrared region, the preparation process required only rapid flame carbonization and

simple physical assembly, resulting in extremely low fabrication cost. More importantly, the direct utilization of abundant natural biomass resources such as wood and straw makes this strategy highly promising for large-scale deployment in practical salt-lake lithium extraction applications.

Three-dimensional carbon materials represent a major developmental direction in photothermal lithium extraction owing to their ability to achieve integrated regulation of light harvesting, thermal localization, water transport, and ion migration through hierarchical porous architectures. Their intrinsic capability for multiphysics coupling enables the construction of integrated platforms that combine solar evaporation, ion enrichment, and lithium adsorption within a single system. Despite these advantages in terms of current three-dimensional carbon materials still face challenges related to structural stability, precise pore architecture control, and limited functional integration. Future studies should leverage advanced fabrication techniques such as ice-templating, self-assembly, three-dimensional printing, and biomass-derived dir-

ectional carbonization to develop next-generation three-dimensional carbon materials with controllable pore structures, directional ion transport capabilities, and intelligent responsiveness. Advances in these key areas facilitate the transition of photothermal lithium extraction systems from simple photothermal enhancement toward comprehensive multiphysics-coupled synergistic optimization.

4 Conclusions

In summary, the development of integrated systems of solar interfacial evaporation with LIS adsorption, membrane separation, and ion transport processes provides a promising strategy toward low-energy and sustainable lithium recovery. Among various photothermal materials, carbon-based systems have emerged as the most representative and competitive candidate due to their broadband light absorption, excellent chemical stability, and tunable multiscale structural features. Through a systematic classification from 0D to 3D carbon materials, this review summarizes their roles and structure-property relationships in photothermal conversion, thermal management, and interfacial mass transport.

It is demonstrated that 0D carbon materials mainly promote interfacial heating through localized thermal accumulation; 1D carbon materials function as efficient pathways for directional heat and ion transport; 2D carbon materials reconstruct large-area, uniform photothermal interfaces and enhance interfacial evaporation behavior; while 3D carbon materials enable multi-field synergistic regulation through hierarchical porous architectures, integrating light harvesting, thermal confinement, and directional transport. Furthermore, the synergistic use of carbon materials across different dimensions has gradually transformed them from simple photothermal converters into multifunctional interfacial microreactor systems coupling solar energy conversion, ion enrichment, and structural support.

5 Prospects

Despite rapid advances in photothermal lithium

extraction, carbon-based composite materials remain at an early stage in practical photothermal lithium recovery applications. Future research should look beyond isolated improvements in evaporation rate or adsorption capacity and toward the holistic optimization of photothermal conversion, thermal management, ion transport, interfacial chemistry, and system-level integration^[125–127]. Owing to their tunable dimensionality, rich surface chemistry, and structural diversity, carbon materials are anticipated to remain a core component of next-generation photothermal lithium extraction technologies.

A fundamental challenge lies in the lack of comprehensive understanding of the structure-function relationships in carbon materials. Although zero-dimensional (0D), one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) carbon materials play distinct roles in localized heating, directional transport, interfacial heating, and thermal confinement, respectively, the coupled dynamics of photon absorption, phonon transport, interfacial evaporation, and Li^+ migration are yet to be explored. Therefore, in situ characterization techniques and multiscale modeling are essential for establishing quantitative structure-property-transport relationships under operational conditions.

Another key direction involves designing the integration of multi-dimensional carbon components to overcome the inherent performance trade-offs in single-component systems. Hierarchical architectures that combine localized photothermal centers, continuous transport networks, and porous scaffolds offer a viable pathway for simultaneously enhancing heat localization, ion diffusion, and anti-scaling performance. Building on existing reports of vertical-aligned structures capable of facilitating directional ion/water transport^[128], designing carbon-based composite systems with vertical channels is expected to overcome mass transport limitations in conventional structures, thereby improving the overall efficiency of photothermal lithium extraction^[89].

Finally, fabrication at scale, and validation under realistic operating conditions remain decisive for technological translation. Compared to high-cost nanocar-

bons, biomass-derived carbons and other low-cost carbonaceous materials may offer more practical pathways^[129]. Establishing standardized evaluation met-

rics and conducting tests under real brine conditions are crucial to bridging laboratory advances with industrial implementation (Fig. 9).



Fig. 9 The Linkage between fundamental research and practical applications of dimensionality-engineered carbons-involved Photothermal lithium extraction

Overall, carbon-based photothermal systems are evolving from passive solar absorbers into integrated interfacial platforms that synergize energy harvesting and ion transport, opening a promising technological route toward sustainable lithium recovery.

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