

Review

Carbon-Based Thermal Management Solutions and Innovations for Improved Battery Safety: A Review

Benjamin Tawiah ^{1,2} , Emmanuel A. Ofori ³, Daming Chen ¹, Yang Ming ¹, Yongdan Hou ^{3,*} , Hao Jia ⁴  and Bin Fei ^{1,*}

¹ School of Fashion and Textiles, The Hong Kong Polytechnic University, Kowloon, Hong Kong SAR, China; benjamin.tawiah@connect.polyu.hk (B.T.); daming.chen@polyu.edu.hk (D.C.); yang23.ming@polyu.edu.hk (Y.M.)

² Department of Industrial Art (Textiles), Kwame Nkrumah University of Science and Technology, PMB, Kumasi AK-417-4732, Ghana

³ Hubei Key Laboratory of Energy Storage and Power Battery, Shiyan Key Laboratory of Quantum Information and Precision Optics, School of Automotive Materials, Hubei University of Automotive Technology, Shiyan 442002, China; 202342064@huat.edu.cn

⁴ Key Laboratory of Eco-Textiles, Ministry of Education, Jiangnan University, Wuxi 214126, China; jiahao@jiangnan.edu.cn

* Correspondence: yongdan.hou@huat.edu.cn (Y.H.); bin.fei@polyu.edu.hk (B.F.)

Abstract: The extensive use of lithium-ion batteries and other energy storage systems (ESS) in recent years has resulted in a critical need for effective thermal management solutions that ensure safe and reliable operations. Carbon-based materials (C-bMs) are a promising candidate for addressing the thermal challenges in ESS due to their unique thermal, electrical, and structural properties. This article provides a concise overview of C-bM thermal management solutions for improved battery safety. The key thermal management requirements and failure modes associated with battery systems are highlighted, underscoring the importance of effective battery thermal management (BTM). Various forms of C-bMs, including graphite, graphene, carbon nanotubes, carbon foams, nanodiamonds, and graphdiyne, are examined for their potential applications in battery thermal management systems. The recent innovations and advancements in C-bM thermal management solutions, such as phase change composites, heat pipes, and thermal interface materials, are highlighted. Furthermore, the latest research trends focus mainly on the development of hybrid battery thermal management solutions, carbon-based aerogels, and complex C-bM structures with tailored thermal pathways for optimized thermal management. Most of the current innovations are still at the laboratory scale; hence, future research efforts will be focused on developing integrated multi-functional C-bMs, sustainable and scalable manufacturing techniques, self-healing C-bMs composites, intelligent C-bMs, and further explorations of uncommon C-bMs. These advancements are bound to enhance performance, sustainability, and application-specific adaptations for BTM. This article provides valuable insights for researchers, and stakeholders interested in leveraging C-bMs for BTM.

Keywords: energy storage; thermal management; battery safety; thermal runaway; sustainable energy; carbon materials



Academic Editor: King Jet Tseng

Received: 28 January 2025

Revised: 7 March 2025

Accepted: 1 April 2025

Published: 7 April 2025

Citation: Tawiah, B.; Ofori, E.A.; Chen, D.; Ming, Y.; Hou, Y.; Jia, H.; Fei, B. Carbon-Based Thermal Management Solutions and Innovations for Improved Battery Safety: A Review. *Batteries* **2025**, *11*, 144. <https://doi.org/10.3390/batteries11040144>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Energy storage systems (ESS) are critical enablers for many applications, from electric vehicles and portable electronics to grid-scale energy storage solutions [1–3]. Most of the energy storage technologies of commercial value are characterized by high energy

density, long cycle life, and relatively low cost [4,5]. However, the inherent safety concerns associated with most commercial ESS in connection to thermal runaway pose significant challenges that ought to be solved to facilitate their wider use in unconventional energy-demanding applications [6,7].

Thermal runaway, a highly exothermic chain reaction triggered by various factors such as overheating, internal short circuits, or mechanical abuse, can lead to the release of flammable gases, fire, and even explosive failure of ESS [7,8]. This catastrophic event not only threatens the safety of end-users but could also lead to significant financial and environmental consequences, hindering the large-scale deployment of ESS in critical areas of high energy security [9,10]. For instance, the National Highway Traffic Safety Administration (NHTSA) reported 52 incidents of BEV battery fires in the United States between 2020 and 2022 with remote causes attributed mainly to thermal runaway reactions, short circuits, and overcharging [11]. Such BEV fires release toxic fumes and vapours, which pose significant health hazards to responders and bystanders. The challenge in extinguishing such BEV fires is due to the high energy density, which makes them reignite even after initial extinguishment [12,13].

Studies suggest that effective thermal management can improve energy retention by approximately 10–30% in battery systems through the prevention of thermal degradation and the enhancement of charge/discharge cycles [14,15]. In terms of energy density, the integration of efficient thermal management solutions can lead to power density improvements of around 15–25% in high-performance applications, such as electric vehicles and portable electronics, by enabling faster charge and discharge rates without overheating [16,17]. Therefore, the development of effective thermal management solutions that reduce the risks associated with high-density ESS has become a crucial research focus with the primary aim of enhancing overall safety and reliability [9,18]. Conventional thermal management solutions often rely on bulky and energy-intensive auxiliary components, which can compromise the energy density and efficiency of the overall ESS [19]. One of the most common conventional thermal management solutions is the use of air-cooling systems [20,21]. These systems rely on fans or blowers to circulate ambient air over the energy storage devices, removing the generated heat. Air-cooling systems are generally simple, inexpensive, and easy to implement, making them a popular choice for many applications. However, they can be limited in their ability to dissipate large amounts of heat, particularly in high-power or high-density ESSs [22]. Another conventional approach is the use of liquid-cooling systems [23]. These systems employ a liquid, such as water or a water-glycol mixture, to absorb and transport the heat away from the energy storage devices. Liquid-cooling systems can be more effective than air-cooling systems in dissipating large amounts of heat; however, they require additional components, such as pumps, heat exchangers, and coolant reservoirs, which can add complexity and cost to the system [24].

In addition to the above solutions, some ESSs also incorporate heat sinks [19,25], thermal interfaces [26,27], or a combination of these technologies to enhance their thermal management capabilities [28]. The choice of the appropriate thermal management solution depends on various factors, such as power density, operating conditions, and cost constraints of the energy storage system. Lately, phase change materials (PCMs) have been undergoing rapid research and development for use as effective thermal management solutions for ESS [29]. PCMs undergo phase change (e.g., solid to liquid or liquid to gas) at a specific temperature, absorbing or releasing large amounts of latent heat in the process. By strategically placing PCMs around the energy storage devices, the heat generated can be absorbed and stored, effectively regulating the temperature of the system. PCM-based thermal management solutions are generally passive and require minimal maintenance, but their effectiveness can be limited by the specific phase change temperature and the

available thermal mass [30]. Beyond PCMs, there is interest in the development of advanced thermal management materials that can effectively mitigate the risks of thermal runaway and improve the intrinsic safety of energy storage devices.

Carbon-based materials (C-bMs) have emerged as promising candidates for thermal management in ESSs, especially in recent years [31,32]. The unique thermal, electrical, and structural properties of C-bMs, including high thermal conductivity, tailorabile thermal properties, and excellent mechanical stability, make them attractive for a range of thermal management applications. These materials can be engineered into various forms such as graphite, graphene, carbon nanotubes, and carbon foams, each with its own set of advantages and potential applications in battery thermal management. Over the last decade, there has been extensive research in carbon-based materials for thermal management [33–35]; while some recent reviews have covered thermal management systems (BTMSs) broadly [36–38], this review specifically highlights the innovations in carbon-based materials like graphene, carbon fibres, expanded graphite, carbon nanotubes, carbon foams, nanodiamonds, and graphdiyne in thermal management solutions for improved battery safety.

Hence, this review synthesizes the latest advancements and innovations in the field, providing a comprehensive overview of carbon-based materials in both conventional and cutting-edge techniques such as hybrid systems combining active and passive cooling strategies in BTMSs for superior performance. Moreover, this review offers a detailed comparison of various carbon-based thermal management strategies, highlighting the strengths and weaknesses of each as well as their potential aspects which are not fully explored. Furthermore, the latest research trends and future directions which are consistent with Sustainable Development Goals (SDG) goals have been highlighted. The integrative literature review approach was adopted using the snowball technique to obtain the necessary documents from Scopus and Google Scholar. An initial 40 seed articles were obtained based on our inclusion criteria using the following search terms: “carbon materials thermal management batteries” and “carbon-based temperature management batteries”. Based on the seed articles, back and forward chaining (bibliographic coupling and co-citation analysis) was performed to generate all the papers used for this review. This technique generated current literature on the subject matter. The results from this review will help researchers and engineers make informed decisions when designing BTMSs for improved battery safety.

2. Fundamentals of Thermal Runaway and Fire Hazards in Batteries

The high energy density requirement of batteries for advanced ESS applications makes them susceptible to exothermic decay due to the volatile nature of the constituent materials [39]. Thermal runaway is the sudden failure of a battery due to temperature growth. The sudden failure could be caused by several factors such as mechanical abuse, electrical abuse, thermal abuse, and internal short circuits, which results in heat generation and possible flames (see Figure 1a,b) [40,41]. A short circuit is an intrinsic phenomenon that happens inside the cell—possibly as a result of a manufacturing defect or a failure in dendritic development, thus resulting in thermal runaway and some instances fire accidents [42]. An intrinsic short circuit happens when a battery separator fails and the cathode and anode come into contact. When the intrinsic short circuit phenomenon is triggered, the electrochemical energy of the materials spontaneously releases heat. Depending on the extent of the thermal event in the system, it could result in a slow decrease in voltage with self-extinguishing behaviour or joule heating as shown in Figure 1c. Beyond level II (see Figure 1c), an unstoppable thermal runaway phenomenon is activated which can result in an explosion and uncontrollable fire. Hydrocarbons such as methane, ethane, and ethylene,

as well as hydrogen, carbon monoxide, and carbon dioxide, are released during thermal runaway [43].

Generally, batteries generate heat during charging and discharging owing to the internal resistance and the electrochemical processes [44]. Heat generation is especially high when the battery management system fails to stop the charging process before the upper voltage limit, resulting in overcharge abuse. Once the cell with the highest voltage is overcharged, the rest of the cells will become affected, resulting in heat and gas generation due to ohmic heat and side reactions [45]. These factors add to the other challenges, such as shorter lifespan, sub-zero temperature working performance, accelerated ageing impact, and potential thermal runaway [46,47]. As a result, several heat management technologies are used on the battery system to optimise safety and extend battery life [48]. Besides the intrinsic heat management systems in batteries, battery pack designs often integrate protection measures at several levels (cell, module, and system) to prevent thermal runaway and propagation mainly by the use of carbon-based materials [49,50]. For complete thermal management in batteries, carbon materials with outstanding heat dissipation qualities have become the material of choice for reducing thermal runaway hazards [51]. These carbon materials are applied in numerous ways, including the fabrication of TIMs, heat spreaders, heat pipes, protective coating layers, and phase change materials.

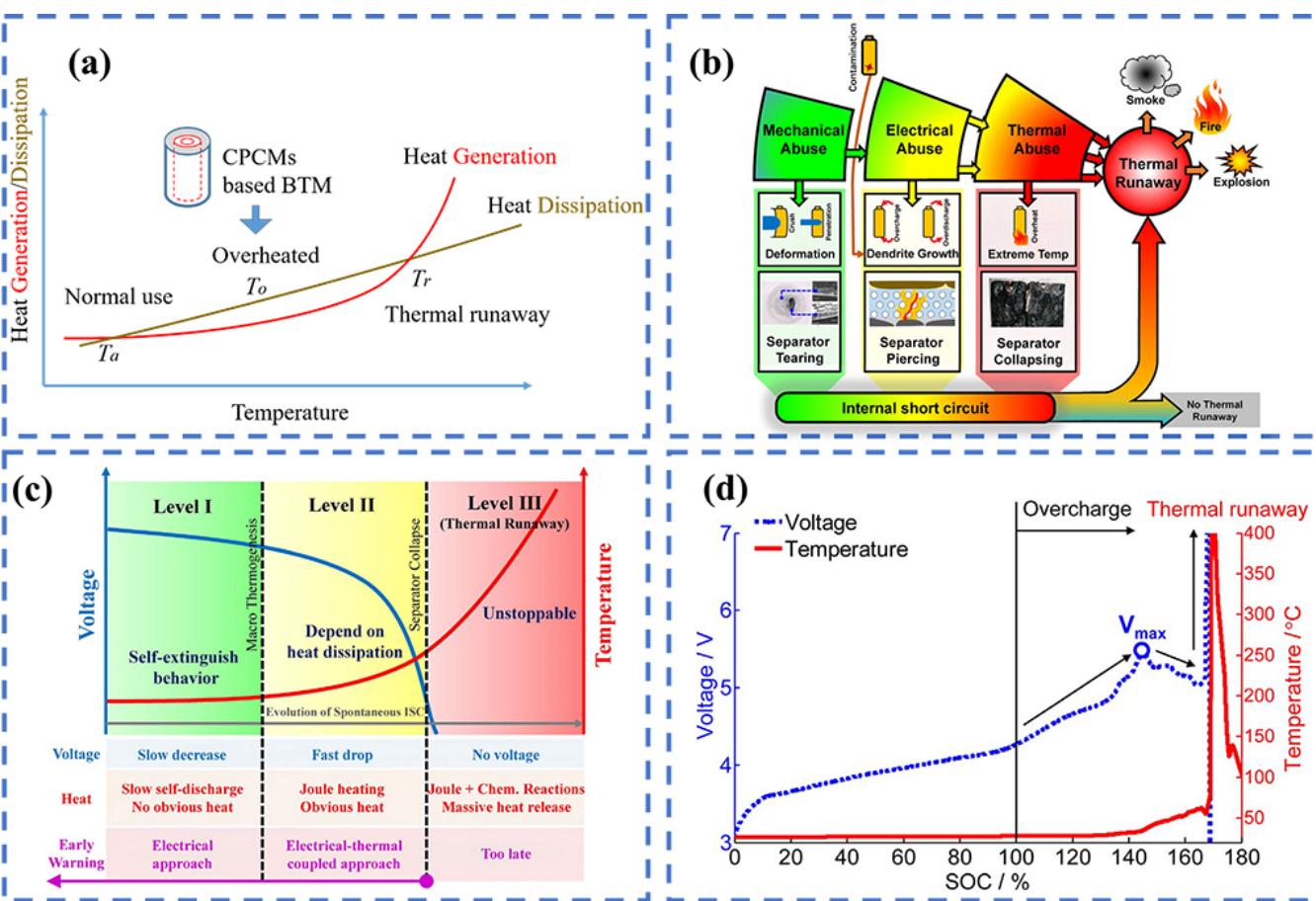


Figure 1. (a) Heat generation/dissipation and thermal runaway. Reprinted from [41], 2023. An open access article by MDPI under CC BY license. (b) Typical abuse conditions in LIBs. (c) Levels of internal short circuits. (d) Typical overcharge-induced thermal runaway for a lithium-ion battery. Reprinted with permission from [45], 2018. Elsevier.

The integration of carbon-based materials into battery design mitigates fire risks by facilitating rapid heat dissipation, thereby preventing localized hot spots that can trigger

thermal runaway [35]. The even distribution of heat throughout the battery helps maintain operational temperatures within safe limits, reducing the likelihood of overheating. Moreover, unlike conventional materials that degrade or combust at elevated temperatures, C-bMs solutions can withstand significant thermal stress without undergoing structural failure [52]. This property enables C-bMs to maintain their integrity and performance even in extreme conditions, providing an essential buffer against the escalation of thermal events. Also, C-bMs increase the overall mechanical strength and flexibility of the battery structure making it more resilient to physical damage of the battery cells during operation, thus preventing the common precursor to thermal runaway [53]. Furthermore, the versatility of C-bMs allows for surface functionalisation with flame-retardant, thereby enhancing their ability to resist ignition and combustion [54]. The use of C-bMs for thermal management solutions enables the development of advanced battery management systems (BMS) for temperature monitoring as well as other critical parameters in real time, allowing for proactive measures to be taken before a thermal runaway event occurs. The integration of C-bMs into battery designs enhances the safety and reliability of battery systems, addressing one of the most pressing concerns in the field of energy storage and electric mobility [55]. Detailed discussions on how specific C-bMs are engineered to reduce thermal runaway can be found in the succeeding sections.

3. Carbon-Based Thermal Management Materials

C-bMs possess unique thermal, electrical, and structural attributes that make them attractive candidates for a range of thermal management applications [56,57]. The various forms of carbon-based materials explored for thermal management include graphite, graphene, carbon nanotubes, nanodiamonds, graphdiyne, and carbon foams, each with its own set of advantages and potential use cases [58,59]. The structural images of some of the carbon materials and their current and potential applications in BTMSs are shown in Figure 2a,b.

Graphite has long been recognized for its high thermal conductivity. Its use is pervasive in thermal management, including heat sinks, and thermal interface [60–62]. It is soft and thermodynamically stable, with the layers parallel to the base plane held together by Van der Waals forces [63]. The layered structure and strong in-plane bonding of graphite contribute to its excellent thermal transport properties [64], making it a valuable material for dissipating heat in battery systems [65]. Recently, graphite-based materials have been engineered with tailored thermal characteristics to optimize their performance in battery thermal management. Graphite sheets are used to delay the spreading of thermal runaway and to provide isothermal conditions on the surface of the cells [66]. For instance, Wang et al. [67] investigated the temperature dependence of the lithium-ion battery (LIB) performance low-energy thermal management system using composite phase change material (PCM) with 10% graphite powder dispersed in paraffin wax via an ultrasonic dispersion. In an extremely cold environment of -20°C , the composite PCM effectively absorbed and regulated the rise in surface temperature for at least 40 min, while also dissipating heat during battery operation. Similarly, Talluri et al. [68] fabricated a composite battery thermal management made of a Li-polymer pouch battery pack and expanded graphite (EG)/PCM for EVs. The PCM/EG composite exhibited an excellent thermal performance at extreme temperatures. Motivated by the body's mechanism for dissipating heat, Zhang et al. [69] integrated graphite-based form-stable phase change material with high enthalpy changes in moisture sorption materials to create a hybrid battery thermal management system (BTMS) using melting-evaporation bilayer technology. The excellent cooling of Li-ion batteries was demonstrated by the skin-inspired hybrid BTMS at very high operation rates. By employing the cooling bilayer, the surface temperature of the ultrafast-cycling batteries dropped by 35.6°C . The capacity of the LIB increased to 244.43 Ah for 318 cycles

of charging and discharging, signalling an extension in the cycle lifetime by 152 cycles. Thanks to its remarkable fire resistance, this cooling bilayer considerably reduced the risk of thermal runaway. Similarly, Lin et al. [65] fabricated phase change (PC) composites made of graphite with excellent shape stability and high thermal conductivity via the melt blending and impregnation method. A long-chain structure and a thermally conductive channel were demonstrated by the expanded graphite in the composite, and it also displayed increased thermal conductivity in the $2.671\text{--}10.019 \text{ W m}^{-1} \text{ K}^{-1}$ range. The battery's operating temperature was also kept below 50°C by the composites under typical charge–discharge and dynamic stress test cycles, demonstrating its excellent thermal management properties. To regulate the surface temperature of batteries, a composite material consisting of EG and paraffin (PA/EG) was fabricated [70]. The composite PA/EG showed better cooling performance under dynamic cycling for a long time, thus keeping the heat away from the battery. To further confirm the thermal performance of carbon-based composites for BTMS, Wang et al. [71] designed a unique PCM/graphite foam with a thermal conductivity of $54.2 \text{ W/m}\cdot\text{K}$ and an equivalent heat capacity of 102.3 J/K , which effectively dissipated the heat battery system despite the high capacity over a long time. Similarly to this, Wu and associates [72] designed a battery enclosure module with 15–20 wt% pyrolytic graphite to boost PCM's thermal conductivity. For prolonged periods, the enclosure prevented the propagation of thermal runaway during full discharge cycles.

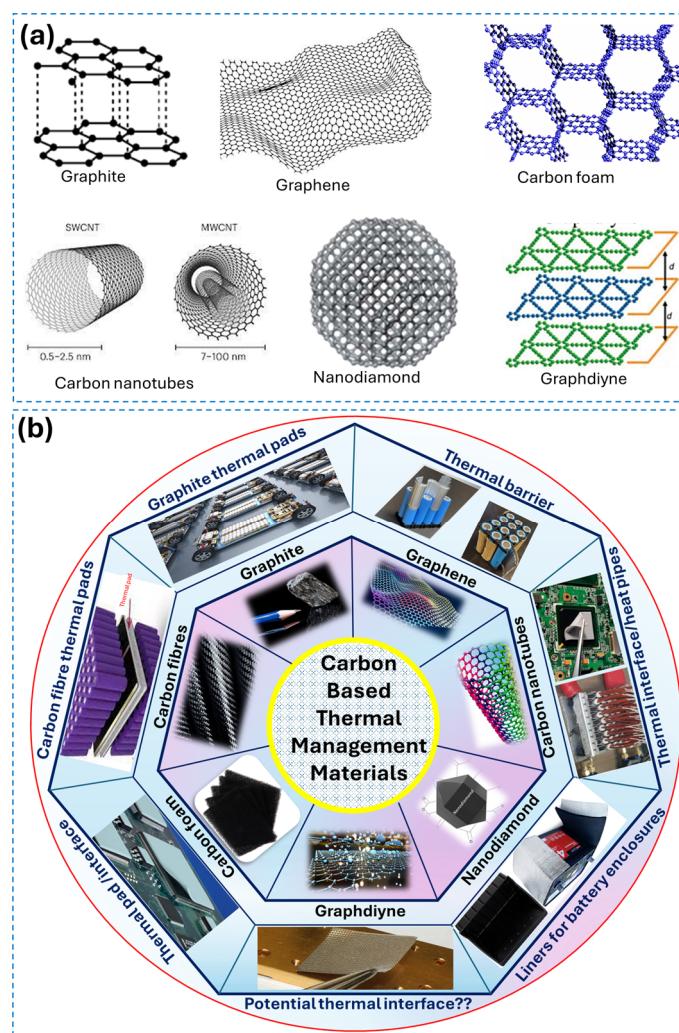


Figure 2. C-bMs for thermal management materials. (a) Structure of some carbon-based materials. (b) Current and potential applications of C-bMs in thermal management.

Zhao et al. [73] fabricated an expanded graphite/polyethylene glycol (EG/PEG) composite PCM through a vacuum impregnation and heating process for application in lithium-ion battery thermal management (refer to Figure 3). The composites improved the heat dissipation and exerted effective thermal regulation through passive thermal management. Typically, passive thermal management utilizes natural processes to regulate temperature without using active components like fans or pumps through key strategies such as heat dissipation through conductive materials and insulation to minimize heat transfer. It also applied the principle of thermal mass for stabilising the temperature variations, phase change materials that absorb or release heat during transitions, and reflective surfaces that reduce heat absorption, thus enhancing energy efficiency and reliability across various applications.

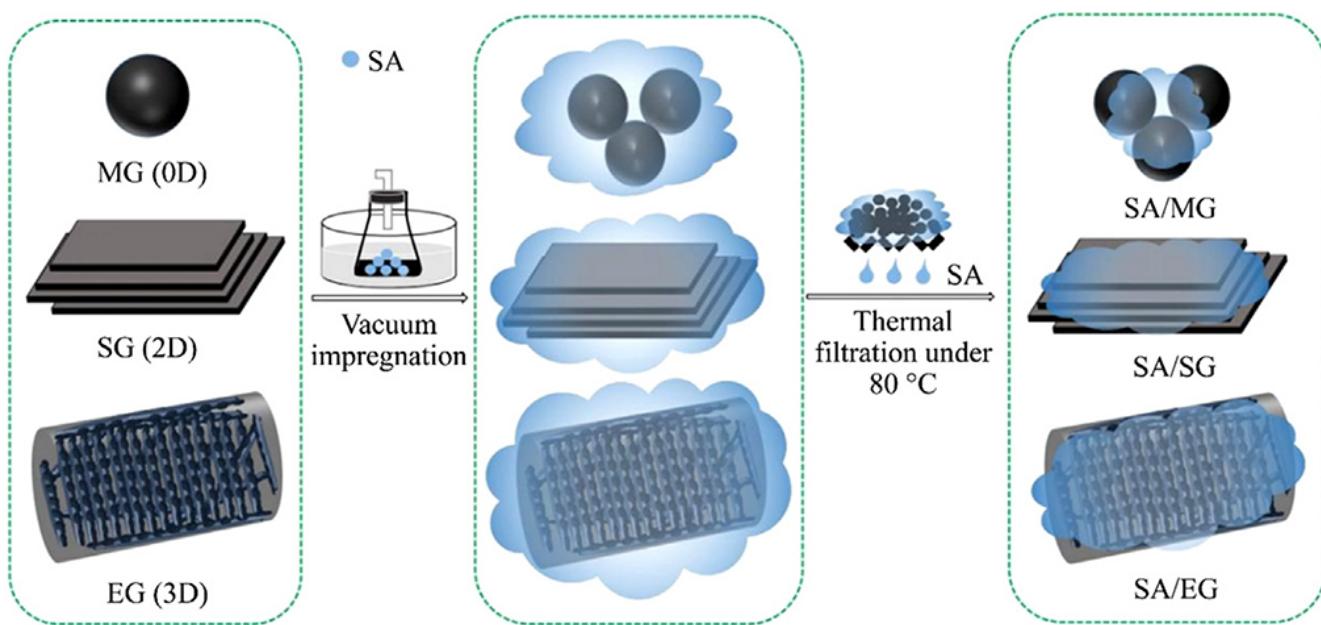


Figure 3. An illustration of the composite preparation process by vacuum impregnation. Reprinted from [73] 2022. An open access article under CC BY-NC-ND 4.0 by Elsevier.

Similarly, graphene is known to possess extraordinarily high thermal conductivity, flexibility, and a wide surface area. Its application in thermal management is noteworthy [74–77]. The unique structure and properties of graphene have enabled the development of novel thermal management solutions, such as graphene-based phase change composites and thermal interface materials, which can effectively enhance heat dissipation and temperature uniformity in battery systems [77,78]. For example, Wu et al. [79] fabricated a 3D hybrid graphene aerogel (HGA) encapsulated with paraffin via the vacuum infusion method and freeze-drying to enhance the thermal conductivity and latent heat of composite PCM for BTMS (see Figure 4a,b). Following 100 thermal cycles, the PW/HGA showed good thermal stability, and excellent thermal conductivity at heating rates of 71.48% and 41.9% higher, respectively. The composite PCMs showed exceptional structure stability and unmatched thermal energy storage/release reliability because of their 3D fibre-bridged construction. The outcomes demonstrated that the porous HGA structure enabled sufficient PW loading exceeding 95 wt.% and thus enhanced the supercooling degree of PW/HGA composite (reduced by 9.37%). In a recent inquiry, Jung et al. [80] developed a laser-induced graphene (LIG) material that is capable of improving BTMS heat transfer properties. It was found that the applied LIG reduced the temperature by up to 84.3% (see Figure 4c). Furthermore, LIG demonstrated a notably greater specific surface area of $340 \text{ m}^2/\text{g}$ and a $13 \text{ W/m}\cdot\text{K}$ thermal conductivity, demonstrating its efficiency in

BTMS applications. Similarly to this, Liu et al. [81] suggested a water-cooling system and a graphene-assembled film-integrated heat sink for effective EV battery cooling and found that Li-ion batteries with a thermal resistance of roughly 76% decrease temperatures by 11 °C and 9 °C, respectively, at discharge rates of 2C and 1C. Based on their results, Wang and colleagues [82] designed an improved multilayered nano-sheet graphene film with a thickness of around 1 μm using an ultrasonic spray on the heat dissipation surface for EV batteries (see Figure 4d).

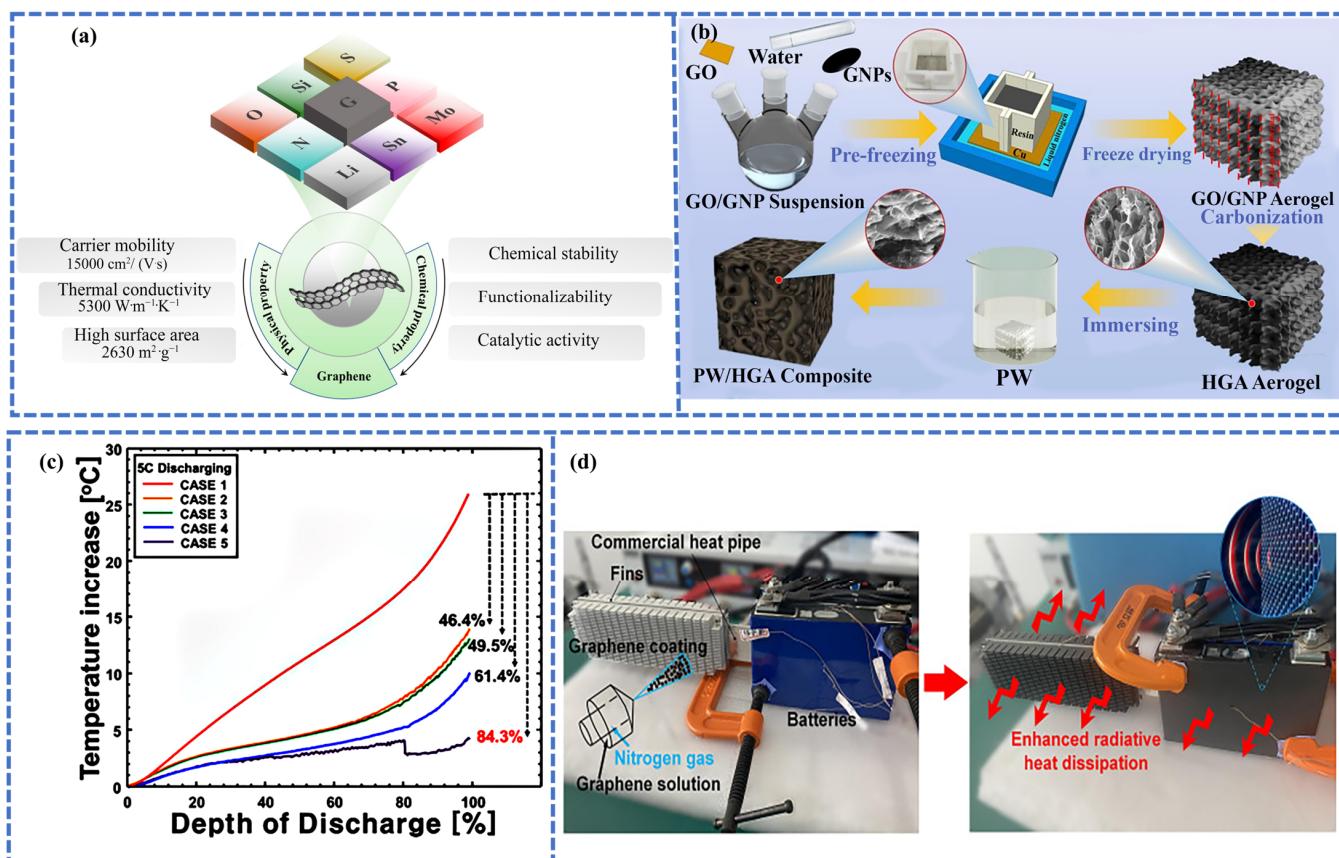


Figure 4. (a) The basic properties of graphene. Reprinted from [77], 2023. An open access article by MDPI under CC BY license. (b) The preparation process of PW/HGA composite. Reprinted with permission from [79], 2024, Elsevier. (c) Superior cooling performance of LiG-coated battery under five different cooling schemes and high environmental temperatures during discharge rates. Reprinted with permission from [80], 2024. Elsevier. (d) HP-radiation system for BTMS with enhanced cooling and heat dissipation effect. Reprinted with permission from [82] 2024. Elsevier.

Thermal studies showed that the graphene-based radiative cooling efficiency produced a 15.1–25.6% reduction in temperature in practical application. In the mid-infrared spectrum, the graphene-based coating exhibits a very high spectral emissivity, ranging from 91% to 95%. In another study by Goli et al. [83], 1% graphene filler was used to fabricate composite PCM with improved thermal conductivity, thus increasing the thermal conductivity by 60 times. These results clearly show that graphene reduces the temperature rise in Li-ion batteries and has the potential to revolutionize battery pack thermal management.

The exceptional thermal conductivity of carbon nanotubes (CNTs) has led to substantial research on their potential for thermal management [84,85]. Both single-walled and multi-walled carbon nanotubes (SWCNTs) are widely used for thermal management purposes [29,86]. These one-dimensional structures exhibit remarkable thermal conductivity along their length, making them suitable for applications as heat pipes and thermal

interface materials [87]. The high aspect ratio and tailorabile thermal properties of CNTs have been explored to create advanced thermal management solutions for battery systems [88]. For instance, Dai et al. [51] fabricated an encapsulated inorganic phase change material (EPCM) using inverse emulsion polymerisation with an enhancement of heat transfer for battery systems, where the thermal conductivity was increased using CNT as an additive and $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$ as the core PCM enclosed in silica (see Figure 5a). The results of the thermal management tests demonstrated that EPCM/CNT enhanced the temperature uniformity during regular operation in addition to slowing down the module's temperature rise. At a 2C discharge rate, the peak battery temperature dropped from 76°C to 61.2°C ; this temperature differential was less than 3°C , which effectively prevented thermal runaway with non-flammable qualities.

Typically, graphene and CNT-based aerogels dissipate heat through phonon transport facilitated by their hierarchical structure, which is a consequence of their intrinsic high thermal conductivity. The presence of larger mesopores in the aerogel structure facilitates air trapping, allowing for improved heat exchange with the surrounding environment. The trapped air forms insulating pockets that reduce heat loss while still enabling effective convective flow. Radiative heat transfer also occurs in such aerogels due to the increased surface area associated with their hierarchical porosity. This structure allows for greater interaction for thermal radiation, enhancing the material's overall capacity to dissipate heat [89,90].

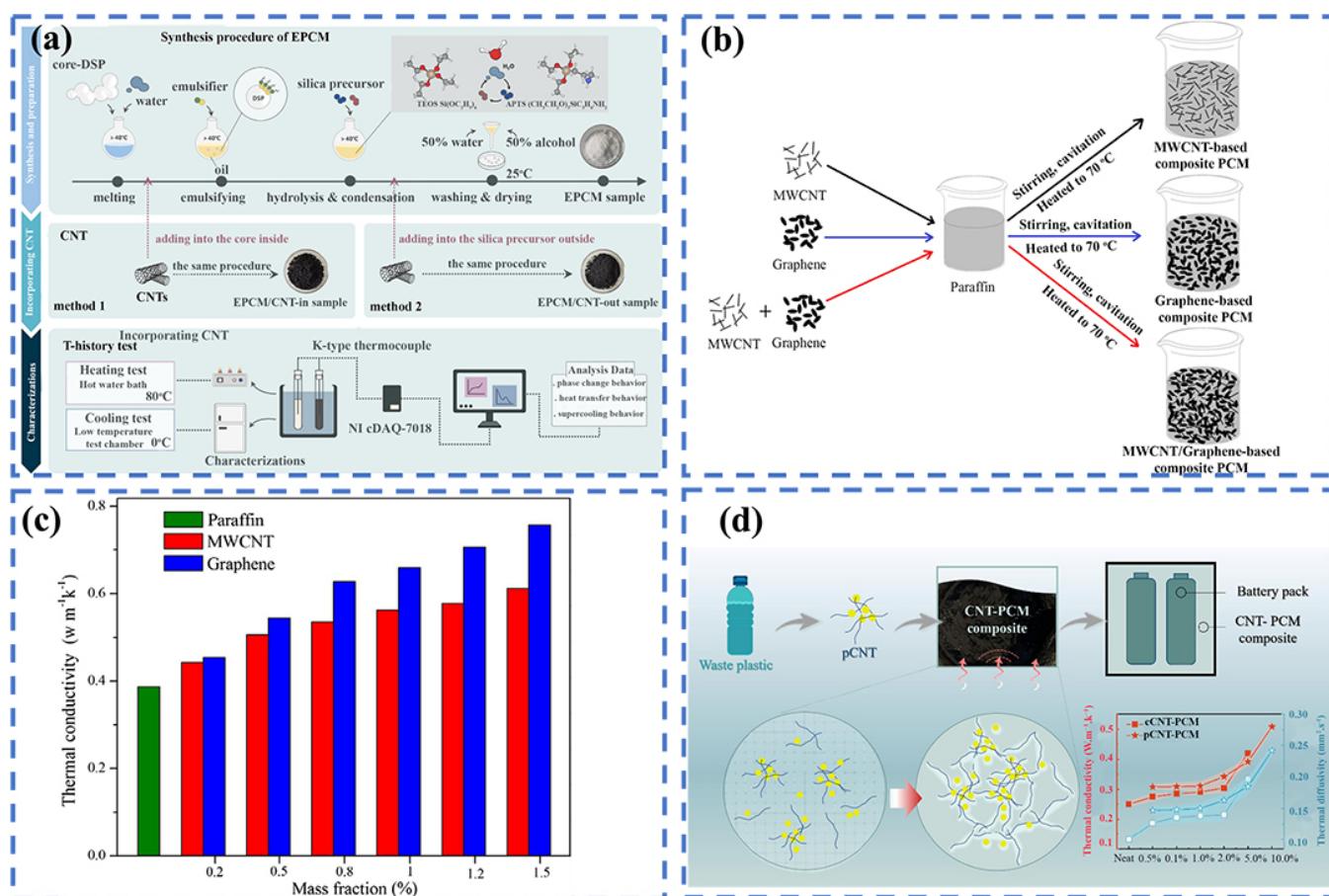


Figure 5. (a) The synthesis process of encapsulated inorganic phase change material (EPCM) with silica and an additive of carbon nanotube (CNT). Reprinted with permission from [51] 2023, Elsevier. (b) Preparation process of MWCNT-based composite PCM. (c) Thermal conductivity of composite PCMs based on graphene and MWCNTs. Reprinted with permission from [91], 2018, Elsevier. (d) CNT production from waste plastic using chemical vapour deposition (pCNT) as a PCM nanofiller. Reprinted from [92], 2022. An open access article by Elsevier under CC BY-NC-ND 4.0 license.

To increase the efficiency of the thermal management system for lithium-ion power batteries, Zou et al. [91] designed a composite phase change material (PCM) based on ternary MWCNT/graphene aerogel using the two-step synthesis process shown in Figure 5b. Thermal conductivity increased by 31.8%, 55.4%, and 124% as the mass ratio of MWCNT/graphene increases as shown in Figure 4c, with a 63.3% decrease in temperature. In a similar endeavour, Zhang et al. [93] utilized a CNT sponge as the reinforcement (40 wt.%) to enhance the thermal conductivity of sebacic acid-based composite ($\lambda = 0.26 \text{ W m}^{-1} \text{ K}^{-1}$) to $7.27 \text{ W m}^{-1} \text{ K}^{-1}$. Consequently, the increased thermal conductivity of the composites led to better performance in several applications, such as photo-thermal energy conversion and better thermal management of lithium-ion batteries. To promote material and environmental sustainability, Wang et al. [92] produced carbon nanotubes (CNT) from waste plastic by chemical vapour deposition (pCNT) and used it as filler in phase change materials (PCM) for BTMS. The 5.0 wt.% pCNT loading resulted in a 104% increase in thermal conductivity and a 90.7% reduction in latent heat. Leakage tests and morphological analysis results showed that the shape and stability of pCNT in encapsulated PCM performance are comparable to the commercial CNT (see Figure 4d), underscoring the drive for material sustainability in thermal management.

Besides CNTs, the potential applications of nanodiamonds for thermal management are huge [94], considering their exceptional thermal conductivity, large surface area, optical properties, and wide bandgap. Their application as a thermal management material in BTMS is promising. In recent years, a few studies have reported their integration into composites as thermal interface materials to enhance heat transfer due to their latent heat performance [95,96]. For example, in a recent study, Nan et al. [97] designed a multifunctional thermal management nanocomposite paper for fire alarm sensors using a vacuum self-assembly process and functionalized graphene oxide nanosheet embellished with nanodiamonds. It was discovered that the in-plane thermal conductivity of the polymer was $16.653 \text{ W m}^{-1} \text{ K}^{-1}$, over 80 times higher than that of standard pure polymers. Moreover, nanocomposite paper (NPG) (consisting of cationic poly (diallyldimethylammonium chloride) (PDDA)-functionalized graphene oxide (PG) and nanodiamond (ND)) had better flame retardancy than GO paper, as evidenced by the potent reduction in peak heat release rate (pHRR). More intriguingly, despite the exceptional insulation of NPG3 paper (which has an electrical resistance of up to $2.647 \times 10^{11} \Omega \text{ cm}$), the ultrafast flame alarm reaction occurred within 1 s of the material being exposed to flame. In another study by Wei et al. [98], uniaxial-polyvinyl alcohol/nanodiamond (U-PVA/ND) and coaxial-polyvinyl alcohol/nanodiamond (C-PVA/ND) composite fibre films were investigated for potential application in heat dissipation at the outer layer of electronic components. The results showed that the fibres demonstrate excellent thermal stability and thermal conductivities. Using the vacuum-assisted filtration process, Gong et al. [99] created an insulating polymer composite to control heat, specifically to cool electronic gadgets and LED lights. The results showed an excellent heat dissipation property and a thermal increase of about $76.23 \text{ W m}^{-1} \text{ K}^{-1}$ when flexible cellulose nanofiber/single-crystal nanodiamond (CNF/SCND) flakes were used as conductive fillers. It is obvious that the application of nanodiamonds for BTMS remains unexplored; hence, more research efforts are needed in this regard.

Furthermore, graphdiyne (GDY), a carbon material that could be synthesized from organic precursors predominantly comprises sp^3 and sp^2 hybridized carbon atoms in a 2D planar structure. Its potential for thermal management in battery systems is enormous yet remains unexplored [100–102]. In thermal management, GDY has shown promising capabilities as a hybrid structure combining graphene and diamond properties, resulting in high thermal conductivity and mechanical strength [103]. GDY possess rich chemical bonding, highly conjugated, super-large π structures, indefinitely dispersed pores, non-uniform charge distribution [104], and an in-plane stiffness of 120 N/m, which is equivalent

to Young's modulus of 375 GPa presumably with a thickness of 0.320 nm [103,105]. The unique attributes of GDY make it a compelling candidate for advanced thermal management solutions in battery applications, although research in this direction is limited at the moment [106]. Besides these well-known carbon allotropes, the potential of carbon foams for thermal management [107] applications is immense due to their porous structure, light weight, and tortuous thermal transport properties [108]. Carbon foams can provide effective heat dissipation and thermal insulation, making them attractive for battery thermal management applications, particularly in high-power or high-energy-density systems [109]. For instance, in a recent study by Yang et al. [109], carbon foam and thermally conductive carbon fibre were used to design an effective BTMS that will extend the life of lithium-ion batteries. Based on the findings, the battery components benefit greatly from cooling and temperature balancing when composite phase change materials are loaded on carbon foam and carbon fibre tape. Peak temperature reductions of 25.13% and 27.83% at 1.3C and 1.5C, as well as maximum temperature differences, were demonstrated. The general characteristics of the various C-bMs for thermal management, opportunities, and challenges in practical applications are presented in Table 1.

Table 1. General characteristics of C-bMs for thermal management.

Carbon Material Type	Genesis Synthesis Approach	Structure	Thermal Properties	Advantages for Thermal Management	Challenges for Thermal Management	Ref.
Graphite	Natural or synthetic graphite Purification and processing of ore graphite	Layered structure with strong in-plane bonding	Anisotropic thermal properties	Well-established manufacturing processes. High thermal stability Cost-effective	Difficulty in achieving uniform and high thermal conductivity in composites Potential thermal expansion mismatch with other materials	[110,111]
Graphene	Mechanical exfoliation of graphite Chemical vapour deposition (CVD) Reduction of graphene oxide	2D honeycomb lattice structure	Extremely high in-plane thermal conductivity (up to 5000 W/m·K)	Flexible and lightweight Large surface area-to-volume ratio Ability to tailor thermal properties through doping and functionalisation	Limitations in large-scale manufacturing and integration Potential thermal interface resistance	[112]
Carbon nanotube	Chemical vapour deposition (CVD) Arc discharge Laser ablation	1D cylindrical structure	High thermal conductivity along the tube axis (up to 3500 W/m·K)	Anisotropic thermal properties High aspect ratio and surface area Compatibility with various matrix materials	Potential for selective heat transfer paths Difficulties in uniform dispersion and alignment within composites Potential thermal interface resistance	[113,114]
Nanodiamonds	Detonation synthesis High-pressure, high-temperature (HPHT) synthesis	Spherical nanostructure with diamond cubic lattice	Exceptionally high thermal conductivity (up to 2000 W/m·K)	Thermal stability at high temperatures Small size and high surface area Ability to form stable dispersions and composites	Limited large-scale production capabilities Challenges in uniform dispersion and integration	[115,116]

Table 1. Cont.

Carbon Material Type	Genesis Synthesis Approach	Structure	Thermal Properties	Advantages for Thermal Management	Challenges for Thermal Management	Ref.
Graphdiyne	Chemical vapour deposition (CVD) Hydrothermal synthesis	Hybrid structure combining graphene and diamond	Extremely high thermal conductivity (up to 2000 W/m·K)	Exceptional mechanical strength Tailorable thermal and electrical properties Potential for multifunctional applications	Emerging material with limited research and development Challenges in scalable synthesis and integration	[105]
Carbon foams	Pyrolysis of organic precursors Template-assisted synthesis	Porous and lightweight structure	Thermal Conductivity: Typically, in the range of 0.1 to 1 W/m·K, depending on the porosity, pore structure, and density of the carbon foam.	Effective thermal insulation and heat dissipation Tunable thermal and mechanical properties High surface area and permeability Potential for thermal management in high-power applications	Limited thermal conductivity compared to other carbon materials Challenges in achieving desired pore structure and density	[117,118]
Carbon fibres	Organic precursors (e.g., polyacrylonitrile, rayon, pitch) Oxidation, carbonisation, and graphitisation processes	Continuous, high-aspect-ratio filaments with predominantly graphitic structure	High thermal conductivity along the fibre axis (up to 1000 W/m·K)	Anisotropic thermal behaviour (high conductivity in the fibre direction, lower in the transverse direction) Ability to create thermally conductive pathways within composites Compatibility with various matrix materials for integration Potential for tailoring thermal and mechanical properties	Achieving uniform dispersion and alignment within composites Potential thermal interface resistance between fibres and matrix	[119,120]

It can be observed from Table 1 that the various carbon-based materials have demonstrated considerable promise in enhancing BTMS; however, their transition to commercial applications is somewhat limited [2], mainly due to challenges in scalable synthesis and integration. This is complicated by the necessity to preserve the structural integrity and performance of these materials throughout the operational lifespan of the battery [36]. Also, cost and scalability present a formidable barrier to the seamless integration of C-bMs in BTMS because the sustainable production of high-quality carbon materials can incur substantial costs, and scaling manufacturing processes for commercial deployment is a complex undertaking [1,2]. Furthermore, the complexity of manufacturing processes required to integrate carbon materials into BTMS can escalate production costs and extend timelines. Advanced fabrication techniques are often necessary for incorporating these materials into battery components, adding another layer of complexity to the production process. This intricacy may also result in variability in the quality and performance of the final products, thereby impeding their commercial viability [30]. Despite these challenges, various innovative fabrication strategies have been developed to fully harness the potential of carbon-based materials in BTMS.

Fabrication Strategies of C-bMs for BTMS

Carbon-derived composites for battery heat management are made via an array of processes, each with its own set of benefits and drawbacks: prepreg layup, filament winding, pultrusion, and resin transfer moulding for carbon fibre composites [121]; solution mixing [122,123], melt blending [124], in situ polymerisation [125], and electrophoretic

deposition [126,127] for carbon nanotube and graphene-based composites [125]; and pyrolysis, template-assisted synthesis, and infiltration techniques for carbon foam composites [128,129]. In composites, the term pultrusion emerges from the words “pull” and “extrusion” [130]. Pultrusion, a continuous or fully automated process, is a growing manufacturing method for creating fibre-reinforced composite profiles with uniform cross-sections. This technique involves forcing materials through a die, which then pulls the resulting profile [131]. The pultrusion process is a highly advantageous method for producing lightweight, high-strength components in the fabrication of C-bMs because of its accuracy, efficiency, and light weight [132]. Pultrusion procedures differ depending on the design, but they usually include laying up the raw material (carbon fibres) which are extracted from a creel and passed through a resin bath. The fibres are impregnated with resin, which might be polyester, vinyl ester, epoxy, or phenolic, saturating them completely [133]. Several guides are passed by the raw material before it enters the pultrusion die, organising and shaping the layup into the appropriate cross-sectional form and ply plan [134–136] (see Figure 6a). The fibre material is pre-soaked with resin and minimally exposed to volatile solvents, and is then fed into the pultrusion dye. Pulling the hardened profile out of the dye repeatedly allows it to cool before a flying cut-off saw divides it into the necessary lengths [133]. Similarly, prepreg and other approaches can be used in filament winding, an efficient and straightforward procedure for producing components in a wide range of diameters [137,138]. The filament winding process, as depicted in Figure 5b, involves creels of continuous ravings that are transferred through a resin tank and onto a rotating mandrel in a fully regulated process [139,140]. The primary processing parameters that impact the outcomes of composite materials made by filament winding are the curing time, helix angle, matrix weight fraction, fibre weight fraction, winding force, fibre architecture, and fibre orientation [137,139]. Because compaction is achieved during the winding process, fibre tension is crucial. Tension has the power to influence the porosity content and proportion of fibre reinforcement in the composite, which in turn influences the stiffness and strength of the finished composite product [141]. For this reason, computerised information systems are used to independently monitor every movement of the entire process [142] to avoid fibre fracture at the surface.

As an advanced manufacturing technique, electrophoretic deposition (EPD) improves the thermal management of batteries. This method employs graphene-derived materials, such as carbon nanotubes and nanoparticles, to enhance performance [143]. The typical setup for the deposition is a two-electrode cell. As illustrated in Figure 6c, EPD is a well-known colloidal process that consists of the transformation and deposition of suspended charged particles under the influence of an electrical field [144,145]. To reinforce the deposited layer and improve its mechanical and adhesive qualities, the coated substrate is dried and cured after deposition. EPD is low-cost, involves simple scaling-up processes, and produces low pollution levels compared to other technologies. EPD is versatile—the finished coating can be thick or thin, uneven or smooth, porous, or compact [146]. Due to its sensitivity, numerous parameters influence the final properties [145]. For instance, parameters like voltage, deposition duration, concentration, and current density must be adjusted since the kind of solvent, whether aqueous or non-aqueous can impact the outcome [144,147,148].

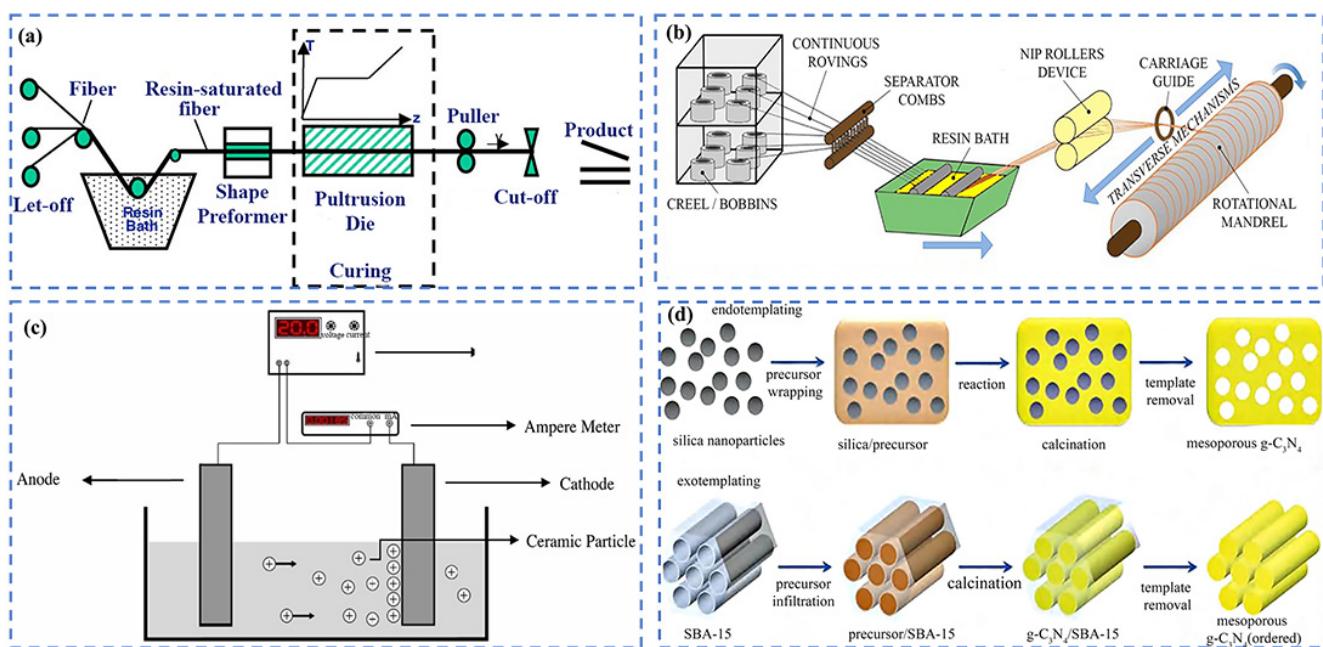


Figure 6. (a) Schematic illustration of the pultrusion process with resin bath. Reprinted with permission from [136], 2006. Elsevier (b) Schematic diagram of filament winding. Reprinted with permission from [139] 2023, an open access article under CC BY license. (c) Schematic view of simple electrophoretic deposition process [145], 2016. Elsevier (d) Synthetic mechanism of the hard template method. Reprinted with permission from [149], 2016. Elsevier.

Template-assisted synthesis is an effective approach in carbon foam composite manufacturing for creating porous carbons (PC) [150]. The template methods are generally categorized as hard templates (endotemplate and exotemplate as shown in Figure 6d), soft templates, and dual templates, offering precise control over the pore size distribution in constructing diverse porous carbon morphologies [151,152], which can affect the BET-specific surface areas of PCs [152]. The usage of polymer templates allows for control of bubble size according to the thickness of the template [153]. In this procedure, several template materials, including inorganic templates such as silica and zeolites; organic templates such as polymers, surfactants, and biomaterials; and salt templates, mainly NaCl, are used for infiltrating into a carbon precursor template structure [154,155]. The carbon precursors are heated in an inert environment before being transformed into pure carbon. The template is eliminated by dissolution or etching, leaving behind a porous carbon foam structure [156]. As a result, the template-assisted method is perfect for synthesising carbon foams with a hierarchical structure to promote quick heat transfer and ion transport, hence improving thermal management and battery performance [157]. Importantly, the optimum production procedure is determined by parameters such as the specific carbon material, matrix material, thermal and mechanical performance requirements, and use within the battery system. The manufacture and integration of these carbon-derived composites face several challenges, including establishing uniform dispersion and alignment, regulating thermal interface resistance, and scaling up production processes. Some typical fabrication processes are described in Table 2.

Table 2. General fabrication approaches and functional characteristics of composite carbon-based thermal management materials.

Fabrication Method	Carbon Material	Polymer Matrix	Thermal Performance	Mechanical Performance	Specific Use in BTMSs	Ref.
Pyrolysis of Organic Precursors	Carbon Foam	Phenolic Resin, Epoxy	High thermal insulation. Low thermal conductivity (0.1–0.5 W/m·K)	Lightweight Compressive strength: 0.5–5 MPa	Thermal barriers between cells/modules	[109]
Template-Assisted Synthesis	Carbon Foam	Polymer, Ceramic	High thermal insulation. Low thermal conductivity (0.1–0.5 W/m·K)	Tailorable mechanical properties. Compressive strength: 0.5–5 MPa	Battery pack enclosures. Thermal barriers between cells/modules	[158]
Infiltration Techniques	Carbon Foam	Polymer, Ceramic	High thermal insulation. Low thermal conductivity (0.1–0.5 W/m·K)	Improved mechanical properties compared to standalone foam. Compressive strength: 1–10 MPa	Battery pack enclosures. Thermal barriers between cells/modules. Thermal interface materials	[52]
Solution Mixing	Graphene, Graphene Oxid	Epoxy, Polymer	Moderate thermal insulation. Thermal conductivity: 0.1–1 W/m·K	Improved mechanical properties compared to neat polymer. Tensile strength: 50–100 MPa	Thermal insulation coatings/liners for battery enclosures. Thermal barriers between cells/modules	[159]
Melt Blending	Graphene, Graphene Nanoplatelets	Thermoplastic Polymer	Moderate thermal insulation. Thermal conductivity: 0.1–1 W/m·K	Improved mechanical properties compared to neat polymer. Tensile strength: 50–100 MPa	Thermal insulation coatings/liners for battery enclosures. Thermal barriers between cells/modules	[160]
Layer-by-Layer Assembly	Graphene	Polymer	High thermal insulation. Low thermal conductivity (0.1–0.5 W/m·K)	Tailorable mechanical properties. Tensile strength: 50–100 MPa	Thermal barriers between cells/modules	[161]
Solution Mixing	Nanodiamonds	Polymer, Ceramic	High thermal insulation. Low thermal conductivity (0.1–0.5 W/m·K)	Improved mechanical properties compared to neat matrix. Tensile strength: 50–100 MPa	Thermal insulation coatings/liners for battery enclosures. Thermal barriers between cells/modules. Thermal interface materials	[98]
Melt Blending	Nanodiamonds	Metal, Polymer	High thermal insulation. Low thermal conductivity (0.1–0.5 W/m·K)	Improved mechanical properties compared to neat matrix. Tensile strength: 50–100 MPa	Thermal insulation coatings/liners for battery enclosures. Thermal barriers between cells/module. Thermal interface materials	[162]

Table 2. *Cont.*

Fabrication Method	Carbon Material	Polymer Matrix	Thermal Performance	Mechanical Performance	Specific Use in BTMSs	Ref.
In situ Growth	Nanodiamonds	Polymer, Ceramic	High thermal insulation. Low thermal conductivity (0.1–0.5 W/m·K)	Improved mechanical properties compared to neat matrix. Tensile strength: 50–100 MPa	Thermal insulation coatings/liners for battery enclosures. Thermal barriers between cells/modules. Thermal interface materials	[163]
	Carbon nanotubes	Epoxy, PMMA, or polyimide	Significantly enhanced thermal conductivity	Improved tensile strength and modulus	Thermal interface materials, heat spreaders in battery packs	[164]

Again, despite the significant advancements in fabrication approaches of C-bMs for BTMS, scaling up these processes to meet industrial demands can sometimes pose technical challenges, especially when in terms of maintaining consistency in the quality and properties of the materials during large-scale production [162]. Moreover, the integration of carbon materials into existing BTMS and battery components at a commercial scale is complex [38]. For instance, ensuring uniform dispersion and effective contact between C-bMs and other components, such as electrodes and electrolytes, without compromising the material's properties can be challenging. Addressing these limitations necessitates a comprehensive approach. Fortunately, ongoing research efforts aimed at identifying cost-effective and scalable synthesis methods that preserve the high quality of C-bMs are being developed [37,159]. Continuous innovations in material processing and manufacturing techniques are vital to enhancing the integration of carbon materials into BTMS and battery components for effective heat management.

4. Recent Innovations in C-bMs BTMS Solutions

For electronic systems and gadgets to operate and perform consistently, effective thermal management is essential [165,166]. With the increasing demand for high-density batteries, innovative thermal management solutions have become imminent in the recent incidents of battery fire hazards. Recent innovations in carbon-derived thermal management systems have made it possible to handle the expanding thermal difficulties presented by improved electrical and energy technologies. This has been achieved by leveraging the unique features of carbon-based materials to facilitate the construction of more efficient, compact, and adaptive thermal management systems to support the ongoing evolution of modern devices and energy storage systems [164]. Some of the recent innovations in the application of carbon-based materials are discussed briefly.

4.1. Carbon-Based Phase Change Composites

PCMs are essential in thermal management in ESS, transport, and conversion applications [167]. The high heat storage density, adaptability, and ease of use of PCM-based latent heat storage mechanisms are the advantages of these systems [168]. Nonetheless, the inefficiency and usability of pure PCMs are often limited by their low electrical and thermal conductivity, weak light absorption, and leakage in their liquid state [169–171]. To address these problems, eutectic PCMs, made up of organic, and inorganic materials are widely used [172–175]. In the correct ratios, these materials exhibit a melting point lower than any of the constituent parts [175]. For instance, the eutectic melting point of an organic eutectic mixture of capric acid and cetyl alcohol at 30% cetyl alcohol is around 22 °C, but the corre-

sponding values for capric acid and cetyl alcohol are 35 and 52 °C [174]. When compared to organic PCMs, inorganic PCMs like salts and salt hydrates are less expensive, non-flammable, and have a higher thermal conductivity [171,176], yet have significant drawbacks such as large volume changes and intense corrosiveness when exposed to overcooling [177,178].

Organic PCMs derived from hydrocarbon chains, such as paraffin waxes and fatty acids [179,180], have a broader melting temperature range and different phase change temperatures. For example, paraffin is a combination of saturated long-chain hydrocarbons with high latent heat capacity and good nucleation melting properties; thus, it has a rapid cycle rate [181,182]. Despite this, their significant susceptibility to heat flow, i.e., poor thermophysical characteristics, as well as difficulties with flammability and volatility, remain points of concern [183]. To address these challenges, C-bMs are increasingly used to form PCMs composite phase change materials (CPCMs) [184–187]. In a recent innovation, PCM C-bM composite was fabricated by encapsulating the PCMs in a protective silica/polymer shell (SS-PCMs) [188] as shown in Figure 7a. The capsule sizes range across the macroscale (above 1 mm), microscale (0–1000 μm), and nanoscale (0–1000 nm) [189]. The encapsulation method allows for efficient heat transfer, improves durability and stability, and adapts to dimensional changes brought on by PCM phase transition [190,191].

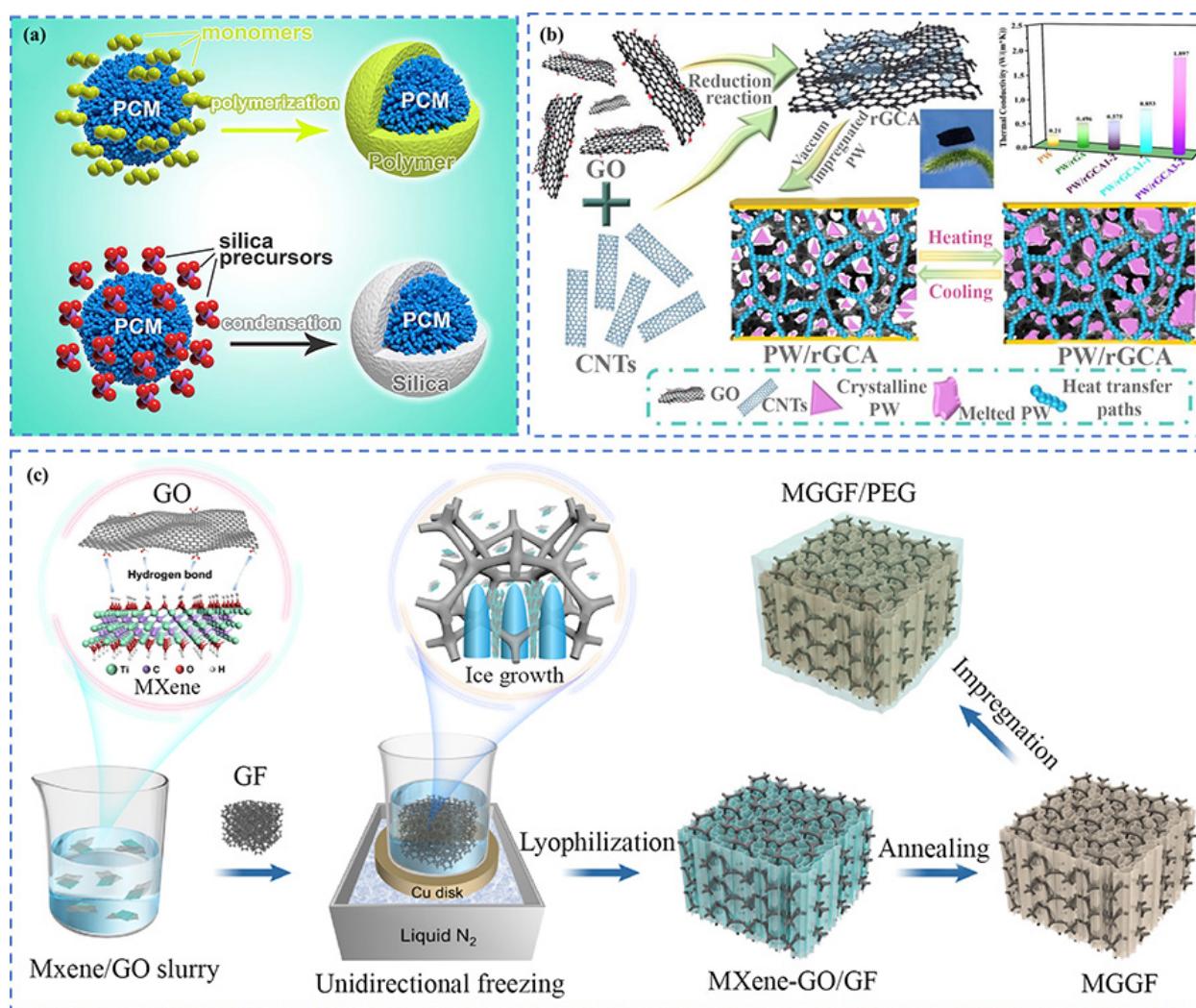


Figure 7. (a) Synthetic illustration of encapsulation process. Reprinted with permission from [188], 2018. Royal Society of Chemistry (b) Synthesis of rGCA 3D scaffold. Reprinted with permission from [192], 2024. Elsevier. (c) Schematic illustration of the fabrication process of dual-encapsulated MGGF/PEG composite. Reprinted with permission from [193], 2023. Elsevier.

Guo et al. [192] devised a unique strategy for increasing PCM performance by using reduced graphene oxide/carbon nanotube hybrid aerogels (rGCA) as an encapsulating 3D scaffold in accommodating paraffin wax (PW) (see Figure 7b). With a high phase change enthalpy of 236.7 J/g and temperatures above the melting point of pure PW, the PW/rGCA phase change composites showed impressive form stability. The phase change enthalpy of PW/rGCA also maintained a steady value of 96.5% even after 100 cycles, and its thermal conductivity increased to 1.897 W/mK on average. In another study by Xueqiang et al. [194], a flexible phase change film with heat management and microwave absorption characteristics was fabricated via encapsulation for applications in wearable devices. The eicosane (EI) in the system acted as the phase change component with the LP33 as the porous carbon encapsulating medium. It was found that during the phase transition process, the melting and crystallisation enthalpies increased to 134.71 J/g and 126.11 J/g, respectively. Furthermore, the encapsulated structure efficiently avoided leakage throughout the phase transition process and demonstrated superior thermal management and energy storage capability. Similarly to this, Hu et al. [193] developed a dual-encapsulation design of vertically aligned MXene-graphene monoliths in graphene foam (MGGF hybrid aerogel) to produce interconnected thermal routes in the PCM matrix (refer to Figure 7c). The MGGF/PEG composite had a high through-plane thermal conductivity of $11.39 \text{ W m}^{-1} \text{ K}^{-1}$, a good EMI shielding effectiveness of $\sim 56.6 \text{ dB}$, a desirable latent heat density of up to 160.3 J g^{-1} , leakage-proof capabilities, and superior thermal dependability. The MGGF/PEG-based technology was also utilised to regulate thermal energy, cool devices, and convert solar-thermoelectric power.

Following the spray-drying technique illustrated in Figure 8a [195], Li et al. [196] calcined attapulgite–carbon nanotube–NiCo alloys composite (ATP-CNT-NiCo) microspheres compounded with paraffin as a solution to heat dissipation for advanced electronic equipment (refer to Figure 8b). It was discovered that the P-ACNCT composite had a melting and solidification enthalpy of 111.6 J/g and 108.1 J/g, respectively, indicating its excellent thermal energy storage capacity. Using the sol–gel technique, Mahdavian et al. [197] fabricated a high-performance precipitated calcium carbonate (PCC) by inserting PEG and a polymeric PCM into the porous structure of modified resorcinol-formaldehyde (RF) hydrogels (see Figure 8c). During the production process, 3-chlorophenol and carbon quantum dots (CQDs) were added to the RF structure resulting in a 40% increase in energy storage and impregnation efficiency. The ideal PCC had a 67% higher melting enthalpy and an encapsulation effectiveness of 92.5%. These PCC systems have long-term storage/release cycle stability and a high latent heat of 109.1 J/g, making them suitable for BTMS applications.

Zhang et al. [198] designed a series of spherical microencapsulated C18 with SiO_2 shells using the sol–gel process at different pH values for enhanced thermal management and energy storage. The spherical microcapsules demonstrated enhanced thermal conductivity, phase change performance, and a distinct core–shell structure, which were very beneficial for dissipating heat emanating from ESSs. In a study by Kong et al. [199], sol–gel and ultra-high temperature graphitisation were used to create a large-scale graphene aerogel with a three-dimensional continuous network for the encapsulation of paraffin. The composite exhibited improved thermal conductivity and latent heat of up to 225.7 J/g. The phase change latent showed remarkable cycle stability with no leakage during phase transition, thus achieving 97.11% capacity retention after 30 heat cycles. Some typical composite C-bM/PCM composite materials and their properties are summarized in Table 3.

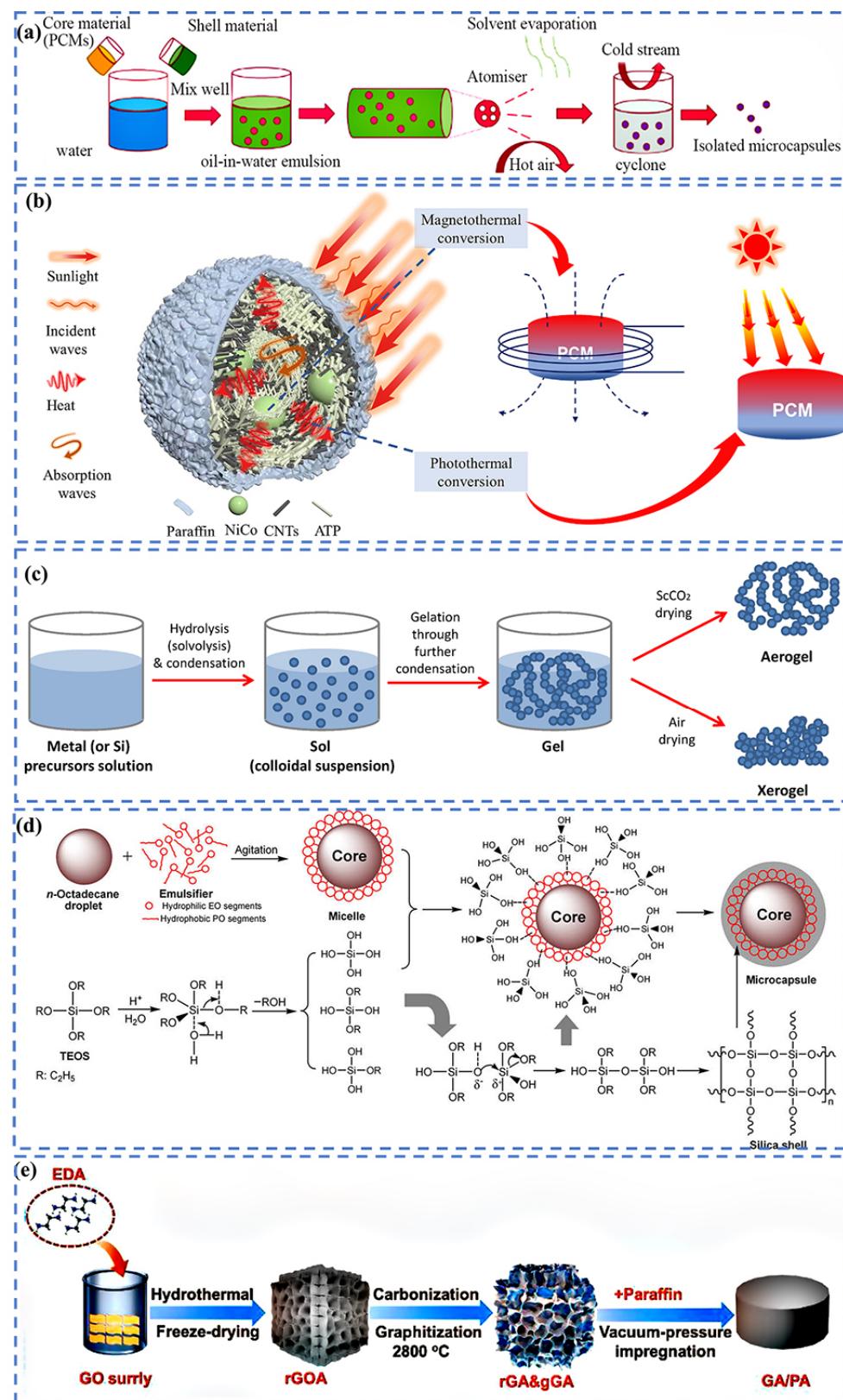


Figure 8. (a) The process of spray-drying for encapsulated PCCs. Reproduced from [195], an open access article by Elsevier under CC BY-NC-ND 4.0 license. (b) The preparation process of the P-ACNCT-F. Reprinted with permission from [196], 2021. Elsevier. (c) Schematic illustration of a sol-gel synthesis method. Reproduced from [200], an open access article by MDPI under CC BY license. (d) Diagrammatic representatin of the sol-gel technique used to create the C₁₈/SiO₂ microcapsules. Reprinted with permission from [198], 2009. Elsevier. (e) Diagram showing the steps involved in making gGA, rGOA, and gGA/PA composites. Reprinted with permission from [199], 2023. Elsevier.

Table 3. C-bM/PCM composite and their performance parameters.

PCM	Type of C-bM	Thermal Conductivity	Latent Heat J/g	Melting Enthalpy	Solidification Enthalpy	Cycling Stability	Ref.
Liquid paraffin	MWCNT	0.2	-	133.60	33.64	-	[201]
CA-TD binary eutectic mixtures	Expanded graphite	6.131	157.3	167.5	158.7	155.4 after 200 cycles	[202]
Polyethylene glycol (PEG)	Graphene oxide	0.628	168.72	153.52	-	100 cycles	[203]
Stearic acid	NPC	1.873	137.89	137.89	136.42	-	[204]
Paraffin	Carbon fibre	1.73	192.2	60.0	50.0	100 after 100 cycles	[205]
Paraffin	Graphene, EG carbon tube,	5.1	131.9	178.5	171.5	-	[206]

Carbon-based phase change composites (CDPCCs) combine the thermal energy storage capabilities of phase change materials (PCMs) with the increased features of carbon-based structures [84,85]. As a proof of concept, Zhao et al. [207] use carbon-based phase change composites (PCCs) with high directional thermal conductivity to dissipate heat associated with most electronic products (see Figure 9a). It has been reported that the incorporation of graphite nanoparticles into adipic acid PCC can result in a composite material with high thermal conductivity (in-plane K_{PCC} s of up to $32.86 \text{ W m}^{-1} \text{ K}^{-1}$), high heat storage density ($158.2\text{--}248.3 \text{ J g}^{-1}$), with excellent thermal cycling stability and leakage resistance [208]. In line with this assertion, Wang et al. [209] utilized SWCNTs to fabricate PEG-based PCCs with improved thermal conductivity. The resultant PEG/SWCNT (2 wt%) PCC had a thermal conductivity of 0.312 W/mK , with an approximately 116.9% increase in pure PEG.

4.2. Carbon-Based Heat Pipes

Heat pipes are self-contained structures that use capillary circulation through two-phase fluid flow to achieve high thermal energy conductance (see Figure 9b) [210,211]. The three types of heat pipes are loop heat pipes (LHPs), pulsing heat pipes (PHPs), and sintered heat pipes (SHPs) [212]. For effective thermal management with LHPs, heat transfer fluids can be designed in various geometries, such as tubular, plate, and spiral configurations as shown in Figure 9e. These designs are intended to optimize heat exchange efficiency by improving fluid flow patterns, increasing surface area contact, and enhancing thermal performance in heating and cooling applications [180]. Loop heat pipes leverage the capillary action of the porous structure inside the evaporator to circulate the working fluid, whereas pulsating heat pipes exploit the working fluid's pressure oscillations to promote heat transfer [213,214]. SHPs are effective instruments for heat dissipation in power systems due to their high efficiency and unique ability to transport heat over a long distance [215]. As a result, heat pipes have become a vital feature of thermal management systems across a diverse variety of sectors [212]. They find uses in microelectronics, ventilation and air conditioning systems (HVAC), and industrial areas such as spaceships as totally intrinsic cooling devices [216,217]. Currently, heat pipes are commonly built using metals with excellent thermal conductivity and good mechanical strength, such as copper, aluminium, or their alloys [218]. However, heat pipes manufactured from these materials present severe issues in power electronics due to their relatively high density [215]. In essence, carbon-based materials have sparked interest in constructing and improving the performance of heat pipes over traditional metal-based heat pipes [219]. This is because of the multiple qualities of carbon materials, such as their thermal conductivity, lightweight

design, corrosion resistance, improved capillary wicking, and capacity to handle high-temperature heat [215,220,221]. In recent work, Ma et al. [222] utilized hydrothermal carbonisation to create a carbon sphere-modified nickel wick (CSs-Ni-Wick) loop heat pipe as a passive heat transfer system for thermal control of electronic components (see Figure 8c).

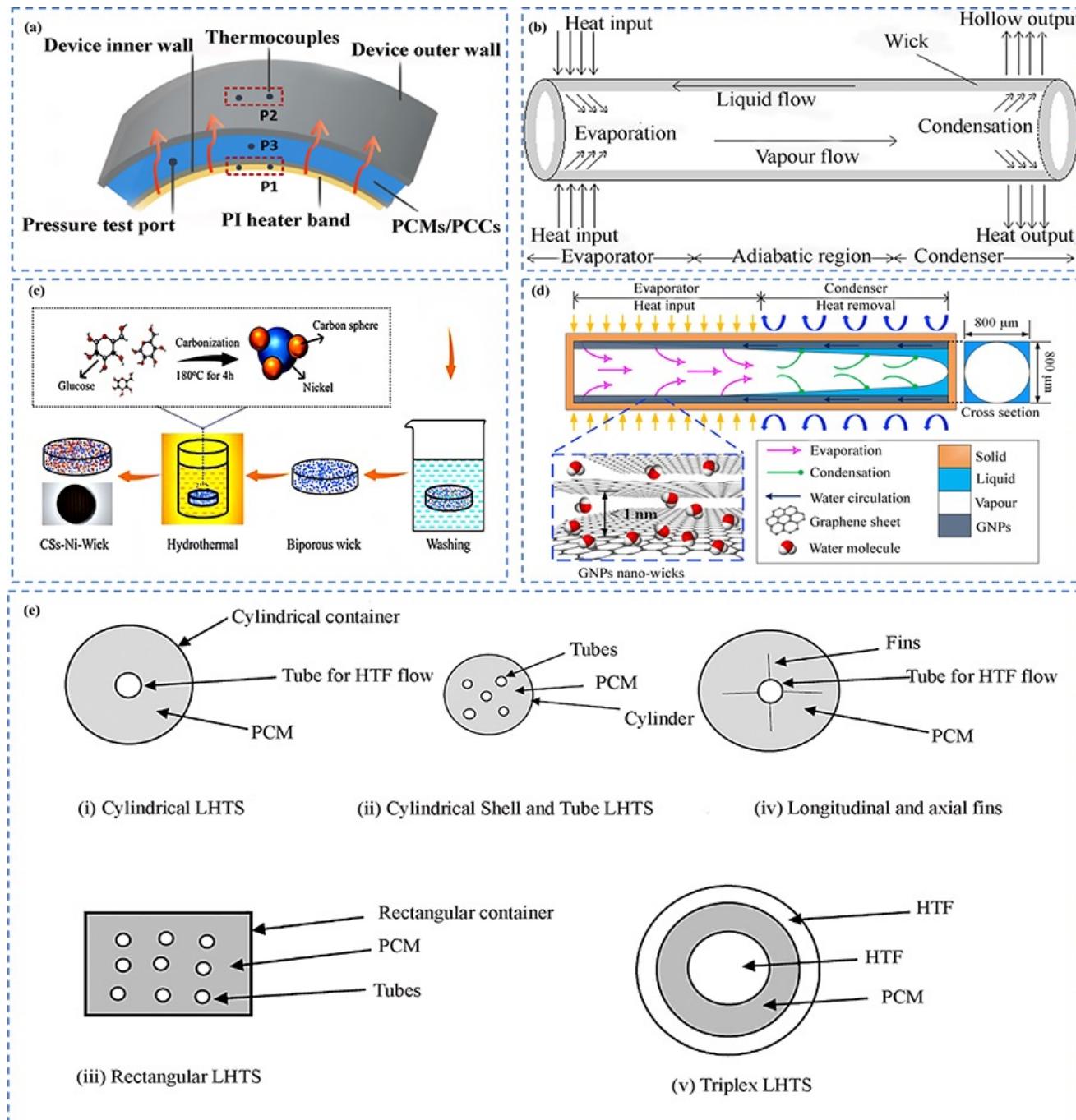


Figure 9. (a) Figure showing how the module's heat storage and release are evaluated. Reprinted with permission from [207], 2024. Elsevier. (b) The structure of a heat pipe. Reprinted with permission from [223], 2015 Elsevier. (c) Diagram illustrating the CSs-Ni-Wick hydrothermal treatment procedure. Reprinted with permission from [222] Elsevier. (d) GNP nano-wicks of micro heat pipes: the ultrafast transfer of water molecules. Reprinted with permission with permission from [221], an open access article by MDPI. (e) Geometric conformations of heat transfer fluid. Reprinted with permission from [180], 2017. Elsevier.

The CSs-Ni-Wick combines enhanced capillarity with the advantages of big pores in lowering flow resistance. With the heat source temperature kept below 85 °C, the LHP showed a maximum heat load of 140 W (20 W/cm²) and a minimum thermal resistance of 0.357 °C/W.

Zhang et al. [224] designed a tiny flat loop heat pipe made of carbon fibre for excellent thermal control. They found that the loop heat pipe kept the heat temperature at 84.47 °C. Similarly, Liu et al. [215] developed a flexible, lightweight graphene-based heat pipe (GHP) with excellent thermal conductivity and a nanostructure-enhanced inner surface. A copper spring was put inside the GHP container to strengthen its mechanical properties. The graphene film's ultra-high in-plane thermal conductivity allows heat to swiftly transfer from the evaporator to the condenser section. The GHP outperformed copper-based commercial heat pipes with a heat dissipation capacity of 7230 W m⁻² K⁻¹ g⁻¹, which is approximately 3.5-fold greater. In furtherance to this, Gan and Hung [221] improved the thermal performance of a water-filled micro-heat pipe (MHP) by introducing GNP nano-wicks into the MHP's microchannels. The GNPs' rapid water penetration property resulted in an improved heat-transfer rate of 1050 W/m·K and a nano-wick of 128%, as shown in Figure 9d. These revolutionary heat pipe designs have broadened the capabilities of thermal management systems, allowing for higher heat transfer rates, better temperature uniformity, and increased adaptability to different operating circumstances [212]. As the demand for efficient thermal solutions increases in industries such as electronics, aerospace, and energy, fundamental principles and improvements in heat pipe technology are critical in tackling the increasing thermal issues

4.3. Carbon-Based Thermal Interface Materials

To increase the efficiency of heat transmission, thermal interface materials (TIMs) are placed between a heat source and a heat sink [225,226]. The main applications for these materials are in electronics packaging and thermal management [227]. Carbon-based TIMs (as shown in Figure 10) range from one-dimensional CNTs and 2D graphene (Gr) films to 3D Gr foams (GF), Gr aerogels (GA), and vertical Gr (VG) [114]. These are some of the most promising options for electrical device heat dissipation materials due to the strong sp² bonding. These materials are known for their minimal thermal expansion, mechanical strength, flexibility, and light weight. CNTs and Gr-related materials can also be employed as TIMs independently or distributed in matrixes such as epoxy (EP), polyimide, and poly(methylmethacrylate) (PMMA) for the manufacturing of composites [114]. The various carbon-based TIMs are discussed briefly.

4.3.1. Graphene-Based TIMs

Graphene, a 2D material with high intrinsic thermal conductivity, is a promising candidate for TIMs [164]. As illustrated in Figure 11a, graphene sheets must be vertically orientated and assembled to produce high-performing graphene-based TIMs. Top-down and bottom-up approaches are used to prepare vertical graphene (VG) structures with good thermal conductivity [228]. Mechanical processing and hydrothermal reduction are the most common top-down processes, using graphene oxide (GO) or reduced graphene oxide (rGO) as raw materials [229]. Bottom-up approaches, on the other hand, are mostly represented by plasma-enhanced chemical vapour deposition (PECVD), which allows for the direct growth of VG with a specified morphology utilising various carbon sources as precursors [230]. The exceptional features of graphene derive from the 2p orbitals, which produce the π state bands that delocalise over the sheet of carbons that make up graphene [231]. These materials have high heat conductivity and mechanical stability, which gives them a competitive advantage over similar materials for usage in high-performance applica-

tions [231]. Murugesan et al. [232] fabricated a high-performance thermally conductive graphene-enhanced TIM (GT-TIM) by chemically cross-linking vertically aligned graphene and silicone polymer. The GT-TIM was used in a 5G wireless technology as a thermal burn-in tester, IC thermal testing equipment, and as a cooling device for a GPU/CPU in electronics. According to the findings, GT-TIM has a very low thermal contact resistance yet a very good elasticity, recovery degree, and reliability. In their investigation, Xu et al. [233] utilized a vertical electric field to align Gr sheets, as shown in Figure 11b. The fabricated TIMs with VG arrays had a low contact thermal resistance of $11.8 \text{ K mm}^2/\text{W}$ and a high thermal conductivity of 53.5 W/mK . In addition to directly evaluating VG's thermal conductivity as a TIM, the device's performance in heat dissipation technologies demonstrates its superior heat dissipation capabilities. Similarly, Gao et al. [234] construct a hierarchical structure of Gr sheets interspersed with a random arrangement of tiny Gr flakes. After a common graphitisation post-treatment, the hierarchically structured graphene paper improved its κ_{\perp} to $12.6 \text{ W m}^{-1} \text{ K}^{-1}$ due to heat channels generated in the through-plane direction (refer to Figure 11c). The improved TIM improved cooling efficiency approximately 2.2-fold, indicating its superior ability to satisfy the rising heat dissipation demands.

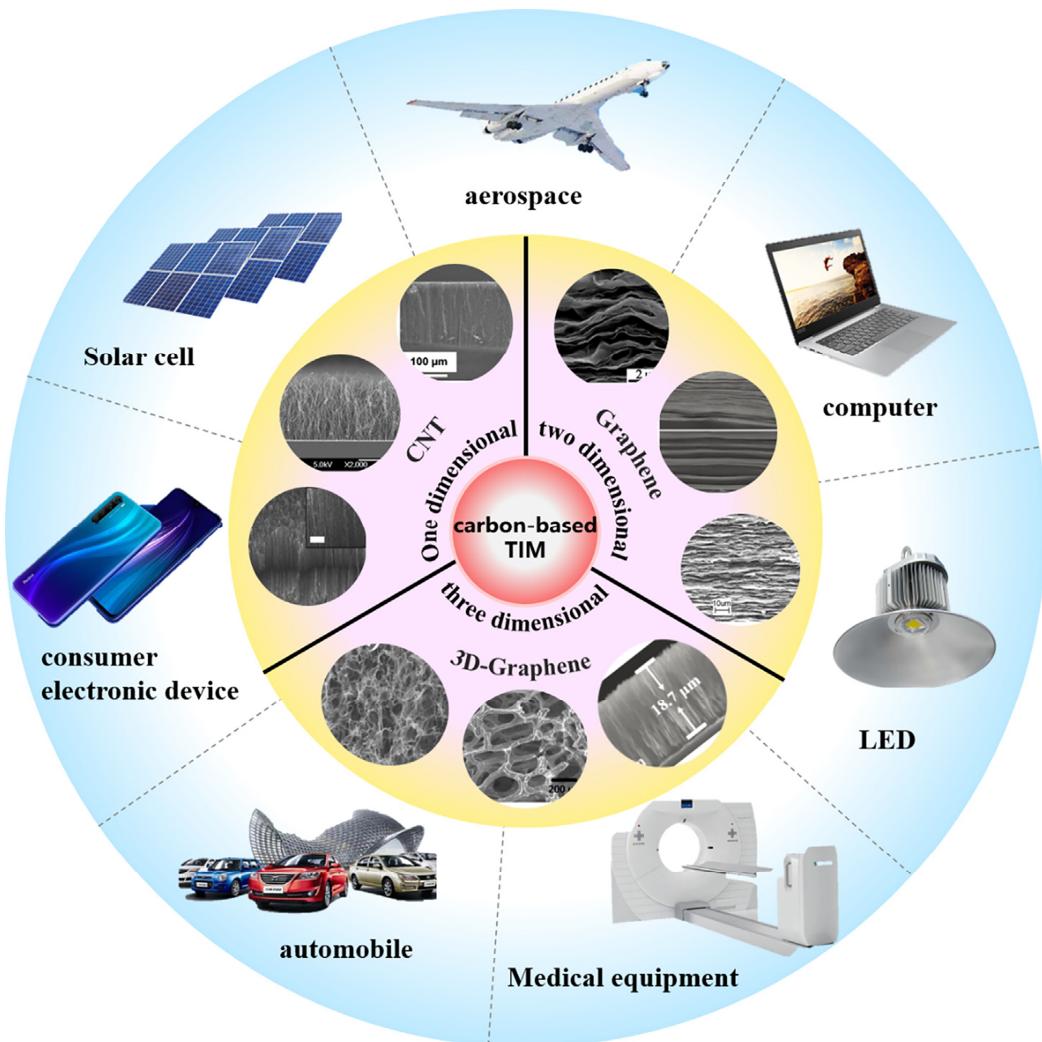


Figure 10. Applications of carbon-based thermal interface materials (TIMs). Reproduced from [114], an open access article by Elsevier under CC BY-NC-ND 4.0 license.

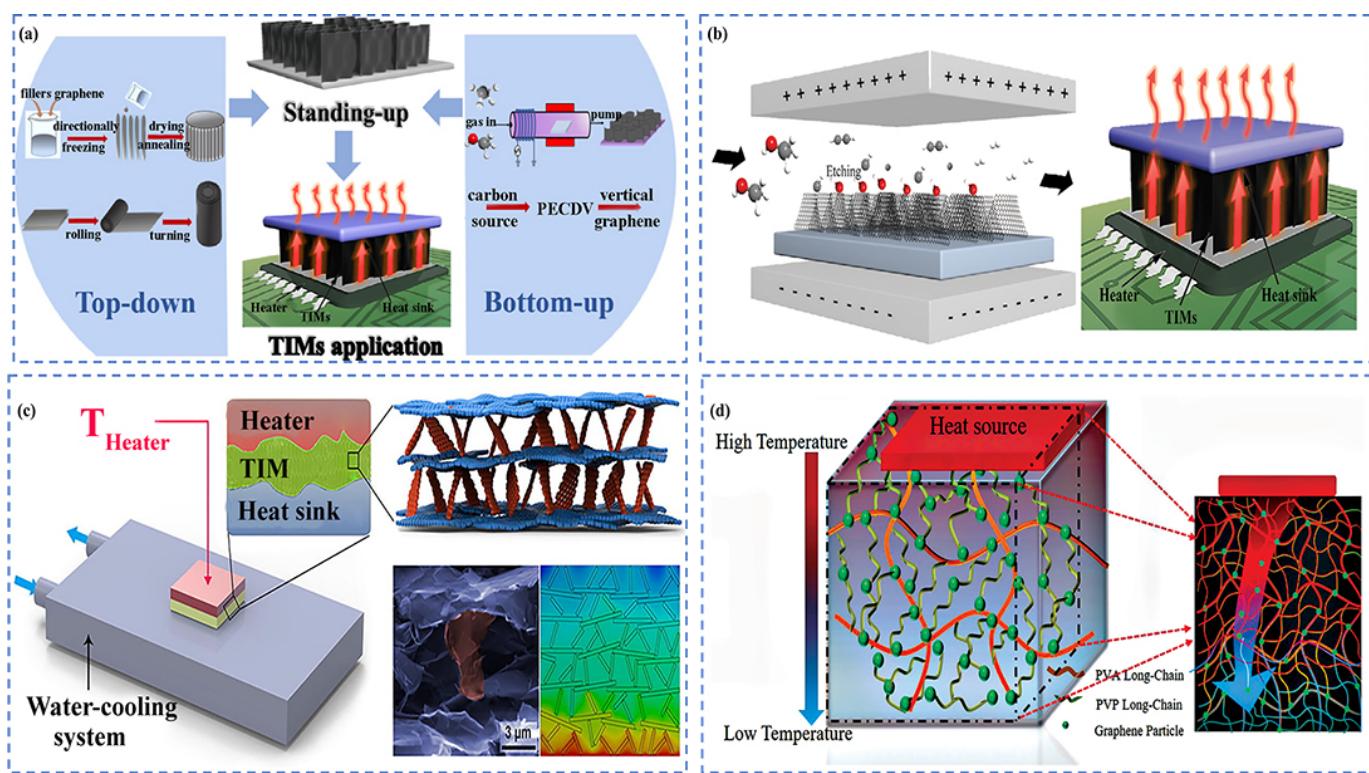


Figure 11. (a) Schematic diagram of VG for TIMs. Reprinted with permission from [228] © 2020 Wiley-VCH GmbH. (b) Experimental setup of an electric-field-assisted based PECVD and heat test system. Reprinted with permission from [233], 2020. Wiley-VCH GmbH. (c) Hierarchically structured graphene paper as TIM. Reprinted with permission from [234], 2021. Elsevier. (d) An illustration of the mechanism of G/PVP-PVA hydrogel heat dissipation. Reprinted from [235], 2023. An open access article under CC BY license by Wiley-VCH GmbH.

Zhang et al. [236] applied CVD to create a 3D Gr skeleton foam with a significantly lower interfacial thermal resistance ($0.04 \text{ cm}^2 \cdot \text{K}^{-1} \cdot \text{W}^{-1}$) compared to traditional TIMs. The soft yet mechanically tough properties of Gr and the 3D interconnected thermal pathways are critical for achieving low interfacial thermal resistance and high thermal conductivity for high-power electronics cooling. In another study, Ma et al. [235] fabricated a high thermally conductive graphene-based hydrogel (G/PVP-PVA) with an interpenetrating network using the physical cross-linking and the freeze-thaw method. It was observed that the Gr acted as a high-speed conduit for phonon transmission as well as heat absorption and transmission along the transfer channel as shown in Figure 11d. The material had a self-recovery rate of 95.4% and a thermal conductivity of up to $1.486 \text{ W m}^{-1} \text{ K}^{-1}$, making it ideal for cooling flexible electronic equipment. Table 4 summarises further studies of some typical Gr-based TIMS for various thermal management applications.

Table 4. A summary of graphene-based TIMs.

Material Composition	Thermal Conductivity (W/m·K)	Interface Resistance (K/W)	TIMs Application	Main Findings	Ref.
GNPs/BNNSS/CNFs	25.5	-	TIMs	GNP layers provide in-plane thermally conductive paths and EMI shielding capability and reinforce the mechanical strength	[237]
Carbon-based graphene foam roll (GFR-TIM)	~17.42	4.96 mm ²	CPU cooling	GFRs are made by hydroplastic foaming (HPF) and interface strengthening methods. Impregnation with GO enables its superior structural integrity and stability after 10,000 cycles as compared to most traditional TIMs. Due to its exceptionally high porosity (>93%), enabling its lower interface thermal resistance	[238]
Graphene/CNT hybrid aerogel	88.5	13.6 mm ²	High-power electronics	Fabrication of graphene/carbon nanotube aerogel TIMs overcomes poor thermal transport problems due to proper entanglement of bonds. This achieves super-elastic properties, improved conductivity, and a low thermal interface resistance	[239]
Graphene fibre	82.4	7.4 mm ²	High-power electronics	The graphene fibre (GF)-based TIM achieves thermal conductivity comparable to metals with enhanced structural and mechanical properties, making it durable and reliable in overcoming the long-standing bottleneck of mechanical–thermal mismatch in TIM design	[240]
LM-VGA/BPDMS	7.11	14.1 mm ²	High-performance electronics and sensors	The fabrication of elastic TIMs made of vertically oriented vertical aerogel with a liquid metal network achieves a directional pathway for heat dissipation with thermal resistance.	[241]

4.3.2. Carbon Nanotube (CNT)-Based TIMs

CNTs are lighter compared to graphite and have similar yield strength, making them an ideal alternative for applications requiring a high strength-to-weight ratio [242]. CNTs are known for their remarkable thermal conductivity of up to 3000 W/m·K, mechanical strength, and flexibility [242–244], and are produced using several processes, as represented in Figure 12a [242]. The different types of CNTs can be employed in TIMs by distributing them in a polymer matrix or growing them directly on substrates [245]. In this regard, using microwave plasma-enhanced chemical vapour deposition (PECVD), Zhang et al. [246] fabricated an aligned CNT array and examined the thermal resistance across the entire array interface. It was discovered that the bulk material and the HB-LED package interfacial conditions have an impact on the thermal performance of the CNT arrayed TIM. The CNT-thermal interface material (CNT-TIM) may dramatically reduce thermal interfacial resistance to as low as 7 mm² K W⁻¹, making it suitable for microelectronic thermal management. Similarly to this concept, Guo et al. [247] utilised a modified multi-wall carbon nanotube and Gr to fabricate a highly thermally conductive PVDF composite with a good thermal conductivity of 711.1%. The composite material successfully inhibits stacking,

promoting the formation of a well-dispersed 3D network structure for heat conduction and reducing the composite interfacial thermal resistance. In another study, Yu et al. [248] constructed a composite thermal interface material using a three-dimensional hybrid carbon network-reinforced polydimethylsiloxane by depositing vertically aligned CNTs on a horizontally orientated Gr layer. It was found that using a cooling system in heat sinks (Figure 12b) resulted in outstanding compressibility and adhesion properties, with a thermal conductivity of $113.61 \text{ W m}^{-1} \text{ K}^{-1}$ and an increase of up to 71.3% in the TIMs performance. Following the impressive results from this, Bahru and Mohammed [249] proposed the usage of CNT as TIMs on a heat spreader by electrophoretic deposition process. Per their concept, an optimal thickness of $56.95 \mu\text{m}$ and a high thermal conductivity of $27.08 \text{ W/m}\cdot\text{K}$ was achieved after six layers of deposition, displaying excellent heat removal.

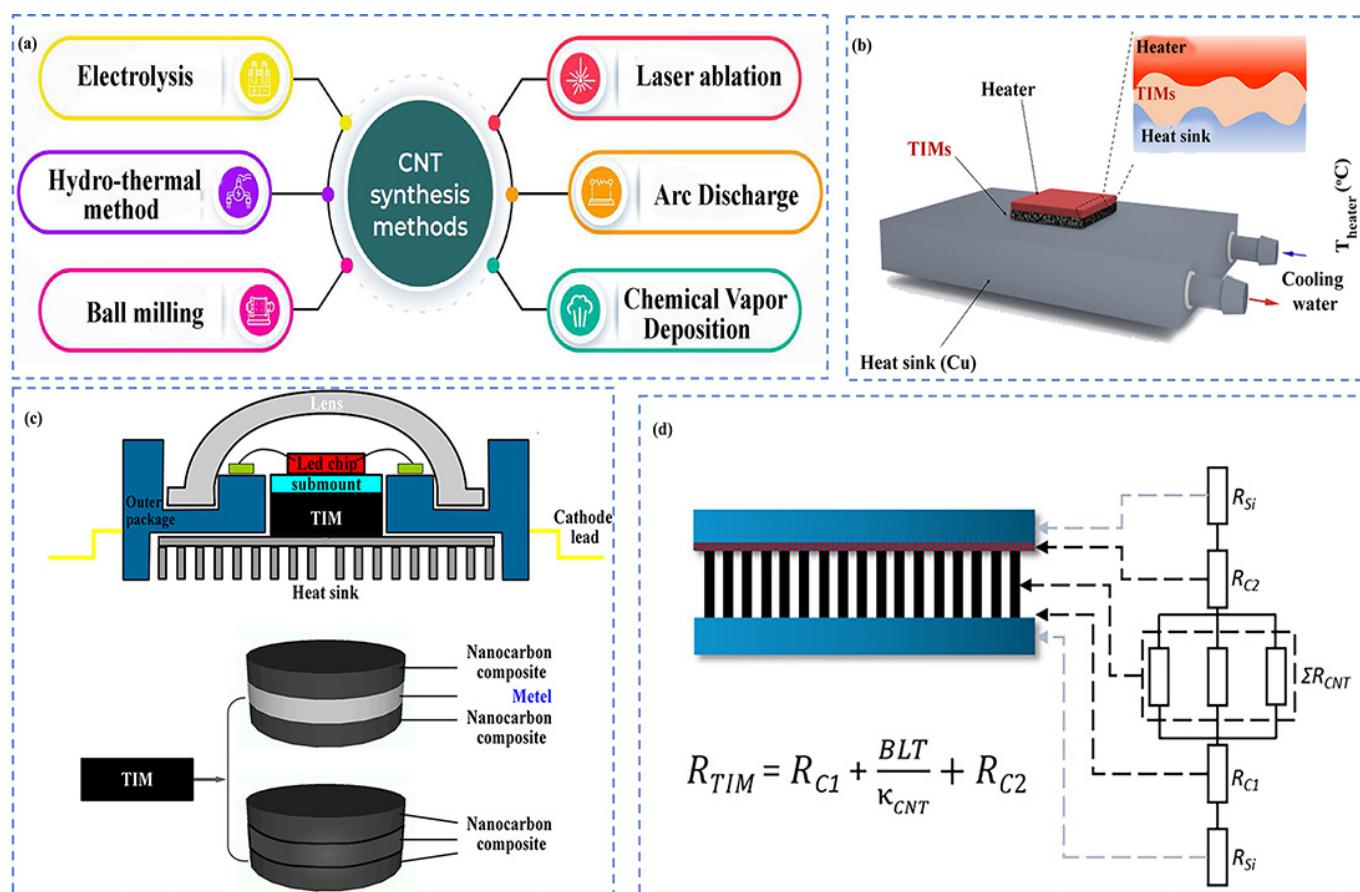


Figure 12. (a) Various synthesis techniques of CNTs. Reprinted from [242], 2023. An open access article under CC BY 4.0 by Elsevier. (b) Diagrammatic representation of the interfacial heat-transfer properties of TIMs. Reproduced from [248], an open access article under CC BY license by Springer Nature. (c) Schematic of the incorporated TIM into the LED package. Reprinted with permission from [250], 2013 Elsevier. (d) A cross-section of the fabricated CNT-based TIM integrated with a thermal circuit. Reprinted from [244], 2023. An open access article under CC BY license by the American Chemical Society.

In another study, Xing et al. [251] prepared an epoxy composite film with high thermal and electrical conductivity by dispersing multi-walled CNTs and copper nanowires in the epoxy matrix using the vacuum filtration process. A toughening ingredient was used to modify the epoxy, resulting in tough but flexible composite films. MWCNTs and Cu NWs have a remarkable synergetic effect, boosting electrical conductivity to 1500 S/m and thermal conductivity to 2.83 W/m·K. Its thermal resistance was as low as 1% for pure epoxy, indicating potential uses as thermal interface materials (TIMs) in electronics. Zhang et al. [250] applied a multi-walled carbon nanotube, graphite material, and epoxy resin as composites to make TIMs for use in LEDs (see Figure 12c). The thermal interface material, with a thermal conductivity of $4.9 \text{ W} (\text{m}\cdot\text{K})^{-1}$, provides efficient cooling and reduces energy usage for HB-LEDs. Nylander et al. [244] investigated the reliability of CNT array TIMs using accelerated ageing. Chemical vapour deposition (CVD) was used to create the CNT arrays on silicon substrates in a base-growth pattern. After ageing, the CNT catalyst is analysed using X-ray photoelectron spectroscopy to assess chemical changes. The CNT-catalyst bond appears to deteriorate over ageing, but not to the point where TIM performance is affected, and it could be incorporated with a thermal circuit (see Figure 12d). Bahru and Mohamed [252] developed a homogeneous thin film composite TIM CNT using electrophoretic deposition (EPD). At a thickness of 14.14 μm , the thermal conductivity was 27.08 W/m·K with a minimum internal resistance of $7.6 \text{ mm}^2 \text{ K/W}$, emphasising the potential for effective heat removal in ESS by CNTs.

4.3.3. Composite-Based TIMs

Composite TIMs made of carbon materials represent a substantial breakthrough in heat control technology. Composite TIMs can be designed with appropriate heat management and mechanical qualities for sophisticated applications. Given their high strength, thermal conductivity, and latent heat capacity, CNTs could be coupled with graphene and nanodiamonds as reinforcement for composites at the meso and macro scales [253]. The excellent electrical and thermal conductivity of CNTs in such a composite makes it useful for applications like heat dissipation [254] and mechanical damage detection [255]. For example, Li et al. [256] developed an advanced Co/N co-doped carbon foam-based multifunctional “five-in-one” composite PCMs that combine dual-temperature thermal management, light-triggered heating, waterproofing, flame retardancy, and microwave absorption. This was achieved through high-temperature calcination of melamine foam@ZIF67 and melting encapsulation of paraffin wax (PW). After 300 heating–cooling cycles with wearable electronics applications, the composite PCMs displayed good thermal management, structural stability, and thermal storage stability due to their combined material properties. He et al. [257] developed a multifunctional phase change material using carbon-based porous materials. The phase change composite (PCC) system was intended to have good electrical and thermal conductivity, thermal energy storage capacity, and temperature management performance. In another study, Bowland et al. [245] describe the usage of graphene-based sheets with high flexibility and durability (over 10,000 tensile cycles) in heat management. Composite TMMs with multifunctionalities and high in-plane thermal conductivity are used in electronic chips and flexible heat spreaders, as demonstrated by finite volume method simulation. The TIMs dissipate excess heat ($20.84 \text{ W}/(\text{m}\cdot\text{K})$) at only 16–22 μm thick and could work even in extremely cold conditions.

5. Hybrid C-bMs Composites for BTMS

A viable route for improving battery system temperature control is hybrid carbon materials with other non-carbon composites. Such a design is essential to the development of safe and effective battery technologies because of their capacity to enhance sustainability, energy storage, and thermal conductivity. As a proof of concept, Shivram and Harish [258] developed dual nano-enhanced phase change materials (NEPCM) using alumina and single-walled carbon nanotubes (SWCNT) to mitigate extreme heat events in battery cells. The results show that adding SWCNT to NEPCM greatly enhances heat absorption and transfer rates during thermal runaway situations. Similarly, Rana et al. [259] designed a liquid-based battery temperature management system for LIBs that provides a cooling effect using nanofluids based on multi-walled carbon nanotubes (MWCNTs). It was found that increasing the number of channels, nanoparticle concentration, and flow topologies improves cooling performance. The nanofluid containing 0.45% ϕ V of MWCNTs reduces battery temperature by approximately $17.1\text{ }^{\circ}\text{C}$ and improves temperature uniformity, preventing thermal runaway (TR). Akin to this, Zhang et al. [260] investigated the cell temperature, temperature differential, and thermal runaway propagation of a hybrid battery thermal management system using phase change materials and liquid cooling in harsh conditions. The findings revealed that the phase change materials not only minimise the energy consumption of the battery thermal management system but also act as a buffer in the thermal runaway propagation of the battery. Similarly, Weng et al. [261] studied the thermal runaway propagation in battery systems using aluminium honeycomb, air cooling, and phase change materials, and concluded that aluminium honeycomb aids in mitigating thermal runaway events in batteries. In another study, Dai et al. [51] utilised encapsulated inorganic phase transition material (EPCM) with a carbon nanotube and silica additive to reduce thermal in batteries (see Figure 13a). It was found that hybrid EPCM/CNT not only reduced the module temperature rise but also enhanced the temperature uniformity during normal operation when compared to materials without EPCM/CNT. The maximum battery temperature dropped from $76\text{ }^{\circ}\text{C}$ to $61.2\text{ }^{\circ}\text{C}$ at a discharge rate of 2C, a temperature differential of less than $3\text{ }^{\circ}\text{C}$. Also, the three cells' trigger times were effectively delayed by 129, 474, and 551 s, respectively, and the propagation intervals were significantly increased. The hybrid material was deemed appropriate for battery thermal management applications because of the reduced latent heat (93.83 kJ kg^{-1}) and the thermal diffusion coefficient ($0.837\text{ mm}^2\text{ s}^{-1}$).

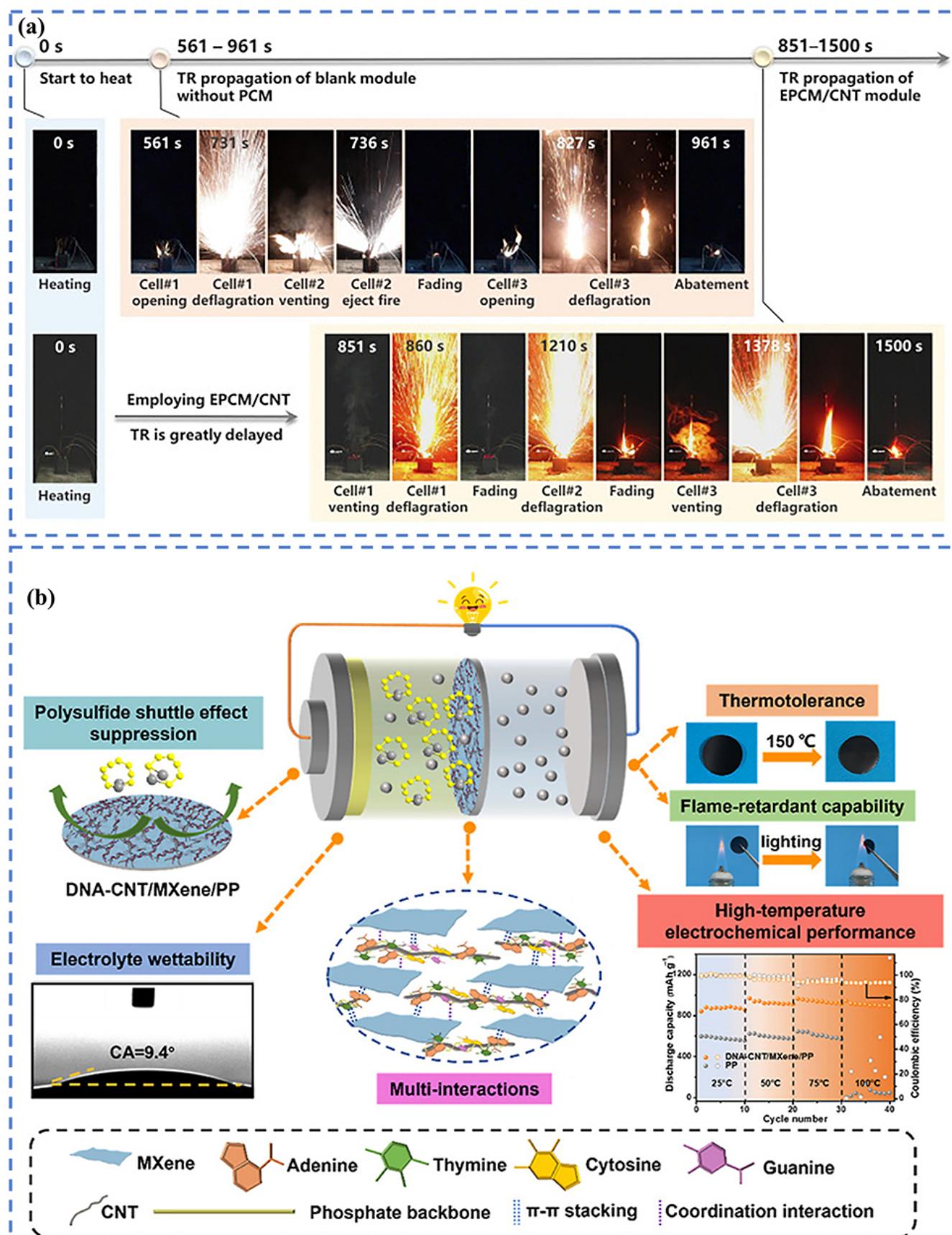


Figure 13. (a) Battery cell TR propagation process with and without EPCM/CNT. Reprinted with permission from [51], 2023, Elsevier. (b) The flame retardancy of commercial PP separators and DNA-CNT/MXene/PP separators. Reprinted with permission from [262], 2022, Elsevier.

Another hybrid approach involves the incorporation of fire-retardant materials into the composite. For instance, in a study by Gong et al. [263], MWCNTs and intumescence flame retardants (IFRs) were incorporated into PEG to fabricate BTM to improve heat dissipation and prevent localised heat accumulation and prevent thermal runaway. The IFR increased the carbon content and minimized organic leakage while improving PCM's thermal stability. Similarly, Li et al. [262] fabricated a multifunctional hybrid separator made up of deoxyribonucleic acid (DNA)-CNT and Ti_3C_2Tx MXene-modified polypropylene (DNA-CNT/MXene/PP). It was found that the Li-S batteries could operate at temperatures ranging from 25 to 100 °C with 79% capacity retention after 100 cycles due to the thermal stability of the DNA-CNT/MXene/PP-based separator. Furthermore, the 3D interconnected networks in the composite showed high-temperature tolerance (even at 180 °C) and excellent flame retardancy in addition to providing superior physical plugging/chemical anchoring capabilities for the shuttled polysulfides and increased the electrolyte wettability (refer to Figure 13b). In a slightly similar fashion, Wu et al. [264] demonstrated that the addition of flame retardants in the electrolyte of LIBs can ameliorate the thermal stability and reduce the risk of thermal runaway in batteries.

Integrated Thermal Management with C-bMs for ESS

In energy storage and thermal management, combining two separate thermal management solutions into a single system presents a viable solution to the difficulties of efficiency, space, and weight, particularly in EVs, renewable energy systems, and portable devices. For example, Liu et al. [265] developed a sophisticated carbon-based PCM nanocomposite with microwave absorption capabilities, thermal management, and solar-driven thermal energy storage by encapsulating $MoS_2@CNTs$ in paraffin wax. Owing to their synergistic effect, the PW/ $MoS_2@CNTs$ composite PCMs demonstrated exceptional long-term thermal storage durability and a high phase change enthalpy of 101.60 J/g. This technology could find application in highly integrated electrical systems. Chen et al. [266] report the fabrication of a multifunctional integrated carbon-based PCM for high-efficiency solar-thermal harvesting (about 40–60%) and thermal control. The paraffin waxes and the nanotube network are consistently interpenetrated, increasing phase transition enthalpy and thermal conductivity making it useful for simultaneous solar absorption, energy storage, and thermal management. Following this integrative approach, Arshad et al. [267] developed a novel, clean, zero-noise thermal management technology (TMT) based on phase change thermal energy storage (TES) using graphene nanoparticles, reduced graphene oxide, and multi-wall carbon nanotubes to achieve excellent subcooling efficiency, thermal stability, and conductivity, with possible applications in electronics.

6. Outlook and Research Direction

As the need for high-performance electronic devices and electric vehicles increases, the future of carbon-based thermal management innovations looks promising. These developments could significantly transform thermal management techniques, paving the way for more sustainable and efficient energy solutions. With the current state of research and development, future efforts will focus on the following thematic areas.

(i) Sustainable and scalable manufacturing of C-bMs

Sustainability considerations will play a crucial role in the future direction of research on C-bMs [268]. Although most carbon-based thermal management technologies appear to be aligned with the Sustainable Development Goals (SDGs), the raw material extraction and synthesis/fabrication processes may not be wholly wholesome. As a result, sustainable and scalable manufacturing of C-bMs based on biomass will thrive in the coming decades due to the perceived cost-effectiveness, reduced complexity in large-scale fabrication, reusability,

and environmental benefits. Therefore, critical factors (see Figure 14) that embrace efficient innovative carbon material manufacturing with relatively cheap cost, facile synthesis processes, low energy consumption, and net-zero carbon dioxide emissions are essential for decreasing the carbon footprint [269] in the energy sector. The innovative and scalable strategies will significantly boost the advancement of battery thermal management systems, ultimately supporting a shift towards cleaner and more efficient energy solutions.

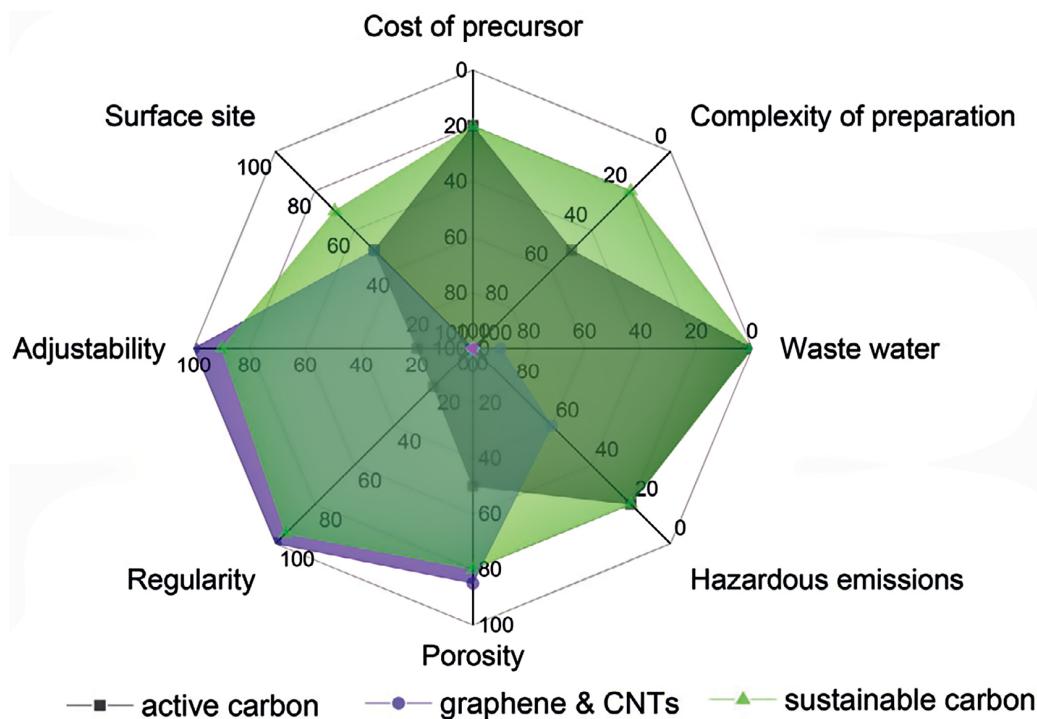


Figure 14. Comparative data on cost, production complexity, energy consumption, emission of environmentally hazardous substances, and porosities of sustainable carbon materials, activated carbon, and crystalline carbon (e.g., graphene and carbon nanotubes (CNTs)). Reprinted with permission from [269] © 2021. Wiley-VCH GmbH.

To support the shift towards a cleaner and more efficient energy solution, it is important to understand the cost–benefit analysis for the provision of a comprehensive framework for decision-making in battery thermal management. As shown in Figure 15, the upscaling of carbon-based thermal solutions necessitates significant initial investment across several domains. These costs can be categorized into three primary areas: material costs, manufacturing costs, and research and development (R&D) expenses. The commercial procurement of advanced carbon materials such as those illustrated in Figure 1a represents a substantial portion of the initial investment. These materials are often more expensive than conventional thermal management solutions due to their unique properties and the complexity of their production processes [2]. Additionally, the integration of carbon-based materials into existing battery manufacturing processes may require new equipment and techniques, leading to increased manufacturing costs. This includes investments in specialized machinery capable of handling and processing advanced carbon materials. Furthermore, significant R&D efforts are necessary to optimise the performance of carbon-based thermal solutions in batteries. This includes experimental studies, prototyping, and testing to ensure that these materials meet industry standards for safety and efficiency [37].

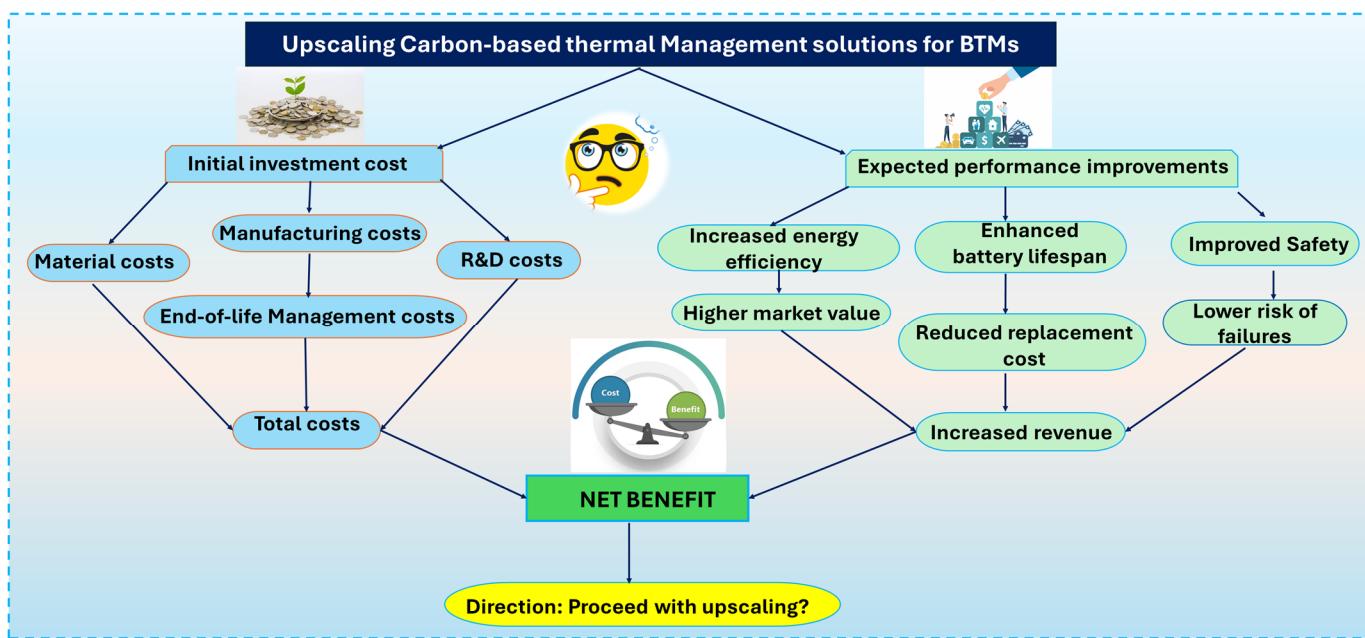


Figure 15. Cost–benefit analysis of C-bMs upscaling.

Despite the high initial costs, the anticipated performance improvements associated with carbon-based thermal solutions present a compelling investment case. The primary benefits can be categorised as increased energy efficiency, enhanced battery lifespan, and improved safety.

Carbon-based materials exhibit superior thermal conductivity, which can enhance the overall energy efficiency of battery systems. Improved thermal management minimizes energy loss during operation, leading to higher effective energy output [24]. Moreover, effective thermal management reduces the risk of overheating, which is a significant factor in battery degradation. By maintaining optimal operating temperatures, carbon-based thermal solutions can extend the lifespan of batteries, resulting in lower replacement frequencies and associated costs [1,9]. Additionally, the integration of advanced thermal management solutions can mitigate the risks associated with thermal runaway, which is a critical safety concern in lithium-ion batteries. Enhanced thermal stability contributes to safer battery operation, thereby reducing liability and potential damage costs.

The net benefits derived from upscaling carbon-based thermal solutions can be substantial. The increased energy efficiency translates to a higher market value for batteries, making them more attractive to consumers and industries alike. Additionally, the extended lifespan of batteries reduces the frequency of replacements, thereby lowering long-term operational costs. Furthermore, improved safety features not only enhance consumer confidence but also minimise the risks of catastrophic failures, which can result in significant financial losses and reputational damage for manufacturers [36]. Collectively, these factors contribute to an increased revenue stream that can offset the initial investment costs over time. Therefore, the cost–benefit analysis of upscaling carbon-based thermal solutions in batteries reveals a complex interplay of initial investment costs and anticipated performance improvements. While the upfront expenses are considerable, the long-term benefits manifested in enhanced energy efficiency, extended battery lifespan, and improved safety present a persuasive argument for investment in these advanced materials.

(ii) Multifunctional carbon-based thermal management solutions

Surface functionalisation and the exploration of synergistic carbon material and other non-carbon advanced materials like boron nitrides, MXenes, layered double hydroxides, etc., that will yield efficient multicomponent thermal management solutions in batteries

will advance the field of BTMS in the next decade [270]. These materials provide a distinct set of features that make them appropriate for addressing complicated thermal challenges while delivering extra functionality. Similarly, organic precursors to carbon compounds can be doped to form heteroatoms that can enhance their characteristics [271]. Doping with heteroatoms modifies the polarity of the carbon surface, increasing the development of binding sites and making the surface active for various processes. N-doping, for instance, improves conductivity without requiring ultrahigh-temperature procedures [272]. Carbon materials could also be coupled with functional metal ions to create a synergistic thermal control system.

(iii) Self-healing C-bMs composites

Self-healing carbon composites hold significant potential for improving battery thermal management [273]. Their ability to autonomously repair damage while maintaining thermal efficiency makes them a valuable asset in the development of safer and more durable battery systems. Self-healing carbon composites align with the growing demand for sustainable materials in battery technology. Although some research has been carried out in this regard [53,274–276], further research is needed to make them commercially viable alternatives. The development of such composites will reduce the need for battery parts replacement and enhance the durability of thermal management systems, contributing to more sustainable battery solutions. This is particularly relevant in this age of electronics miniaturisation and electric vehicles, where efficient thermal management is critical for performance and safety.

(iv) Seamless intelligent IoT C-bMs composites

In the wake of digital technologies, further involving machine learning and AI in the design of C-bMs proactive thermal management solutions for BTMS will proliferate. In this regard, thermal runaway prevention innovations involve carbon-based sensors that can monitor temperature and thermal events in BTMS and provide feedback in real-time will ultimately be helpful. Some of these technologies have been investigated for in situ battery monitoring [55,277]. However, further developments are based on smart thermal monitoring systems that utilise artificial intelligence to monitor environmental conditions, including temperature, and adjust heating and cooling systems accordingly in ESS.

(v) Further exploration of uncommon C-bMs

Other less-explored carbon-based materials such as carbon aerogels, carbon black, fullerene, graphitic carbon nitrides, carbon dots, carbon black, activated carbons, biochar, etc., and their combinations could prove useful in BTMS. For instance, carbon foam is a lightweight and highly porous material that could improve thermal insulation and heat dissipation, potentially reducing the risk of thermal runaway. Although carbon foams have been used in some instances for thermal management, the potential benefit in this regard is endless. Also, the unique structure of carbon nitrides for instance may offer potential for thermal management and could be explored for their thermal conductivity and stability like carbon black.

7. Conclusions

This review highlighted the critical role of carbon-based materials in addressing the growing thermal management challenges faced by advanced ESS. As the demand for high-energy density and high-power batteries continues to increase, particularly in electric vehicles and grid-scale energy storage, the need for effective thermal control is imminent. The exceptional thermal properties of carbon-based materials, such as high thermal conductivity, light weight, and chemical stability, make them attractive candidates for a wide range of thermal management applications in battery systems. Innovations in this

field have resulted in the development of advanced carbon-derived solutions, including graphene-based heat sinks, carbon nanotube-enhanced thermal interface materials, and hybrid carbon-metal composites. These innovative approaches have demonstrated significant improvements in heat dissipation, temperature uniformity, and overall battery safety and reliability. As the field of carbon-based thermal management materials continues to evolve, further advancements in scalable manufacturing, cost-effective production, and integration with emerging battery chemistries will be crucial. Additionally, the exploration of hybrid and multi-functional carbon-based solutions, which combine thermal management with other functionalities like structural support or energy storage, holds promising potential for next-generation ESSs. As the demand for high-performance, sustainable energy solutions continues to grow, the ongoing research and development in this field will be instrumental in meeting the evolving needs of the industry.

Author Contributions: Conceptualisation and initial draft were carried out by B.T., B.F. and E.A.O. Subsequent data curation, validation, and editing were carried out by E.A.O., D.C., Y.M., H.J. and Y.H.; B.F. supervised the work. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Hong Kong Polytechnic University (1-WZ2H, 1-BBCB), and the Innovation and Technology Council of Hong Kong SAR (Project number ITP/023/22TP).

Data Availability Statement: No new data were used for this article.

Conflicts of Interest: The authors declare no conflicts of interest for this work.

References

1. Nikolaidis, P.; Poulikkas, A. Battery energy storage systems: A methodical enabler of reliable power. In *Advanced Materials for Battery Separators*; Elsevier: Amsterdam, The Netherlands, 2024; pp. 1–33.
2. Bahloul, M.; Trivedi, R.; Cardo-Miota, J.; Papadimitriou, C.; Efthymiou, V.; Nouri, A.; Khadem, S. Analysis of barriers and key enablers toward citizen ESS successful integration. *J. Energy Storage* **2024**, *86*, 111166.
3. Tawiah, B.; Seidu, R.K.; Asinyo, B.K.; Fei, B. A review of fiber-based supercapacitors and sensors for energy-autonomous systems. *J. Power Sources* **2024**, *595*, 234069. [[CrossRef](#)]
4. Tawiah, B.; Ofori, E.A.; Chen, D.; Jia, H.; Fei, B. Sciento-qualitative study of zinc-iodine energy storage systems. *J. Energy Storage* **2024**, *79*, 110086.
5. Gao, J.; Xie, Y.; Zeng, P.; Zhang, L. Strategies for Optimizing the Zn Anode/Electrolyte Interfaces Toward Stable Zn-Based Batteries. *Small Methods* **2023**, *7*, 2300855. [[CrossRef](#)]
6. Duh, Y.-S.; Sun, Y.; Lin, X.; Zheng, J.; Wang, M.; Wang, Y.; Lin, X.; Jiang, X.; Zheng, Z.; Zheng, S. Characterization on thermal runaway of commercial 18650 lithium-ion batteries used in electric vehicles: A review. *J. Energy Storage* **2021**, *41*, 102888.
7. Qin, P.; Jia, Z.; Wu, J.; Jin, K.; Duan, Q.; Jiang, L.; Sun, J.; Ding, J.; Shi, C.; Wang, Q. The thermal runaway analysis on LiFePO₄ electrical energy storage packs with different venting areas and void volumes. *Appl. Energy* **2022**, *313*, 118767.
8. Mallick, S.; Gayen, D. Thermal behaviour and thermal runaway propagation in lithium-ion battery systems—A critical review. *J. Energy Storage* **2023**, *62*, 106894. [[CrossRef](#)]
9. Jeevarajan, J.A.; Joshi, T.; Parhizi, M.; Rauhala, T.; Juarez-Robles, D. *Battery Hazards for Large Energy Storage Systems*; ACS Publications: Washington, DC, USA, 2022.
10. Zalosh, R.; Gandhi, P.; Barowy, A. Lithium-ion energy storage battery explosion incidents. *J. Loss Prev. Process Ind.* **2021**, *72*, 104560.
11. The National Highway Traffic Safety Administration (NHTSA). Vehicle Recalls. 2023. Available online: <https://www.safercar.gov/recalls> (accessed on 25 June 2024).
12. Sun, P.; Bisschop, R.; Niu, H.; Huang, X. A Review of Battery Fires in Electric Vehicles. *Fire Technol.* **2020**, *56*, 1361–1410. [[CrossRef](#)]
13. Shi, C.; Hamann, T.; Takeuchi, S.; Alexander, G.V.; Nolan, A.M.; Limpert, M.; Fu, Z.; O'Neill, J.; Godbey, G.; Dura, J.A. 3D asymmetric bilayer garnet-hybridized high-energy-density lithium–sulfur batteries. *ACS Appl. Mater. Interfaces* **2022**, *15*, 751–760.
14. Thakur, A.K.; Ahmed, M.S.; Kang, H.; Prabakaran, R.; Said, Z.; Rahman, S.; Sathyamurthy, R.; Kim, J.; Hwang, J.Y. Critical review on internal and external battery thermal management systems for fast charging applications. *Adv. Energy Mater.* **2023**, *13*, 2202944. [[CrossRef](#)]
15. Yue, Q.; He, C.; Wu, M.; Zhao, T. Advances in thermal management systems for next-generation power batteries. *Int. J. Heat Mass Transf.* **2021**, *181*, 121853. [[CrossRef](#)]

16. Lohrasbi, S.; Hammer, R.; Essl, W.; Reiss, G.; Defregger, S.; Sanz, W. A comprehensive review on the core thermal management improvement concepts in power electronics. *IEEE Access* **2020**, *8*, 166880–166906. [[CrossRef](#)]
17. Togun, H.; Aljibori, H.S.S.; Biswas, N.; Mohammed, H.I.; Sadeq, A.M.; Rashid, F.L.; Abdulrazzaq, T.; Zearah, S.A. A critical review on the efficient cooling strategy of batteries of electric vehicles: Advances, challenges, future perspectives. *Renew. Sustain. Energy Rev.* **2024**, *203*, 114732. [[CrossRef](#)]
18. Liu, X.; Jia, H.; Li, H. Flame-retarding quasi-solid polymer electrolytes for high-safety lithium metal batteries. *Energy Storage Mater.* **2024**, *67*, 103263. [[CrossRef](#)]
19. Mohammadian, S.K.; Zhang, Y. Thermal management optimization of an air-cooled Li-ion battery module using pin-fin heat sinks for hybrid electric vehicles. *J. Power Sources* **2015**, *273*, 431–439. [[CrossRef](#)]
20. Widhyantara, R.D.; Naufal, M.A.; Sambegoro, P.L.; Nurprasetio, I.P.; Triawan, F.; Djamari, D.W.; Nandiyanto, A.B.D.; Budiman, B.A.; Aziz, M. Low-cost air-cooling system optimization on battery pack of electric vehicle. *Energies* **2021**, *14*, 7954. [[CrossRef](#)]
21. Zhao, G.; Wang, X.; Negnevitsky, M.; Zhang, H. A review of air-cooling battery thermal management systems for electric and hybrid electric vehicles. *J. Power Sources* **2021**, *501*, 230001. [[CrossRef](#)]
22. Teng, H.; Ma, Y.; Yeow, K.; Thelliez, M. An analysis of a lithium-ion battery system with indirect air cooling and warm-up. *SAE Int. J. Passeng. Cars-Mech. Syst.* **2011**, *4*, 1343–1357. [[CrossRef](#)]
23. Ding, Y.; Ji, H.; Wei, M.; Liu, R. Effect of liquid cooling system structure on lithium-ion battery pack temperature fields. *Int. J. Heat Mass Transf.* **2022**, *183*, 122178. [[CrossRef](#)]
24. Saw, L.; Tay, A.; Zhang, L.W. Thermal management of lithium-ion battery pack with liquid cooling. In Proceedings of the 2015 31st Thermal Measurement, Modeling & Management Symposium (SEMI-THERM), San Jose, CA, USA, 15–19 March 2015; pp. 298–302.
25. Wang, Y.; Yu, Y.; Jing, Z.; Wang, C.; Zhou, G.; Zhao, W. Thermal performance of lithium-ion batteries applying forced air cooling with an improved aluminium foam heat sink design. *Int. J. Heat Mass Transf.* **2021**, *167*, 120827.
26. Lee, N.; Choi, J.; Lee, J.; Shin, D.; Um, S. Prognostic analysis of thermal interface material effects on anisotropic heat transfer characteristics and state of health of a 21700 cylindrical lithium-ion battery module. *J. Energy Storage* **2023**, *72*, 108594.
27. Maddila, R.V.; Rostami, S. Investigation of the Effect of Thermal Interface Materials on the Cooling of Battery Cells: A Comparative Study on the Heat Transfer Properties. Master’s Thesis, Chalmers University of Technology, Gothenburg, Sweden, 2023.
28. Wang, X.; Liu, S.; Zhang, Y.; Lv, S.; Ni, H.; Deng, Y.; Yuan, Y. A review of the power battery thermal management system with different cooling, heating and coupling system. *Energies* **2022**, *15*, 1963. [[CrossRef](#)]
29. Liu, C.; Xu, D.; Weng, J.; Zhou, S.; Li, W.; Wan, Y.; Jiang, S.; Zhou, D.; Wang, J.; Huang, Q. Phase change materials application in battery thermal management system: A review. *Materials* **2020**, *13*, 4622. [[CrossRef](#)] [[PubMed](#)]
30. Jilte, R.; Afzal, A.; Panchal, S. A novel battery thermal management system using nano-enhanced phase change materials. *Energy* **2021**, *219*, 119564.
31. Burchell, T.D. *Carbon Materials for Advanced Technologies*; Elsevier: Amsterdam, The Netherlands, 1999.
32. Jia, H.; Qiu, M.; Tang, C.; Liu, H.; Xu, J.; Tawiah, B.; Jiang, S.-X.; Zhang, X. Advanced flexible carbon-based current collector for zinc storage. *Adv. Fiber Mater.* **2022**, *4*, 1500–1510. [[CrossRef](#)]
33. Wang, M.; Liu, M.; Li, P.; Yu, F. Lauric acid encapsulated in P-doped carbon matrix with reinforced heat storage performance for efficient battery cooling. *J. Energy Storage* **2021**, *44*, 103461.
34. Hu, L.; An, Y.; Zhang, L.; Mai, L.; Ma, T.; An, Q.; Wang, Q. Shape-stabilized phase change material based on MOF-derived oriented carbon nanotubes for thermal management of lithium-ion battery. *J. Energy Storage* **2023**, *72*, 108520. [[CrossRef](#)]
35. Adams, R.A.; Varma, A.; Pol, V.G. Carbon anodes for nonaqueous alkali metal-ion batteries and their thermal safety aspects. *Adv. Energy Mater.* **2019**, *9*, 1900550.
36. Hwang, F.S.; Confrey, T.; Reidy, C.; Picovici, D.; Callaghan, D.; Culliton, D.; Nolan, C. Review of battery thermal management systems in electric vehicles. *Renew. Sustain. Energy Rev.* **2024**, *192*, 114171.
37. Leoncini, G.; Mothier, R.; Michel, B.; Clausse, M. A review on challenges concerning thermal management system design for medium duty electric vehicles. *Appl. Therm. Eng.* **2024**, *236*, 121464. [[CrossRef](#)]
38. Khan, S.A.; Hussain, I.; Thakur, A.K.; Yu, S.; Lau, K.T.; He, S.; Dong, K.; Chen, J.; Li, X.; Ahmad, M. Advancements in battery thermal management system for fast charging/discharging applications. *Energy Storage Mater.* **2024**, *65*, 103144. [[CrossRef](#)]
39. Quintiere, J.G. On a method to mitigate thermal runaway and propagation in packages of lithium ion batteries. *Fire Saf. J.* **2022**, *130*, 103573. [[CrossRef](#)]
40. Niu, H.; Chen, C.; Ji, D.; Li, L.; Li, Z.; Liu, Y.; Huang, X. Thermal-Runaway Propagation over a Linear Cylindrical Battery Module. *Fire Technol.* **2020**, *56*, 2491–2507. [[CrossRef](#)]
41. Zhang, K.; Wang, L.; Xu, C.; Wu, H.; Huang, D.; Jin, K.; Xu, X. Study on Thermal Runaway Risk Prevention of Lithium-Ion Battery with Composite Phase Change Materials. *Fire* **2023**, *6*, 208. [[CrossRef](#)]
42. Huang, J.; Fan, Z.; Xu, C.; Jiang, F.; Feng, X. Experimental Investigation of Thermal Runaway Characteristics of Large-Format Li(Ni0.8Co0.1Mn0.1)O₂ Battery under Different Heating Powers and Areas. *Batteries* **2024**, *10*, 241. [[CrossRef](#)]

43. Mallarapu, A.; Sunderlin, N.; Boovaragavan, V.; Tamashiro, M.; Peabody, C.; Pelloux-gervais, T.; Li, X.X.; Sizikov, G. Effects of Trigger Method on Fire Propagation during the Thermal Runaway Process in Li-ion Batteries. *J. Electrochem. Soc.* **2024**, *171*, 040514. [CrossRef]
44. Liu, G.; Ouyang, M.; Lu, L.; Jianqiu, L.; Han, X. Analysis of the heat generation of lithium-ion battery during charging and discharging considering different influencing factors. *J. Therm. Anal. Calorim.* **2014**, *116*, 1001–1010. [CrossRef]
45. Feng, X.; Ouyang, M.; Liu, X.; Lu, L.; Xia, Y.; He, X. Thermal runaway mechanism of lithium ion battery for electric vehicles: A review. *Energy Storage Mater.* **2018**, *10*, 246–267. [CrossRef]
46. Zhao, J.; Feng, X.; Tran, M.-K.; Fowler, M.; Ouyang, M.; Burke, A.F. Battery safety: Fault diagnosis from laboratory to real world. *J. Power Sources* **2024**, *598*, 234111. [CrossRef]
47. Wang, Q.; Jiang, B.; Li, B.; Yan, Y. A critical review of thermal management models and solutions of lithium-ion batteries for the development of pure electric vehicles. *Renew. Sustain. Energy Rev.* **2016**, *64*, 106–128. [CrossRef]
48. Wu, T.; Wang, C.; Hu, Y.; Liang, Z.; Fan, C. Research on electrochemical characteristics and heat generating properties of power battery based on multi-time scales. *Energy* **2023**, *265*, 126416. [CrossRef]
49. Wilke, S.; Schweitzer, B.; Khateeb Razack, S.A.; Al-Hallaj, S. Preventing thermal runaway propagation in lithium ion battery packs using a phase change composite material: An experimental study. *J. Power Sources* **2017**, *340*, 51–59. [CrossRef]
50. Chai, Z.; Li, J.; Liu, Z.; Liu, Z.; Jin, X. Comprehensive Modeling and Safety Protection Strategy for Thermal Runway Propagation in Lithium-Ion Battery Modules under Multi-Factor Influences. *Batteries* **2024**, *10*, 31. [CrossRef]
51. Dai, X.; Ping, P.; Kong, D.; Gao, X.; Zhang, Y.; Wang, G.; Peng, R. Heat transfer enhanced inorganic phase change material compositing carbon nanotubes for battery thermal management and thermal runaway propagation mitigation. *J. Energy Chem.* **2024**, *89*, 226–238. [CrossRef]
52. Duston, C.; Seghi, S.; Watts, R.; Carney, B. *Strength Enhancement and Application Development of Carbon Foam for Thermal Management Systems*; Work Sponsored under SBIR Contract; Defense Technical Information Center: Fort Belvoir, VA, USA, 2004. Available online: <https://apps.dtic.mil/sti/citations/ADA457609> (accessed on 27 January 2025).
53. Joo, S.-J.; Yu, M.-H.; Kim, W.S.; Kim, H.-S. Damage detection and self-healing of carbon fiber polypropylene (CFPP)/carbon nanotube (CNT) nano-composite via addressable conducting network. *Compos. Sci. Technol.* **2018**, *167*, 62–70. [CrossRef]
54. Wang, Y.; Zhao, L.; Zhan, W.; Chen, Y.; Chen, M. Flame retardant composite phase change materials with MXene for lithium-ion battery thermal management systems. *J. Energy Storage* **2024**, *86*, 111293.
55. Gulsoy, B.; Vincent, T.; Sansom, J.; Marco, J. In-situ temperature monitoring of a lithium-ion battery using an embedded thermocouple for smart battery applications. *J. Energy Storage* **2022**, *54*, 105260. [CrossRef]
56. Zhong, L.; Guo, L.; Wang, J.; Song, Q.; Li, H.; Li, Y. Excellent heat transfer and mechanical properties of graphite material with rolled-up graphene layers. *Carbon* **2023**, *208*, 123–130. [CrossRef]
57. Li, Z.; Wang, L.; Li, Y.; Feng, Y.; Feng, W. Carbon-based functional nanomaterials: Preparation, properties and applications. *Compos. Sci. Technol.* **2019**, *179*, 10–40. [CrossRef]
58. Xie, Y.; Wang, X. Thermal conductivity of carbon-based nanomaterials: Deep understanding of the structural effects. *Green Carbon* **2023**, *1*, 47–57. [CrossRef]
59. Slepčková Kasálková, N.; Slepčíkova, P.; Švorčík, V. Carbon Nanostructures, Nanolayers, and Their Composites. *Nanomaterials* **2021**, *11*, 2368. [CrossRef]
60. Nasir, S.; Hussein, M.Z.; Zainal, Z.; Yusof, N.A. Carbon-Based Nanomaterials/Allotropes: A Glimpse of Their Synthesis, Properties and Some Applications. *Materials* **2018**, *11*, 295. [CrossRef]
61. Jarosinski, L.; Rybak, A.; Gaska, K.; Kmita, G.; Porebska, R.; Kapusta, C. Enhanced thermal conductivity of graphene nanoplatelets epoxy composites. *Mater. Sci. Pol.* **2017**, *35*, 382–389. [CrossRef]
62. Karimi, D.; Behi, H.; Van Mierlo, J.; Berecibar, M. An Experimental Study on Thermal Performance of Graphite-Based Phase-Change Materials for High-Power Batteries. *Energies* **2022**, *15*, 2515. [CrossRef]
63. Teboho Clement, M.; Mokgaotsa Jonas, M.; Jeremia Shale, S.; Setumo Victor, M.; Dickson Mubera, A. Thermal conductivity of graphite-based polymer composites. In *Impact of Thermal Conductivity on Energy Technologies*; Aamir, S., Ed.; IntechOpen: Rijeka, Croatia, 2018; Chapter 11.
64. Zhang, L.; Deng, K.K.; Nie, K.B.; Wang, C.J.; Xu, C.; Shi, Q.X.; Liu, Y.; Wang, J. Thermal conductivity and mechanical properties of graphite/Mg composite with a super-nano CaCO₃) interfacial layer. *iScience* **2023**, *26*, 106505. [CrossRef] [PubMed]
65. Lin, X.; Zhang, X.; Liu, L.; Liang, J.; Liu, W. Polymer/expanded graphite-based flexible phase change material with high thermal conductivity for battery thermal management. *J. Clean. Prod.* **2022**, *331*, 130014. [CrossRef]
66. Jiang, G.; Huang, J.; Fu, Y.; Cao, M.; Liu, M. Thermal optimization of composite phase change material/expanded graphite for Li-ion battery thermal management. *Appl. Therm. Eng.* **2016**, *108*, 1119–1125. [CrossRef]
67. Wang, Z.; Du, C.; Qi, R.; Wang, Y. Experimental study on thermal management of lithium-ion battery with graphite powder based composite phase change materials covering the whole climatic range. *Appl. Therm. Eng.* **2022**, *216*, 119072. [CrossRef]
68. Talluri, T.; Angani, A.; Shin, K.; Hwang, M.-H.; Cha, H.-R. A novel design of lithium-polymer pouch battery pack with passive thermal management for electric vehicles. *Energy* **2024**, *304*, 132205. [CrossRef]

69. Zhang, X.; Wu, S.; Tang, K.; Xu, Y.; Tang, Y.; Ma, Y.; Li, T. A biomimetic melting-evaporation cooling bilayer for efficient thermal management of ultrafast-cycling batteries. *Energy Storage Mater.* **2024**, *71*, 103602. [[CrossRef](#)]
70. Yan, J.; Li, K.; Chen, H.; Wang, Q.; Sun, J. Experimental study on the application of phase change material in the dynamic cycling of battery pack system. *Energy Convers. Manag.* **2016**, *128*, 12–19. [[CrossRef](#)]
71. Wang, S.; Xing, Y.; Hao, Z.; Yin, J.; Hou, X.; Wang, Z. Experimental study on the thermal performance of PCMs based heat sink using higher alcohol/graphite foam. *Appl. Therm. Eng.* **2021**, *198*, 117452. [[CrossRef](#)]
72. Wu, W.; Wu, W.; Wang, S. Thermal optimization of composite PCM based large-format lithium-ion battery modules under extreme operating conditions. *Energy Convers. Manag.* **2017**, *153*, 22–33. [[CrossRef](#)]
73. Zhao, X.; Li, C.; Bai, K.; Xie, B.; Chen, J.; Liu, Q. Multiple structure graphite stabilized stearic acid as composite phase change materials for thermal energy storage. *Int. J. Min. Sci. Technol.* **2022**, *32*, 1419–1428. [[CrossRef](#)]
74. Menaa, F.; Fatemeh, Y.; Vashist, S.K.; Iqbal, H.; Sharts, O.N.; Menaa, B. Graphene, an Interesting Nanocarbon Allotrope for Biosensing Applications: Advances, Insights, and Prospects. *Biomed. Eng. Comput. Biol.* **2021**, *12*, 1179597220983821. [[CrossRef](#)]
75. Mbayachi, V.B.; Ndayiragije, E.; Sammani, T.; Taj, S.; Mbuta, E.R.; khan, A.U. Graphene synthesis, characterization and its applications: A review. *Results Chem.* **2021**, *3*, 100163. [[CrossRef](#)]
76. Yusaf, T.; Mahamude, A.S.; Farhana, K.; Harun, W.S.; Kadirgama, K.; Ramasamy, D.; Kamarulzaman, M.K.; Subramonian, S.; Hall, S.; Dhahad, H.A. A Comprehensive Review on Graphene Nanoparticles: Preparation, Properties, and Applications. *Sustainability* **2022**, *14*, 12336. [[CrossRef](#)]
77. Du, Y.; Wang, M.; Ye, X.; Liu, B.; Han, L.; Jafri, S.H.; Liu, W.; Zheng, X.; Ning, Y.; Li, H. Advances in the Field of Graphene-Based Composites for Energy–Storage Applications. *Crystals* **2023**, *13*, 912. [[CrossRef](#)]
78. Zhu, Q.; Ong, P.J.; Goh, S.H.A.; Yeo, R.J.; Wang, S.; Liu, Z.; Loh, X.J. Recent advances in graphene-based phase change composites for thermal energy storage and management. *Nano Mater. Sci.* **2024**, *6*, 115–138. [[CrossRef](#)]
79. Wu, S.; Cao, S.; Xie, H.; Wu, Z.; He, X. Enhanced thermal performance of 3D hybrid graphene aerogel encapsulating paraffin for battery thermal management. *Int. Commun. Heat Mass Transf.* **2024**, *156*, 107618. [[CrossRef](#)]
80. Jung, E.; Kong, D.; Kang, M.; Park, J.; Kim, J.-H.; Jeong, J.; In, J.B.; Oh, K.-Y.; Lee, H. Enhanced immersion cooling using laser-induced graphene for Li-ion battery thermal management. *Int. Commun. Heat Mass Transf.* **2024**, *155*, 107558. [[CrossRef](#)]
81. Liu, Y.; Thiringer, T.; Wang, N.; Fu, Y.; Lu, H.; Liu, J. Graphene based thermal management system for battery cooling in electric vehicles. In Proceedings of the 2020 IEEE 8th Electronics System-Integration Technology Conference (ESTC), Tonsberg, Norway, 15–18 September 2020; pp. 1–4.
82. Wang, J.-X.; Salmean, C.; Li, J.-X.; Lei, C.; Li, J.; Zhong, M.; Qi, B.; Mao, Y. A nano-sheet graphene-based enhanced thermal radiation composite for passive heat dissipation from vehicle batteries. *Nano Mater. Sci.* **2024**, *6*, 443–455. [[CrossRef](#)]
83. Goli, P.; Legedza, S.; Dhar, A.; Salgado, R.; Renteria, J.; Balandin, A.A. Graphene-enhanced hybrid phase change materials for thermal management of Li-ion batteries. *J. Power Sources* **2014**, *248*, 37–43. [[CrossRef](#)]
84. Chen, X.; Cheng, P.; Tang, Z.; Xu, X.; Gao, H.; Wang, G. Carbon-Based Composite Phase Change Materials for Thermal Energy Storage, Transfer, and Conversion. *Adv. Sci.* **2021**, *8*, 2001274. [[CrossRef](#)] [[PubMed](#)]
85. Singh, P.; Sharma, R.K.; Khalid, M.; Goyal, R.; Sari, A.; Tyagi, V.V. Evaluation of carbon based-supporting materials for developing form-stable organic phase change materials for thermal energy storage: A review. *Sol. Energy Mater. Sol. Cells* **2022**, *246*, 111896. [[CrossRef](#)]
86. Xing, M.; Yu, J.; Wang, R. Experimental study on the thermal conductivity enhancement of water based nanofluids using different types of carbon nanotubes. *Int. J. Heat Mass Transf.* **2015**, *88*, 609–616. [[CrossRef](#)]
87. Razeeb, K.M.; Dalton, E.; Cross, G.L.W.; Robinson, A.J. Present and future thermal interface materials for electronic devices. *Int. Mater. Rev.* **2018**, *63*, 1–21. [[CrossRef](#)]
88. Han, Z.; Fina, A. Thermal conductivity of carbon nanotubes and their polymer nanocomposites: A review. *Prog. Polym. Sci.* **2011**, *36*, 914–944. [[CrossRef](#)]
89. Liu, L.; Wang, X.; Jin, H.; Wang, J.; Li, Q. Carbon Nanotube-Derived Materials for Smart Thermal Management. *Adv. Sustain. Syst.* **2025**, *9*, 2400757.
90. Liu, P.; Chen, X.; Li, Y.; Cheng, P.; Tang, Z.; Lv, J.; Aftab, W.; Wang, G. Aerogels meet phase change materials: Fundamentals, advances, and beyond. *ACS Nano* **2022**, *16*, 15586–15626. [[CrossRef](#)]
91. Zou, D.; Ma, X.; Liu, X.; Zheng, P.; Hu, Y. Thermal performance enhancement of composite phase change materials (PCM) using graphene and carbon nanotubes as additives for the potential application in lithium-ion power battery. *Int. J. Heat Mass Transf.* **2018**, *120*, 33–41. [[CrossRef](#)]
92. Wang, Y.; Bailey, J.; Zhu, Y.; Zhang, Y.; Boetcher, S.K.S.; Li, Y.; Wu, C. Application of carbon nanotube prepared from waste plastic to phase change materials: The potential for battery thermal management. *Waste Manag.* **2022**, *154*, 96–104. [[CrossRef](#)] [[PubMed](#)]
93. Zhang, Q.; Liu, J. Sebacic acid/CNT sponge phase change material with excellent thermal conductivity and photo-thermal performance. *Sol. Energy Mater. Sol. Cells* **2018**, *179*, 217–222. [[CrossRef](#)]

94. Sahoo, R.; Chaudhuri, P.; Nayak, A.K. Introduction to different types of 2D carbon and nanodiamond. In *Diamane*; IOP Publishing: Bristol, UK, 2024; pp. 1-1–1-29.
95. Shang, B.; Yang, G.; Zhang, B. Phase change nanocapsules incorporated with nanodiamonds for efficient photothermal energy conversion and storage. *Appl. Energy* **2024**, *360*, 122806. [[CrossRef](#)]
96. Zhao, W.; Zhang, M.; Li, H.; Du, Y.; Bu, Q.; Cao, L.; Zong, C. Mussel inspired modification of nanodiamonds for thermally conductive, and electrically insulating rubber composites. *Diam. Relat. Mater.* **2022**, *130*, 109457. [[CrossRef](#)]
97. Nan, B.; Wu, K.; Qu, Z.; Xiao, L.; Xu, C.; Shi, J.; Lu, M. A multifunctional thermal management paper based on functionalized graphene oxide nanosheets decorated with nanodiamond. *Carbon* **2020**, *161*, 132–145. [[CrossRef](#)]
98. Wei, Z.; Gong, P.; Kong, X.; Li, M.; Cheng, J.; Zhou, H.; Li, D.; Ye, Y.; Lu, X.; Yu, J.; et al. Enhanced Thermal Conductivity of Nanodiamond Nanosheets/Polymer Nanofiber Composite Films by Uniaxial and Coaxial Electrospinning: Implications for Thermal Management of Nanodevices. *ACS Appl. Nano Mater.* **2023**, *6*, 8358–8366. [[CrossRef](#)]
99. Gong, P.; Li, L.; Fu, G.-e.; Shu, S.; Li, M.; Wang, Y.; Qin, Y.; Kong, X.; Chen, H.; Jiao, C.; et al. Highly flexible cellulose nanofiber/single-crystal nanodiamond flake heat spreader films for heat dissipation. *J. Mater. Chem. C* **2022**, *10*, 12070–12079. [[CrossRef](#)]
100. Kang, J.; Wei, Z.; Li, J. Graphyne and Its Family: Recent Theoretical Advances. *ACS Appl. Mater. Interfaces* **2019**, *11*, 2692–2706. [[CrossRef](#)]
101. Zhao, Y.; Yang, N.; Yu, R.; Zhang, Y.; Zhang, J.; Li, Y.; Wang, D. Unique structural advances of graphdiyne for energy applications. *EnergyChem* **2020**, *2*, 100041. [[CrossRef](#)]
102. Dang, X.; Zhao, H. Graphdiyne: A promising 2D all-carbon nanomaterial for sensing and biosensing. *TrAC Trends Anal. Chem.* **2021**, *137*, 116194. [[CrossRef](#)]
103. Ivanovskii, A.L. Graphynes and graphdyines. *Prog. Solid State Chem.* **2013**, *41*, 1–19. [[CrossRef](#)]
104. Fang, Y.; Liu, Y.; Qi, L.; Xue, Y.; Li, Y. 2D graphdiyne: An emerging carbon material. *Chem. Soc. Rev.* **2022**, *51*, 2681–2709. [[CrossRef](#)]
105. Peng, Q.; Dearden, A.K.; Crean, J.; Han, L.; Liu, S.; Wen, X.; De, S. New materials graphyne, graphdiyne, graphene, and graphane: Review of properties, synthesis, and application in nanotechnology. *Nanotechnol. Sci. Appl.* **2014**, *7*, 1–29. [[CrossRef](#)]
106. Yang, F.; Xin, Y.; Zhu, X.; Tang, A.; Yu, L.; Han, D.; Jia, J.; Lu, Y.; Zhang, Z. Hard Template-Assisted Trans-Crystallization Synthesis of Hierarchically Porous Cu-SSZ-13 with Enhanced NH₃-SCR Performance. *Catalysts* **2023**, *13*, 1217. [[CrossRef](#)]
107. Liu, H.; Wu, S.; Tian, N.; Yan, F.; You, C.; Yang, Y. Carbon foams: 3D porous carbon materials holding immense potential. *J. Mater. Chem. A* **2020**, *8*, 23699–23723. [[CrossRef](#)]
108. Jana, P.; Palomo del Barrio, E.; Fierro, V.; Medjahdi, G.; Celzard, A. Design of carbon foams for seasonal solar thermal energy storage. *Carbon* **2016**, *109*, 771–787. [[CrossRef](#)]
109. Yang, H.; Zhang, G.; Yan, X.; Dou, B.; Zhang, D.; Cui, G.; Yang, Q. Composite phase change materials with carbon foam and fibre combination for efficient battery thermal management: Dual modulation roles of interfacial heat transfer. *J. Mater. Res. Technol.* **2023**, *23*, 551–563.
110. Zhao, L. Purification of Engineered Graphite for Advanced Application. Master’s Thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2022.
111. Malik, M.; Dincer, I.; Rosen, M.A. Review on use of phase change materials in battery thermal management for electric and hybrid electric vehicles. *Int. J. Energy Res.* **2016**, *40*, 1011–1031. [[CrossRef](#)]
112. Fu, Y.; Hansson, J.; Liu, Y.; Chen, S.; Zehri, A.; Samani, M.K.; Wang, N.; Ni, Y.; Zhang, Y.; Zhang, Z.-B. 2D Materials Graphene related materials for thermal management Graphene related materials for thermal management. *2D Materials* **2019**. [[CrossRef](#)]
113. Gspann, T.S.; Juckles, S.M.; Niven, J.F.; Johnson, M.B.; Elliott, J.A.; White, M.A.; Windle, A.H. High thermal conductivities of carbon nanotube films and micro-fibres and their dependence on morphology. *Carbon* **2017**, *114*, 160–168. [[CrossRef](#)]
114. Guo, X.; Cheng, S.; Cai, W.; Zhang, Y.; Zhang, X.-A. A review of carbon-based thermal interface materials: Mechanism, thermal measurements and thermal properties. *Mater. Des.* **2021**, *209*, 109936. [[CrossRef](#)]
115. Ekimov, E.A.; Kondrin, M.V. Chapter Six—High-pressure, high-temperature synthesis and doping of nanodiamonds. In *Semiconductors and Semimetals*; Nebel, C.E., Aharonovich, I., Mizuochi, N., Hatano, M., Eds.; Elsevier: Amsterdam, The Netherlands, 2020; Volume 103, pp. 161–199.
116. Zhang, Y.; Choi, J.R.; Park, S.-J. Thermal conductivity and thermo-physical properties of nanodiamond-attached exfoliated hexagonal boron nitride/epoxy nanocomposites for microelectronics. *Compos. Part A Appl. Sci. Manuf.* **2017**, *101*, 227–236. [[CrossRef](#)]
117. Jana, P.; Fierro, V.; Pizzi, A.P.; Celzard, A. Thermal conductivity improvement of composite carbon foams based on tannin-based disordered carbon matrix and graphite fillers. *Mater. Des.* **2015**, *83*, 635–643. [[CrossRef](#)]
118. Nada, S.A.; Alshaer, W.G. Comprehensive parametric study of using carbon foam structures saturated with PCMs in thermal management of electronic systems. *Energy Convers. Manag.* **2015**, *105*, 93–102. [[CrossRef](#)]

119. Park, S.-J.; Heo, G.-Y. *Precursors and Manufacturing of Carbon Fibers*; Springer Series in Materials Science; Springer: Dordrecht, The Netherland, 2015; Volume 210, pp. 31–66. [CrossRef]
120. Ali, Z.; Gao, Y.; Tang, B.; Wu, X.; Wang, Y.; Li, M.; Xiao, H.; Li, L.; Jiang, N.; Yu, J. Preparation, Properties and Mechanisms of Carbon Fiber/Polymer Composites for Thermal Management Applications. *Polymers* **2021**, *13*, 169. [CrossRef]
121. Maiti, S.; Islam, M.R.; Uddin, M.A.; Afroj, S.; Eichhorn, S.J.; Karim, N. Sustainable Fiber-Reinforced Composites: A Review. *Adv. Sustain. Syst.* **2022**, *6*, 2200258. [CrossRef]
122. Huang, X.; Qi, X.; Boey, F.; Zhang, H. Graphene-based composites. *Chem. Soc. Rev.* **2012**, *41*, 666–686. [CrossRef]
123. Verdejo, R.; Bernal, M.M.; Romasanta, L.J.; Lopez-Manchado, M.A. Graphene filled polymer nanocomposites. *J. Mater. Chem.* **2011**, *21*, 3301–3310. [CrossRef]
124. Verma, D.; Goh, K.L. Chapter 11—Functionalized Graphene-Based Nanocomposites for Energy Applications. In *Functionalized Graphene Nanocomposites and Their Derivatives*; Jawaid, M., Bouhfid, R., Kacem Qaiss, A.E., Eds.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 219–243.
125. Al Faruque, M.A.; Syduzzaman, M.; Sarkar, J.; Bilisik, K.; Naebe, M. A Review on the Production Methods and Applications of Graphene-Based Materials. *Nanomaterials* **2021**, *11*, 2414. [CrossRef] [PubMed]
126. Ma, Y.; Han, J.; Wang, M.; Chen, X.; Jia, S. Electrophoretic deposition of graphene-based materials: A review of materials and their applications. *J. Mater.* **2018**, *4*, 108–120. [CrossRef]
127. González, Z.; Pérez-Mas, A.M.; Blanco, C.; Granda, M.; Santamaría, R. Influence of the electrophoretic deposition parameters on the formation of suspended graphene-based films. *Mater. Des.* **2018**, *160*, 58–64. [CrossRef]
128. Kumanek, B.; Pusz, S.; Trzebicka, B. Review: Tailoring the properties of macroporous carbon foams. *J. Mater. Sci.* **2014**, *49*, 1–17. [CrossRef]
129. Wang, R.; Yu, J.; Islam, F.; Tahmasebi, A.; Lee, S.; Chen, Y. State-of-the-Art Research and Applications of Carbon Foam Composite Materials as Electrodes for High-Capacity Lithium Batteries. *Energy Fuels* **2020**, *34*, 7935–7954. [CrossRef]
130. Bussiba, A.; Gilad, I.; Lugassi, S.; David, S.; Bortman, J.; Yosibash, Z. Mechanical Response and Fracture of Pultruded Carbon Fiber/Epoxy in Various Modes of Loading. *Crystals* **2022**, *12*, 850. [CrossRef]
131. Volk, M.; Yuksel, O.; Baran, I.; Hattel, J.H.; Spangenberg, J.; Sandberg, M. Cost-efficient, automated, and sustainable composite profile manufacture: A review of the state of the art, innovations, and future of pultrusion technologies. *Compos. Part B Eng.* **2022**, *246*, 110135. [CrossRef]
132. Vedernikov, A.; Safonov, A.; Tucci, F.; Carbone, P.; Akhatov, I. Pultruded materials and structures: A review. *J. Compos. Mater.* **2020**, *54*, 002199832092289. [CrossRef]
133. Stiller, J.H.M.; Roder, K.; Löpitz, D.; Knobloch, M.; Nestler, D.; Drossel, W.-G.; Kroll, L. Combining Pultrusion with Carbonization: Process Analysis and Material Properties of CFRP and C/C. *Ceramics* **2023**, *6*, 330–341. [CrossRef]
134. Shrivastava, A. 5—Plastics Processing. In *Introduction to Plastics Engineering*; Shrivastava, A., Ed.; William Andrew Publishing: New York, NY, USA, 2018; pp. 143–177.
135. Riedel, U. 10.18—Biocomposites: Long Natural Fiber-Reinforced Biopolymers. In *Polymer Science: A Comprehensive Reference*; Matyjaszewski, K., Möller, M., Eds.; Elsevier: Amsterdam, The Netherlands, 2012; pp. 295–315.
136. Acquah, C.; Datskov, I.; Mawardi, A.; Zhang, F.; Achenie, L.; Pitchumani, R.; Santos, E. Optimization under uncertainty of a composite fabrication process using a deterministic one-stage approach. *Comput. Chem. Eng.* **2006**, *30*, 947–960. [CrossRef]
137. Mahmoud Zaghloul, M.Y.; Yousry Zaghloul, M.M.; Yousry Zaghloul, M.M. Developments in polyester composite materials—An in-depth review on natural fibres and nano fillers. *Compos. Struct.* **2021**, *278*, 114698. [CrossRef]
138. Boon, Y.D.; Joshi, S.C.; Bhudolia, S.K. Review: Filament Winding and Automated Fiber Placement with In Situ Consolidation for Fiber Reinforced Thermoplastic Polymer Composites. *Polymers* **2021**, *13*, 1951. [CrossRef]
139. Srebrenkoska, S.; Kochoski, F.; Srebrenkoska, V.; Risteska, S.; Kotynia, R. Effect of Process Parameters on Thermal and Mechanical Properties of Filament Wound Polymer-Based Composite Pipes. *Polymers* **2023**, *15*, 2829. [CrossRef]
140. Mertiny, P.; Ellyin, F.; Hothan, A. An experimental investigation on the effect of multi-angle filament winding on the strength of tubular composite structures. *Compos. Sci. Technol.* **2004**, *64*, 1–9. [CrossRef]
141. Dorigato, A.; Pegoretti, A. Flexural and impact behaviour of carbon/basalt fibers hybrid laminates. *J. Compos. Mater.* **2013**, *48*, 1121–1130. [CrossRef]
142. Risteska, S.; Samakoski, B.; Stefanovska, M. Properties of composite trapezoidal parts manufactured with help of filament winding technology using Taguchi method. *Int. J. Eng. Res. Technol.* **2014**, *3*, 250–255.
143. Boccaccini, A.R.; Cho, J.; Subhani, T.; Kaya, C.; Kaya, F. Electrophoretic deposition of carbon nanotube–ceramic nanocomposites. *J. Eur. Ceram. Soc.* **2010**, *30*, 1115–1129. [CrossRef]
144. Hajizadeh, A.; Shahalizade, T.; Riahifar, R.; Yaghmaee, M.S.; Raissi, B.; Gholam, S.; Aghaei, A.; Rahimisheikh, S.; Ghazvini, A.S. Electrophoretic deposition as a fabrication method for Li-ion battery electrodes and separators—A review. *J. Power Sources* **2022**, *535*, 231448. [CrossRef]

145. Sa'adati, H.; Raissi, B.; Riahifar, R.; Yaghmaee, M.S. How preparation of suspensions affects the electrophoretic deposition phenomenon. *J. Eur. Ceram. Soc.* **2016**, *36*, 299–305. [CrossRef]
146. Lalau, C.C.; Low, C.T.J. Electrophoretic Deposition for Lithium-Ion Battery Electrode Manufacture. *Batter. Supercaps* **2019**, *2*, 551–559. [CrossRef]
147. Chakrabarti, B.K.; Gençten, M.; Bree, G.; Dao, A.H.; Mandler, D.; Low, C.T.J. Modern practices in electrophoretic deposition to manufacture energy storage electrodes. *Int. J. Energy Res.* **2022**, *46*, 13205–13250. [CrossRef]
148. Arinova, A.; Kalimuldina, G.; Nurpeissova, A.; Bakenov, Z. Electrophoretic Deposition of Poly(ethylene oxide) Gel-Polymer Electrolyte for 3D NiO/Ni Foam Anode Based Lithium-Ion Batteries. *J. Electrochem. Soc.* **2023**, *170*, 100501. [CrossRef]
149. Wang, Y.; Jiang, Q.; Shang, J.-K.; Xu, J.; Li, Y.-X. Advances in the synthesis of mesoporous carbon nitride materials. *Acta Phys. Chim. Sin.* **2016**, *32*, 1913–1928.
150. Inagaki, M.; Toyoda, M.; Soneda, Y.; Tsujimura, S.; Morishita, T. Tempered mesoporous carbons: Synthesis and applications. *Carbon* **2016**, *107*, 448–473. [CrossRef]
151. Wang, C.; Yan, B.; Zheng, J.; Feng, L.; Chen, Z.; Zhang, Q.; Liao, T.; Chen, J.; Jiang, S.; Du, C.; et al. Recent progress in template-assisted synthesis of porous carbons for supercapacitors. *Adv. Powder Mater.* **2022**, *1*, 100018. [CrossRef]
152. Yin, J.; Zhang, W.; Alhebshi, N.A.; Salah, N.; Alshareef, H.N. Synthesis Strategies of Porous Carbon for Supercapacitor Applications. *Small Methods* **2020**, *4*, 1900853. [CrossRef]
153. Yadav, A.; Kumar, R.; Bhatia, G.; Verma, G.L. Development of mesophase pitch derived high thermal conductivity graphite foam using a template method. *Carbon* **2011**, *49*, 3622–3630. [CrossRef]
154. Li, H.; Wang, L.; Wei, Y.; Yan, W.; Feng, J. Preparation of Tempered Materials and Their Application to Typical Pollutants in Wastewater: A Review. *Front. Chem.* **2022**, *10*, 882876. [CrossRef]
155. Keyhani-Asl, A.; Perera, N.; Lahr, J.; Hasan, R. Porous media and foam application in battery thermal management systems: A comprehensive review focused on its impact, numerical modeling, and experimental preparation. *J. Energy Storage* **2024**, *93*, 112306. [CrossRef]
156. Pavlenko, V.; Khosravi, H.S.; Żółtowska, S.; Haruna, A.B.; Zahid, M.; Mansurov, Z.; Supiyeva, Z.; Galal, A.; Ozoemena, K.I.; Abbas, Q.; et al. A comprehensive review of template-assisted porous carbons: Modern preparation methods and advanced applications. *Mater. Sci. Eng. R Rep.* **2022**, *149*, 100682. [CrossRef]
157. Zhou, Z.; Zhang, H.; Zhou, Y.; Qiao, H.; Gurung, A.; Naderi, R.; Elbohy, H.; Smirnova, A.L.; Lu, H.; Chen, S.; et al. Binder Free Hierarchical Mesoporous Carbon Foam for High Performance Lithium Ion Battery. *Sci. Rep.* **2017**, *7*, 1440. [CrossRef]
158. Qiu, H.-J.; Liu, L.; Wang, Y. Template-directed fabrication of 3D graphene-based composite and their electrochemical energy-related applications. *Sci. Bull.* **2016**, *61*, 443–450.
159. Sequino, L.; Sebastianelli, G.; Vaglieco, B.M. Carbon and Graphene Coatings for the Thermal Management of Sustainable LMP Batteries for Automotive Applications. *Materials* **2022**, *15*, 7744. [CrossRef]
160. Song, N.; Cao, D.; Luo, X.; Wang, Q.; Ding, P.; Shi, L. Highly thermally conductive polypropylene/graphene composites for thermal management. *Compos. Part A Appl. Sci. Manuf.* **2020**, *135*, 105912. [CrossRef]
161. Ke, F.; Song, F.; Zhang, H.; Xu, J.; Wang, H.; Chen, Y. Layer-by-layer assembly for all-graphene coated conductive fibers toward superior temperature sensitivity and humidity independence. *Compos. Part B Eng.* **2020**, *200*, 108253. [CrossRef]
162. Nan, B.; Zhan, Y.; Xu, C.-A. A review on the thermal conductivity properties of polymer/nanodiamond nanocomposites. *Polym. Plast. Technol. Mater.* **2023**, *62*, 486–509.
163. Zhang, Y.; Rhee, K.Y.; Hui, D.; Park, S.-J. A critical review of nanodiamond based nanocomposites: Synthesis, properties and applications. *Compos. Part B Eng.* **2018**, *143*, 19–27.
164. Khan, J.; Momin, S.A.; Mariatti, M. A review on advanced carbon-based thermal interface materials for electronic devices. *Carbon* **2020**, *168*, 65–112. [CrossRef]
165. Dhumal, A.R.; Kulkarni, A.P.; Ambiore, N.H. A comprehensive review on thermal management of electronic devices. *J. Eng. Appl. Sci.* **2023**, *70*, 140. [CrossRef]
166. Bianco, V.; De Rosa, M.; Vafai, K. Phase-change materials for thermal management of electronic devices. *Appl. Therm. Eng.* **2022**, *214*, 118839. [CrossRef]
167. Samykano, M. Role of phase change materials in thermal energy storage: Potential, recent progress and technical challenges. *Sustain. Energy Technol. Assess.* **2022**, *52*, 102234. [CrossRef]
168. Li, Y.; Zhao, X.; Li, D.; Zuo, X.; Yang, H. Multifunctional composite phase change materials: Preparation, enhanced properties and applications. *Compos. Part A Appl. Sci. Manuf.* **2024**, *185*, 108331. [CrossRef]
169. Tien Nguyen, G.; Minh Tam, L.; Thi Nhun, T. Using Carbonized Cotton Fabric Waste to Prepare Poly(ethylene glycol) Composite Phase Change Materials with Improved Thermal Conductivity and Solar-to-Thermal Conversion. *ACS Omega* **2024**, *9*, 2559–2567. [CrossRef] [PubMed]
170. Liu, C.; Wan, Y.; Gao, Y.; Dong, C.; Chen, X. Polypyrrole-coated expanded graphite-based phase change materials for photothermal energy storage. *Mater. Today Nano* **2023**, *23*, 100376. [CrossRef]

171. Nartowska, E.; Styś-Maniara, M.; Kozłowski, T. The Potential Environmental and Social Influence of the Inorganic Salt Hydrates Used as a Phase Change Material for Thermal Energy Storage in Solar Installations. *Int. J. Environ. Res. Public Health* **2023**, *20*, 1331. [[CrossRef](#)]
172. Rashid, F.L.; Al-Obaidi, M.A.; Dulaimi, A.; Bernardo, L.F.; Redha, Z.A.; Hoshi, H.A.; Mahood, H.B.; Hashim, A. Recent Advances on The Applications of Phase Change Materials in Cold Thermal Energy Storage: A Critical Review. *J. Compos. Sci.* **2023**, *7*, 338. [[CrossRef](#)]
173. Hekimoğlu, G.; Sari, A. A review on phase change materials (PCMs) for thermal energy storage implementations. *Mater. Today Proc.* **2022**, *58*, 1360–1367. [[CrossRef](#)]
174. Singh, P.; Sharma, R.K.; Ansu, A.K.; Goyal, R.; Sari, A.; Tyagi, V.V. A comprehensive review on development of eutectic organic phase change materials and their composites for low and medium range thermal energy storage applications. *Sol. Energy Mater. Sol. Cells* **2021**, *223*, 110955. [[CrossRef](#)]
175. Olabi, A.G.; Wilberforce, T.; Elsaid, K.; Sayed, E.T.; Ramadan, M.; Atique Rahman, S.M.; Abdelkareem, M.A. Recent progress on Carbon-based nanomaterial for phase change materials: Prospects and challenges. *Therm. Sci. Eng. Prog.* **2021**, *23*, 100920. [[CrossRef](#)]
176. Li, J.; Chen, H.; Jia, L.; Zhu, X.; Qin, G.; Chen, Y. Preparation and characterization of Na₂HPO₄·12H₂O@polymethyl methacrylate nanocapsule for efficient thermal energy storage. *J. Energy Storage* **2022**, *53*, 105133. [[CrossRef](#)]
177. Choo, Y.M.; Wei, W. Salt hydrates as phase change materials for photovoltaics thermal management. *Energy Sci. Eng.* **2022**, *10*, 1630–1642. [[CrossRef](#)]
178. Adeel Hassan, H.M.; Lund, I. Inorganic PCMs applications in passive cooling of buildings—A review. *J. Phys. Conf. Ser.* **2021**, *2116*, 012103. [[CrossRef](#)]
179. Sharma, A.; Tyagi, V.V.; Chen, C.R.; Buddhi, D. Review on thermal energy storage with phase change materials and applications. *Renew. Sustain. Energy Rev.* **2009**, *13*, 318–345. [[CrossRef](#)]
180. Dinker, A.; Agarwal, M.; Agarwal, G.D. Heat storage materials, geometry and applications: A review. *J. Energy Inst.* **2017**, *90*, 1–11. [[CrossRef](#)]
181. Afdhol, M.K.; Abdurrahman, M.; Hidayat, F.; Chong, F.K.; Mohd Zaid, H.F. Review of Solvents Based on Biomass for Mitigation of Wax Paraffin in Indonesian Oilfield. *Appl. Sci.* **2019**, *9*, 499. [[CrossRef](#)]
182. Amir Reza, V. Paraffin as Phase Change Material. In *Paraffin*; Fathi Samir, S., Ed.; IntechOpen: Rijeka, Croatia, 2019; Chapter 5.
183. Magendran, S.S.; Khan, F.S.A.; Mubarak, N.M.; Vaka, M.; Walvekar, R.; Khalid, M.; Abdullah, E.C.; Nizamuddin, S.; Karri, R.R. Synthesis of organic phase change materials (PCM) for energy storage applications: A review. *Nano-Struct. Nano-Objects* **2019**, *20*, 100399. [[CrossRef](#)]
184. Gandhi, M.; Kumar, A.; Elangovan, R.; Meena, C.S.; Kulkarni, K.S.; Kumar, A.; Bhanot, G.; Kapoor, N.R. A Review on Shape-Stabilized Phase Change Materials for Latent Energy Storage in Buildings. *Sustainability* **2020**, *12*, 9481. [[CrossRef](#)]
185. Radouane, N. A Comprehensive Review of Composite Phase Change Materials (cPCMs) for Thermal Management Applications, Including Manufacturing Processes, Performance, and Applications. *Energies* **2022**, *15*, 8271. [[CrossRef](#)]
186. Liu, Y.; Wang, N.; Ding, Y. Preparation and properties of composite phase change material based on solar heat storage system. *J. Energy Storage* **2021**, *40*, 102805. [[CrossRef](#)]
187. Song, J.; He, H.; Wang, Y.; Shao, L.; Wang, Q.; Wei, Q.; Cai, Y. Shape-stabilized phase change composites supported by biomass loofah sponge-derived microtubular carbon scaffold toward thermal energy storage and electric-to-thermal conversion. *J. Energy Storage* **2022**, *56*, 105891. [[CrossRef](#)]
188. Aftab, W.; Huang, X.; Wu, W.; Liang, Z.; Mahmood, A.; Zou, R. Nanoconfined phase change materials for thermal energy applications. *Energy Environ. Sci.* **2018**, *11*, 1392–1424. [[CrossRef](#)]
189. Kumar, N.; Hirschev, J.; LaClair, T.J.; Gluesenkamp, K.R.; Graham, S. Review of stability and thermal conductivity enhancements for salt hydrates. *J. Energy Storage* **2019**, *24*, 100794. [[CrossRef](#)]
190. Khadiran, T.; Hussein, M.; Zainal, Z.; Rusli, R. Encapsulation techniques for organic phase change materials as thermal energy storage medium: A review. *Sol. Energy Mater. Sol. Cells* **2015**, *143*, 78–98. [[CrossRef](#)]
191. Shchukina, E.M.; Graham, M.; Zheng, Z.; Shchukin, D.G. Nanoencapsulation of phase change materials for advanced thermal energy storage systems. *Chem. Soc. Rev.* **2018**, *47*, 4156–4175. [[CrossRef](#)]
192. Guo, J.; Han, X.; Ma, S.; Sun, Y.; Li, C.; Li, R.; Li, C. Form-Stable phase change composites with high thermal conductivity and enthalpy enabled by Graphene/Carbon nanotubes aerogel skeleton for thermal energy storage. *Appl. Therm. Eng.* **2024**, *255*, 123954. [[CrossRef](#)]
193. Hu, B.; Guo, H.; Li, J.; Li, T.; Cao, M.; Qi, W.; Wu, Z.; Li, Y.; Li, B. Dual-encapsulated phase change composites with hierarchical MXene-graphene monoliths in graphene foam for high-efficiency thermal management and electromagnetic interference shielding. *Compos. Part B Eng.* **2023**, *266*, 110998. [[CrossRef](#)]

194. Fu, X.; Pan, H.; Xu, L.; Wang, M.; Dou, M.; Zhang, Y.; Liu, Z.; Huang, X.; Teng, Y.; Hu, L.; et al. Flexible phase change film based on lignin-derived porous carbon/Eicosane for wearable thermal management and microwave absorption. *Int. J. Biol. Macromol.* **2024**, *275*, 133630. [[CrossRef](#)]
195. Huang, Y.; Stonehouse, A.; Abeykoon, C. Encapsulation methods for phase change materials—A critical review. *Int. J. Heat Mass Transf.* **2023**, *200*, 123458. [[CrossRef](#)]
196. Li, D.; Tang, Y.; Zuo, X.; Zhang, X.; Zhao, X.; Zhang, Y.; Yang, H. Functionally constructed magnetic-dielectric mineral microspheres for efficient thermal energy storage and microwave absorption. *J. Colloid Interface Sci.* **2023**, *650*, 764–774. [[CrossRef](#)]
197. Mahdavian, F.; Allahbakhsh, A.; Rodrigue, D.; Bahramian, A.R. Polyethylene glycol-impregnated carbon quantum dots-phenolic phase change composites for highly efficient thermal energy storage. *Carbon* **2024**, *219*, 118840. [[CrossRef](#)]
198. Zhang, H.; Wang, X.; Wu, D. Silica encapsulation of n-octadecane via sol-gel process: A novel microencapsulated phase-change material with enhanced thermal conductivity and performance. *J. Colloid Interface Sci.* **2010**, *343*, 246–255. [[CrossRef](#)] [[PubMed](#)]
199. Kong, Q.-Q.; Jia, H.; Xie, L.-J.; Tao, Z.-C.; Yang, X.; Liu, D.; Sun, G.-H.; Guo, Q.-G.; Lu, C.-X.; Chen, C.-M. Ultra-high temperature graphitization of three-dimensional large-sized graphene aerogel for the encapsulation of phase change materials. *Compos. Part A Appl. Sci. Manuf.* **2021**, *145*, 106391. [[CrossRef](#)]
200. Tao, Y.; Pescarmona, P.P. Nanostructured Oxides Synthesised via scCO₂-Assisted Sol-Gel Methods and Their Application in Catalysis. *Catalysts* **2018**, *8*, 212. [[CrossRef](#)]
201. Kumaresan, V.; Velraj, R.; Das, S.K. The effect of carbon nanotubes in enhancing the thermal transport properties of PCM during solidification. *Heat Mass Transf.* **2012**, *48*, 1345–1355. [[CrossRef](#)]
202. Xu, Y.; Huang, Y.; Li, L.; Gu, M.; Li, Y.; Cheng, X. Modulation and optimisation of the properties of n-decanoic acid-tetradecanol phase change materials by nanocomposite carbon materials prepared by atomic layer deposition methods. *Mater. Today Commun.* **2024**, *39*, 108650. [[CrossRef](#)]
203. Chen, W.; Zhang, B.; Wang, S.; Xue, B.; Liu, S.; An, M.; Yang, Z.; Xu, G. Effect of GO on the Structure and Properties of PEG/Biochar Phase Change Composites. *Polymers* **2023**, *15*, 963. [[CrossRef](#)]
204. Ma, Y.; Wei, R.; Zuo, H.; Zuo, Q.; Luo, X.; Chen, Y.; Wu, S.; Chen, W. N-doped EG@MOFs derived porous carbon composite phase change materials for thermal optimization of Li-ion batteries at low temperature. *Energy* **2024**, *286*, 129637. [[CrossRef](#)]
205. Sheng, N.; Rao, Z.; Zhu, C.; Habazaki, H. Honeycomb carbon fibers strengthened composite phase change materials for superior thermal energy storage. *Appl. Therm. Eng.* **2020**, *164*, 114493. [[CrossRef](#)]
206. Zou, D.; Liu, X.; He, R.; Zhu, S.; Bao, J.; Guo, J.; Hu, Z.; Wang, B. Preparation of a novel composite phase change material (PCM) and its locally enhanced heat transfer for power battery module. *Energy Convers. Manag.* **2019**, *180*, 1196–1202. [[CrossRef](#)]
207. Zhao, Z.; Liu, W.; Du, R.; Wang, S.; Han, H.; Jing, Y.; Wu, S.; Wang, R.; Li, T. Carbon-based phase change composites with directional high thermal conductivity for interface thermal management. *Chem. Eng. J.* **2024**, *496*, 154305. [[CrossRef](#)]
208. Rajeswari, K.; Suganthi, K.; Thiruvenkatam, S.; Devaraj, S.; Rajan, K. Graphene oxide-adipic acid nanocomposites for thermal energy storage: Assessment of thermophysical properties and energy storage performance. *J. Energy Storage* **2024**, *77*, 109949.
209. Wang, Y.; Tang, B.; Zhang, S. Single-Walled Carbon Nanotube/Phase Change Material Composites: Sunlight-Driven, Reversible, Form-Stable Phase Transitions for Solar Thermal Energy Storage. *Adv. Funct. Mater.* **2013**, *23*, 4354–4360. [[CrossRef](#)]
210. Pathak, S.K.; Kumar, R.; Goel, V.; Pandey, A.K.; Tyagi, V.V. Recent advancements in thermal performance of nano-fluids charged heat pipes used for thermal management applications: A comprehensive review. *Appl. Therm. Eng.* **2022**, *216*, 119023. [[CrossRef](#)]
211. Sikora, K. Use of Waste Heat Using Heat Pipes. *Acta Mech. Slovaca* **2023**, *27*, 54–59. [[CrossRef](#)]
212. Bernagozzi, M.; Georgoulas, A.; Miché, N.; Marengo, M. Heat pipes in battery thermal management systems for electric vehicles: A critical review. *Appl. Therm. Eng.* **2023**, *219*, 119495. [[CrossRef](#)]
213. Pagliarini, L.; Iwata, N.; Bozzoli, F. Pulsating heat pipes: Critical review on different experimental techniques. *Exp. Therm. Fluid Sci.* **2023**, *148*, 110980. [[CrossRef](#)]
214. Liu, L.; Ma, X.; Ji, X.; Yang, X.; Wei, J. Performance improvement of loop heat pipe by micro-pin-fins/powders composite surface. *Int. J. Heat Mass Transf.* **2023**, *208*, 124093. [[CrossRef](#)]
215. Liu, Y.; Chen, S.; Fu, Y.; Wang, N.; Mencarelli, D.; Pierantoni, L.; Lu, H.; Liu, J. A lightweight and high thermal performance graphene heat pipe. *Nano Sel.* **2021**, *2*, 364–372. [[CrossRef](#)]
216. Zohuri, B. *Heat Pipe Design and Technology: Modern Applications for Practical Thermal Management*; Springer: Berlin/Heidelberg, Germany, 2016.
217. Vadakkann, U.; Chrysler, G.M.; Maveety, J.; Tirumala, M. A Novel Carbon Nano Tube based Wick Structure for Heat Pipes/Vapor Chambers. In Proceedings of the Twenty-Third Annual IEEE Semiconductor Thermal Measurement and Management Symposium, San Jose, CA, USA, 18–22 March 2007; pp. 102–104.
218. Rassamakin, B.; Khairnasov, S.; Zaripov, V.; Rassamakin, A.; Alforova, O. Aluminum heat pipes applied in solar collectors. *Sol. Energy* **2013**, *94*, 145–154. [[CrossRef](#)]
219. Wang, Q.; Han, X.H.; Sommers, A.; T'Joen, C.; Jacobi, A. A review on application of carbonaceous materials and carbon matrix composites for heat exchangers and heat sinks. *Int. J. Refrig.* **2012**, *35*, 7–26. [[CrossRef](#)]

220. Zhang, G.; Jiang, S.; Zhang, H.; Yao, W.; Liu, C. Excellent heat dissipation properties of the super-aligned carbon nanotube films. *RSC Adv.* **2016**, *6*, 61686–61694. [[CrossRef](#)]
221. Gan, J.S.; Hung, Y.M. Remarkable Thermal Performance Enhancement of Micro Heat Pipes with Graphene-Nanoplatelet Nano-Wicks. *Nanomaterials* **2023**, *13*, 232. [[CrossRef](#)] [[PubMed](#)]
222. Ma, Z.; Tan, Y.; Zhang, Z.; Liu, W.; Liu, Z. Experimental investigation on the heat transfer characteristics of loop heat pipe with carbon spheres modified nickel wick. *Appl. Therm. Eng.* **2024**, *255*, 123956. [[CrossRef](#)]
223. Chan, C.W.; Siqueiros, E.; Ling-Chin, J.; Royapoor, M.; Roskilly, A.P. Heat utilisation technologies: A critical review of heat pipes. *Renew. Sustain. Energy Rev.* **2015**, *50*, 615–627. [[CrossRef](#)]
224. Zhang, Y.; Liu, J.; Wang, J.; Luan, T.; Chen, H.; Xue, H. Experimental study on the characteristics of loop heat pipe with modified carbon fiber felt wick. *Appl. Therm. Eng.* **2023**, *234*, 121239. [[CrossRef](#)]
225. Sreekumar, E.N.; Senthil Saravanan, M.S. A review on Aluminium based thermal interface materials for heat transfer application. *Mater. Today Proc.* **2023**, *72*, 3036–3039. [[CrossRef](#)]
226. Chung, S.-H.; Kim, H.; Jeong, S.W. Improved thermal conductivity of carbon-based thermal interface materials by high-magnetic-field alignment. *Carbon* **2018**, *140*, 24–29. [[CrossRef](#)]
227. Naghibi, S.; Kargar, F.; Wright, D.; Huang, C.Y.T.; Mohammadzadeh, A.; Barani, Z.; Salgado, R.; Balandin, A.A. Noncuring Graphene Thermal Interface Materials for Advanced Electronics. *Adv. Electron. Mater.* **2020**, *6*, 1901303. [[CrossRef](#)]
228. Xu, S.; Zhang, J. Vertically aligned graphene for thermal interface materials. *Small Struct.* **2020**, *1*, 2000034.
229. Kumar, N.; Salehiyan, R.; Chauke, V.; Bothhoko, O.; Setshedi, K.; Scriba, M.; Masukume, M.; Sinha Ray, S. Top-down synthesis of graphene: A comprehensive review. *FlatChem* **2021**, *27*, 100224. [[CrossRef](#)]
230. Bo, Z.; Yang, Y.; Chen, J.; Yu, K.; Yan, J.; Cen, K. Plasma-enhanced chemical vapor deposition synthesis of vertically oriented graphene nanosheets. *Nanoscale* **2013**, *5*, 5180–5204. [[CrossRef](#)] [[PubMed](#)]
231. Papageorgiou, D.G.; Kinloch, I.A.; Young, R.J. Mechanical properties of graphene and graphene-based nanocomposites. *Prog. Mater. Sci.* **2017**, *90*, 75–127. [[CrossRef](#)]
232. Murugesan, M.; Martinson, K.; Nikos, A.; Zhou, T.; Zhang, H.; Almhem, L.; Liu, J. High Performance Graphene Enhanced Thermal Interface Technology for Electronics Cooling Applications. *IEEE Electron. Packag. Soc.* **2022**. Available online: <https://eps.ieee.org/publications/enews/december-2022/956-high-performance-graphene-enhanced-thermal-interface-technology-for-electronics-cooling-applications.html> (accessed on 27 January 2025).
233. Xu, S.; Wang, S.; Chen, Z.; Sun, Y.; Gao, Z.; Zhang, H.; Zhang, J. Electric-Field-Assisted Growth of Vertical Graphene Arrays and the Application in Thermal Interface Materials. *Adv. Funct. Mater.* **2020**, *30*, 2003302. [[CrossRef](#)]
234. Gao, J.; Yan, Q.; Lv, L.; Tan, X.; Ying, J.; Yang, K.; Yu, J.; Du, S.; Wei, Q.; Xiang, R.; et al. Lightweight thermal interface materials based on hierarchically structured graphene paper with superior through-plane thermal conductivity. *Chem. Eng. J.* **2021**, *419*, 129609. [[CrossRef](#)]
235. Ma, J.; Du, W.; Chen, Z.; Wang, W.; Zhang, L. Preparation of Graphene-Based Hydrogel Thermal Interface Materials with Excellent Heat Dissipation and Mechanical Properties. *Macromol. Mater. Eng.* **2023**, *308*, 2200332. [[CrossRef](#)]
236. Zhang, X.; Yeung, K.K.; Gao, Z.; Li, J.; Sun, H.; Xu, H.; Zhang, K.; Zhang, M.; Chen, Z.; Yuen, M.M.F.; et al. Exceptional thermal interface properties of a three-dimensional graphene foam. *Carbon* **2014**, *66*, 201–209. [[CrossRef](#)]
237. Yun, J.; Lee, J.; Kim, J.; Lee, J.; Choi, W. Hexagonal boron nitride nanosheets/graphene nanoplatelets/cellulose nanofibers-based multifunctional thermal interface materials enabling electromagnetic interference shielding and electrical insulation. *Carbon* **2024**, *228*, 119397. [[CrossRef](#)]
238. Chen, Y.; Pang, K.; Liu, X.; Li, K.; Lu, J.; Cai, S.; Liu, Y.; Xu, Z.; Gao, C. Environment-adaptive, anti-fatigue thermal interface graphene foam. *Carbon* **2023**, *212*, 118142. [[CrossRef](#)]
239. Lv, P.; Tan, X.-W.; Yu, K.-H.; Zheng, R.-L.; Zheng, J.-J.; Wei, W. Super-elastic graphene/carbon nanotube aerogel: A novel thermal interface material with highly thermal transport properties. *Carbon* **2016**, *99*, 222–228. [[CrossRef](#)]
240. Lu, J.; Ming, X.; Cao, M.; Liu, Y.; Wang, B.; Shi, H.; Hao, Y.; Zhang, P.; Li, K.; Wang, L.; et al. Scalable Compliant Graphene Fiber-Based Thermal Interface Material with Metal-Level Thermal Conductivity via Dual-Field Synergistic Alignment Engineering. *ACS Nano* **2024**, *18*, 18560–18571. [[CrossRef](#)] [[PubMed](#)]
241. He, Q.; Qin, M.; Zhang, H.; Yue, J.; Peng, L.; Liu, G.; Feng, Y.; Feng, W. Patterned liquid metal embedded in brush-shaped polymers for dynamic thermal management. *Mater. Horiz.* **2024**, *11*, 531–544. [[CrossRef](#)]
242. Ali, A.; Rahimian Koloor, S.S.; Alshehri, A.H.; Arockiarajan, A. Carbon nanotube characteristics and enhancement effects on the mechanical features of polymer-based materials and structures—A review. *J. Mater. Res. Technol.* **2023**, *24*, 6495–6521. [[CrossRef](#)]
243. Zhan, H.; Chen, Y.W.; Shi, Q.; Zhang, Y.; Mo, R.; Wang, J. Highly Aligned and Densified Carbon Nanotube Films with Superior Thermal Conductivity and Mechanical Strength. *Carbon* **2021**, *186*, 205–214. [[CrossRef](#)]
244. Nylander, A.; Hansson, J.; Nilsson, T.; Ye, L.; Fu, Y.; Liu, J. Degradation of Carbon Nanotube Array Thermal Interface Materials through Thermal Aging: Effects of Bonding, Array Height, and Catalyst Oxidation. *ACS Appl. Mater. Interfaces* **2021**, *13*, 30992–31000. [[CrossRef](#)]

245. Bowland, C.C.; Wang, Y.; Naskar, A.K. Development of nanoparticle embedded sizing for enhanced structural health monitoring of carbon fiber composites. *Proc. SPIE* **2017**, *101690L*. [[CrossRef](#)]
246. Zhang, K.; Chai, Y.; Yuen, M.M.F.; Xiao, D.G.W.; Chan, P.C.H. Carbon nanotube thermal interface material for high-brightness light-emitting-diode cooling. *Nanotechnology* **2008**, *19*, 215706. [[CrossRef](#)]
247. Guo, H.; Liu, J.; Wang, Q.; Liu, M.; Du, C.; Li, B.; Feng, L. High thermal conductive poly(vinylidene fluoride)-based composites with well-dispersed carbon nanotubes/graphene three-dimensional network structure via reduced interfacial thermal resistance. *Compos. Sci. Technol.* **2019**, *181*, 107713. [[CrossRef](#)]
248. Yu, H.; Peng, L.; Chen, C.; Qin, M.; Feng, W. Regulatable Orthotropic 3D Hybrid Continuous Carbon Networks for Efficient Bi-Directional Thermal Conduction. *Nano-Micro Lett.* **2024**, *16*, 198. [[CrossRef](#)]
249. Bahru, R.; Mohamed, A. Effect of Carbon Nanotubes as Thermal Interface Materials on Thermal Conductivity Using Electrophoretic Deposition. *J. Phys. Sci.* **2019**, *30*, 149–158. [[CrossRef](#)]
250. Zhang, G.; Song, M.; Li, Z.; Zhao, P.; Gu, Z.; Wang, H.; Xu, Y.; Wang, M. A novel heat dissipation material for high-brightness light-emitting-diode devices. *Mater. Chem. Phys.* **2013**, *139*, 741–746. [[CrossRef](#)]
251. Xing, Y.; Cao, W.; Li, W.; Chen, H.; Wang, M.; Wei, H.; Hu, D.; Chen, M.; Li, Q. Carbon Nanotube/Cu Nanowires/Epoxy Composite Mats with Improved Thermal and Electrical Conductivity. *J. Nanosci. Nanotechnol.* **2015**, *15*, 3265–3270. [[CrossRef](#)]
252. Bahru, R.; Mohamed, M.A. Enhancement of thermal interface material properties using carbon nanotubes through simple electrophoretic deposition method. *Int. J. Energy Res.* **2020**, *44*, 4944–4960. [[CrossRef](#)]
253. Kalnaus, S.; Asp, L.E.; Li, J.; Veith, G.M.; Nanda, J.; Daniel, C.; Chen, X.C.; Westover, A.; Dudney, N.J. Multifunctional approaches for safe structural batteries. *J. Energy Storage* **2021**, *40*, 102747. [[CrossRef](#)]
254. Kaul, P.B.; Bifano, M.F.P.; Prakash, V. Multifunctional carbon nanotube–epoxy composites for thermal energy management. *J. Compos. Mater.* **2013**, *47*, 77–95. [[CrossRef](#)]
255. Baltopoulos, A.; Polydorides, N.; Pambagian, L.; Vavouliotis, A.; Kostopoulos, V. Exploiting carbon nanotube networks for damage assessment of fiber reinforced composites. *Compos. Part B Eng.* **2015**, *76*, 149–158. [[CrossRef](#)]
256. Li, Y.; Diao, X.; Li, P.; Liu, P.; Gao, Y.; Zhao, Z.; Chen, X.; Wang, G. Advanced multifunctional Co/N co-doped carbon foam-based phase change materials for wearable thermal management. *Chem. Eng. J.* **2024**, *485*, 149858. [[CrossRef](#)]
257. He, H.; Dong, M.; Wang, Q.; Zhang, J.; Feng, Q.; Wei, Q.; Cai, Y. A multifunctional carbon-base phase change composite inspired by “fruit growth”. *Carbon* **2023**, *205*, 499–509. [[CrossRef](#)]
258. Shivram, S.; Harish, R. Impact of dual nano-enhanced phase change materials on mitigating thermal runaway in lithium-ion battery cell. *Case Stud. Therm. Eng.* **2024**, *60*, 104667. [[CrossRef](#)]
259. Rana, S.; Zahid, H.; Kumar, R.; Bharj, R.S.; Rathore, P.K.S.; Ali, H.M. Lithium-ion battery thermal management system using MWCNT-based nanofluid flowing through parallel distributed channels: An experimental investigation. *J. Energy Storage* **2024**, *81*, 110372. [[CrossRef](#)]
260. Zhang, W.; Liang, Z.; Yin, X.; Ling, G. Avoiding thermal runaway propagation of lithium-ion battery modules by using hybrid phase change material and liquid cooling. *Appl. Therm. Eng.* **2021**, *184*, 116380. [[CrossRef](#)]
261. Weng, J.; He, Y.; Ouyang, D.; Yang, X.; Chen, M.; Cui, S.; Zhang, G.; Yuen, R.K.K.; Wang, J. Honeycomb-inspired design of a thermal management module and its mitigation effect on thermal runaway propagation. *Appl. Therm. Eng.* **2021**, *195*, 117147. [[CrossRef](#)]
262. Li, Y.; Li, M.; Zhu, Y.-C.; Song, S.; Li, S.-N.; Aarons, J.; Tang, L.-C.; Bae, J. Polysulfide-inhibiting, thermotolerant and nonflammable separators enabled by DNA co-assembled CNT/MXene networks for stable high-safety Li-S batteries. *Compos. Part B Eng.* **2023**, *251*, 110465. [[CrossRef](#)]
263. Gong, Y.; Zhang, J.; Chen, Y.; Ouyang, D.; Chen, M. Application of Polyethylene Glycol-Based Flame-Retardant Phase Change Materials in the Thermal Management of Lithium-Ion Batteries. *Polymers* **2023**, *15*, 4450. [[CrossRef](#)]
264. Wu, Z.-H.; Huang, A.-C.; Tang, Y.; Yang, Y.-P.; Liu, Y.-C.; Li, Z.-P.; Zhou, H.-L.; Huang, C.-F.; Xing, Z.-X.; Shu, C.-M.; et al. Thermal Effect and Mechanism Analysis of Flame-Retardant Modified Polymer Electrolyte for Lithium-Ion Battery. *Polymers* **2021**, *13*, 1675. [[CrossRef](#)]
265. Liu, P.; Li, Y.; Tang, Z.; Lv, J.; Cheng, P.; Diao, X.; Jiang, Y.; Chen, X.; Wang, G. Integrating thermal energy storage and microwave absorption in phase change material-encapsulated core-sheath MoS₂@CNTs. *J. Energy Chem.* **2023**, *84*, 41–49. [[CrossRef](#)]
266. Chen, L.; Zou, R.; Xia, W.; Liu, Z.; Shang, Y.; Zhu, J.; Wang, Y.; Lin, J.; Xia, D.; Cao, A. Electro- and Photodriven Phase Change Composites Based on Wax-Infiltrated Carbon Nanotube Sponges. *ACS Nano* **2012**, *6*, 10884–10892. [[CrossRef](#)]
267. Arshad, A.; Jabbal, M.; Shi, L.; Yan, Y. Thermophysical characteristics and enhancement analysis of carbon-additives phase change mono and hybrid materials for thermal management of electronic devices. *J. Energy Storage* **2021**, *34*, 102231. [[CrossRef](#)]
268. Bontempi, E.; Sorrentino, G.P.; Zanoletti, A.; Alessandri, I.; Depero, L.E.; Caneschi, A. Sustainable Materials and their Contribution to the Sustainable Development Goals (SDGs): A Critical Review Based on an Italian Example. *Molecules* **2021**, *26*, 1407. [[CrossRef](#)]
269. Lan, G.; Yang, J.; Ye, R.; Boyjoo, Y.; Liang, J.; Liu, X.; Li, Y.; Liu, J.; Qian, K. Sustainable Carbon Materials toward Emerging Applications. *Small Methods* **2021**, *5*, 2001250. [[CrossRef](#)]

270. Ince, J.C.; Peerzada, M.; Mathews, L.D.; Pai, A.R.; Al-qatatsheh, A.; Abbasi, S.; Yin, Y.; Hameed, N.; Duffy, A.R.; Lau, A.K.; et al. Overview of emerging hybrid and composite materials for space applications. *Adv. Compos. Hybrid Mater.* **2023**, *6*, 130. [[CrossRef](#)]
271. Chen, W.; Wan, M.; Liu, Q.; Xiong, X.; Yu, F.; Huang, Y. Heteroatom-Doped Carbon Materials: Synthesis, Mechanism, and Application for Sodium-Ion Batteries. *Small Methods* **2019**, *3*, 1800323. [[CrossRef](#)]
272. Long, W.; Fang, B.; Ignaszak, A.; Wu, Z.; Wang, Y.-J.; Wilkinson, D. Biomass-derived nanostructured carbons and their composites as anode materials for lithium ion batteries. *Chem. Soc. Rev.* **2017**, *46*, 7176–7190. [[CrossRef](#)]
273. Narayan, R.; Laberty-Robert, C.; Pelta, J.; Tarascon, J.-M.; Dominko, R. Self-healing: An emerging technology for next-generation smart batteries. *Adv. Energy Mater.* **2022**, *12*, 2102652.
274. Bandodkar, A.J.; López, C.S.; Vinu Mohan, A.M.; Yin, L.; Kumar, R.; Wang, J. All-printed magnetically self-healing electrochemical devices. *Sci. Adv.* **2016**, *2*, e1601465. [[PubMed](#)]
275. Wu, Y.; Huang, L.; Huang, X.; Guo, X.; Liu, D.; Zheng, D.; Zhang, X.; Ren, R.; Qu, D.; Chen, J. A room-temperature liquid metal-based self-healing anode for lithium-ion batteries with an ultra-long cycle life. *Energy Environ. Sci.* **2017**, *10*, 1854–1861.
276. Zhao, Y.; Zhang, Y.; Sun, H.; Dong, X.; Cao, J.; Wang, L.; Xu, Y.; Ren, J.; Hwang, Y.; Son, I.H. A self-healing aqueous lithium-ion battery. *Angew. Chem. Int. Ed.* **2016**, *55*, 14384–14388.
277. Fortier, A.; Tsao, M.; Williard, N.D.; Xing, Y.; Pecht, M.G. Preliminary study on integration of fiber optic Bragg grating sensors in li-ion batteries and in situ strain and temperature monitoring of battery cells. *Energies* **2017**, *10*, 838. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.