

Advancements in Foam-Based Phase Change Materials: Unveiling Leakage Control, Enhanced Thermal Conductivity, and Promising Applications

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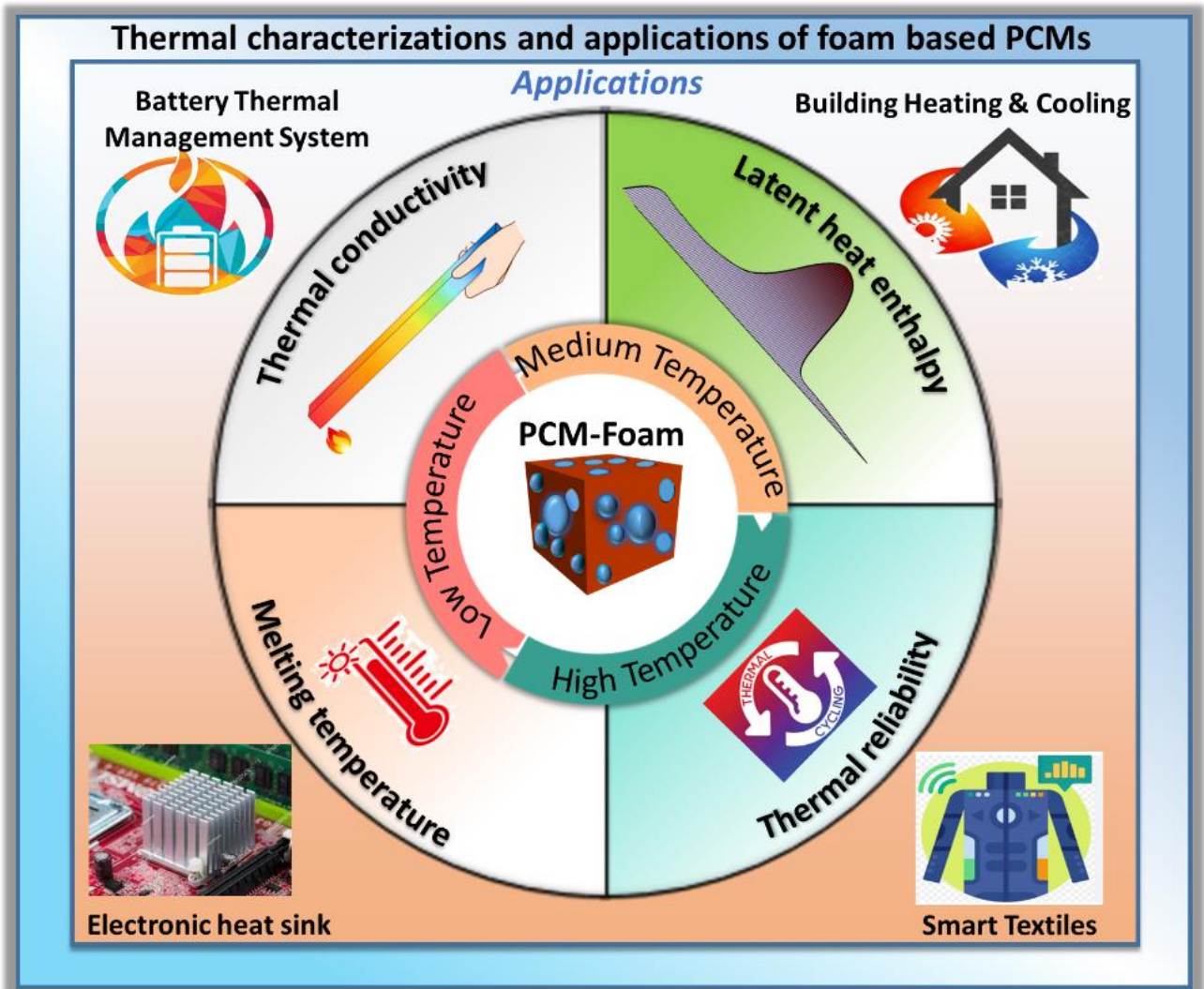
Abstract

In recent years, phase change materials (PCMs) have attracted considerable interest due to their capacity to store and release enormous energy during phase transitions. However, low thermal conductivity and leakage are significant obstacles that hinder the efficacy of PCMs. Foams and porous matrices have been investigated as potential solutions to the leakage problem in PCMs. This review examines the use of foam to improve the thermal energy storage performance of PCMs. The primary objective of this paper is to unveil the leakage control using foams and discuss the effect on the thermophysical properties of foam-based PCMs. To achieve this objective, we have reviewed previous research in this area, established the research's rationale, and filled any voids in the literature. The paper examines the utilization of carbon-based and metallic foams for PCMs at varying temperatures. It evaluates the methodologies used to evaluate the efficacy of PCMs with foam reinforcement. Key findings include the significant enhancement in thermo-physical properties of PCM performance due to the use of foam and the potential applications of these materials in various fields, including thermal management of batteries, heating and cooling of buildings, smart textiles and electronic heat sinks. The study also summarizes the foams and other porous matrices to compare their performance with PCM. Foam-based PCMs prove to be a strong candidate by solving the leakage issue in PCMs without compromising their thermophysical properties.

Keywords: Foam stable phase change material; Leakage control; FSPCMs' thermo-physical properties; Carbon foam; Metallic Foam

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Graphical Abstract:



Highlights:

- Carbon and metallic foams have been investigated for multiple temperatures of PCMs
- Impact of foams on the thermophysical properties of PCM
- Factors affecting the performance of FSPCM at different temperature range
- Insights into FSPCM based applications and experimental arrangements

Outlines

1. Introduction.....	4
2. Foams used in low temperature PCMs	10
2.1. Carbon foam based low temperature PCMs.....	10
2.2. Metallic foams based low temperature PCMs	18
3. Foam-based medium temperature PCMs	24
3.1. Carbon-based foam for medium temperature PCM.....	25
3.2. Metallic foam based medium temperature PCM	29
4. High temperature PCM.....	31
4.1. High temperature carbon based FSPCM.....	32
4.2. High temperature metal based FSPCM.....	35
5. Various factors affecting the performance	41
5.1. Low-temperature FSPCMs	41
5.2. Medium temperature FSPCMs.....	41
5.3. High temperature FSPCMs:	41
6. Applications of FSPCM.....	43
6.1. Building heating cooling.....	44
6.2. Battery thermal management	45
6.3. Electronic heat sink.....	45
6.4. Light/electric-to-thermal energy conversion.....	48
6.5. Smart textiles	49
7. Conclusions and Future Recommendations	50
7.1. Conclusions.....	50
7.2. Future Recommendation.....	51
Acknowledgement	52
References.....	Error! Bookmark not defined.

1. Introduction

In order to combat climate change and address the global energy resource shortage, the energy sector is rapidly switching to more sustainable energy sources [1]. Several United Nations Sustainable Development Goals (SDGs) align with the shift to more sustainable energy sources. It specifically backs Goals 7 ("Affordable and Clean Energy"), advocating the use of renewable energy sources, and 13 ("Climate Action"), urging prompt actions against climate change impact. Since burning fossil fuels is a significant source of air pollution, which harms human health, this transition towards sustainability can also help achieve Goal 3 ("Good Health and Well-Being"). Finally, using more renewable energy can lessen our reliance on fossil fuels, which are limited in supply.

Solar energy is a rapidly expanding renewable energy source, but its intermittent nature remains challenging. To utilize solar energy effectively, reliable methods are imperative to store the energy generated for later use. Solar thermal energy can be stored using various techniques, such as thermal energy storage tanks, molten salt storage, battery-based latent heat storage, ice storage, compressed air energy storage, flywheel energy storage, etc. However, energy storage through PCM is an attractive option for several applications due to its relative advantages over other energy storage methods. PCMs are a passive, two-phase thermal storage technology that utilizes latent heat to absorb thermal energy. A notable advantage is the high energy density of PCMs, enabling them to store heat in a relatively small volume, making them beneficial for applications with limited space [2–4]. The latent heat associated with melting and freezing allows PCMs to store more heat compared to sensible thermal storage alone. PCMs can be used for long-term energy storage due to their high thermal stability, which prevents them from deteriorating over time.

PCMs can be categorized according to their physical characteristics, such as thermal conductivity, specific heat capacity, and chemical composition (organic or inorganic) [5]. Compared to inorganic phase change materials, organic phase change materials (O-PCMs) have many advantages, including high latent heat, non-toxic, a low tendency to supercool, non-corrosive, and high thermal stability [6–8]. O-PCMs like polyethylene glycol (PEG) and paraffin wax are preferred due to their stable volume during temperature variations. However, the orderly crystalline structure of paraffin can become disordered and amorphous when exposed to temperatures above its melting point due to increased molecular vibrations that break supramolecular bonds[9,10]. PCMs are also categorized according to their melting point, which indicates the transition point from solid to liquid state. For instance, low-temperature PCMs melt below 40°C, medium-temperature PCMs have melting points ranging

from 40 to 100°C, and high-temperature PCMs melt at temperatures exceeding 100°C [11]. PCMs have the potential to be energy-efficient material for practical implementation but they encounter significant challenges such as low thermal conductivity, liquid phase leakage, overtime degradation, and others [12]. Factors such as repeated heating and cooling cycles, exposure to UV light, and other environmental factors contribute to PCM degradation. These issues affect the usage of PCMs in real-world applications, such as heating and cooling systems thereby diminishes component effectiveness [13]. Thus, recognizing and mitigating these concerns is vital to ensure the effective use of PCMs. The performance of PCMs can be improved using a variety of techniques, including adding nanoparticles [14], heat pipes [15], microencapsulation [16], dispersing highly conductive fillers [17–19] and nanoencapsulation [20].

Several studies primarily focused on improving thermo-physical properties, while a significant challenge in using PCMs lies in their potential leakage during phase transitions which limits their optimal utilization. To overcome this drawback, researchers have developed shape stable PCM (SSPCM) composites that are stable during phase transition and easily integrated into various thermal energy storage systems. There are two SSPCM Composites: Form-Stable using porous matrices and Foam-Stable (FS) PCM composites using foams or foam matrices. The distinction lies in the type of porous matrix utilized. In simple form-stable PCM composites, the PCM is encapsulated within a solid porous matrix like expanded graphite, whereas in foam-stable PCM composites, the PCM is entrapped within a porous foam material. The foam matrix provides a high surface area for PCM to interact, improving heat transfer, stability, and storage capacity. Foam-Stable PCM composites have been founded to be superior to traditional form-stable PCM composites regarding leakage issues, thermal stability, heat transfer performance, and thermal conductivity [21] [22].

A significant drawback associated with traditional form stable PCM is its constrained thermal conductivity, attributed to the inherent nature of solid matrices that inhibit effective heat transfer. This limitation leads to slow charging and discharging rates, reducing the effectiveness of the thermal energy storage system. Various methods have been proposed to improve the thermal conductivity of form stable PCM composites, such as adding high thermal conductivity fillers/nanoparticles or using heat pipes [23]. For instance, Li et al. (2009) used additional 8.8 weight percentage (wt%) Micro-mist graphite (MMG) to increase the thermal conductivity of high-density polyethylene (HDPE)/wood flour compound form-stable PCM by 17.7% [24]. Effective leakage control is also a concern for form-stable (PCMs) because the lack of effective containment mechanisms can result in PCM seepage. To address

this issue, one approach involves increasing the weight percentage of the porous matrix, although this compromises the latent heat of the PCM. Another way is to impregnate PCMs into cellulose-based aerogels or to use microencapsulation or 3D porous infiltration to fabricate PCM composites [25]. While impregnating PCMs into cellulose-based aerogels, microencapsulation, or 3D porous infiltration contributes to maintaining the initial solid state of the PCM composite without any leakage during the melting process, these methods have some drawbacks. Notably, cellulose-based aerogels can be complex and time-consuming, involving multiple steps such as dissolution, gelation, solvent exchange, and drying with supercritical CO₂ [26]. Additionally, using 3D porous infiltration to fabricate PCM composites can be challenging due to the need for precise control over the infiltration process to avoid shrinkage [27].

On the other hand, foam-Stable PCM composites have a higher surface area and interconnected porosity, which enhances the contact between PCM and the surrounding matrix, resulting in improved heat transfer and storage capacity. Foam matrices, such as carbon and metal foam, effectively improve PCM composites' performance [28,29]. Mhiri et al. (2020) also investigated the potential of utilizing foam materials to enhance thermal conductivity and address leakage issues in a PCM intended for TES applications. In their study, they developed a nanocomposite consisting of a paraffin/graphite mixture embedded within a carbon foam using vacuum impregnation. They conducted a 3D numerical simulation in COMSOL Multiphysics, considering three different volume fractions (0, 1, and 2 wt%) for each porosity level (0.9, 0.95, and 0.98). Their findings indicated that the inclusion of both graphite and foam significantly increased the material's thermal conductivity, reaching up to 9 times that of pure paraffin. Furthermore, this approach enhanced the melting process of the PCM by a range of 21-42% [30]. Chen et al. (2019) introduced an enhancement strategy involving metal foam for a TES system based on FSPCM. They conducted a numerical analysis using ANSYS, considering materials such as Water, Paraffin RT 58 as PCM and copper foam, with varying porosities of 0.85, 0.90, and 0.95. Their study involved exploring different inlet velocities (ranging from 0.04 to 0.10 m/s) and inlet temperatures (ranging from 340 to 360 K). Their findings demonstrated a significant enhancement in the system's performance when metal foam was incorporated into both the storage medium and the heat transfer fluid (HTF). This enhancement led to a remarkable reduction in charging and discharging times, by as much as 84.9% [31]. Therefore, using foam-stable PCMs can provide a more reliable solution for preventing leakage when properly designed and implemented [32].

The structure of foam-stable PCMs (FSPCMs) is meant to resemble that of foam or a sponge. This configuration can improve the properties of the PCM in several ways. For instance, the PCM's surface area may increase due to the pores and voids in the foam structure, which enhance the PCM's capacity to absorb and release heat. The foam structure can also increase the thermal conductivity of the PCM, sometimes up to 500 times [33], than pristine PCM, which can help to distribute heat more evenly throughout the material. Additionally, the foam structure can make the composite PCM lightweight and flexible [34] [35], benefiting certain applications. The porosity and pore density of foams impacts PCM's capacity to absorb and release heat. Larger pores enable more effective heat transfer, so foams with higher pore densities and porosities typically have higher heat transfer rates [36]. The foam's composition also influences the heat transfer rate, with materials like copper and aluminium having higher heat transfer rates than polyurethane and carbon foams [37]. To sum up, the performance and efficiency of thermal energy storage systems (TES) can be increased by using foam-based PCMs [21]. At present, porous materials such as carbon foam [38], carbon nanoparticles [39], metallic foams [40], expanded graphite [41], and porous silicate materials [42] are commonly used as matrix materials to prepare shape-stable (form-stable) PCMs. The FSPCM (shape stabilized) is made by directly combining PCM with the matrix material [43]. The foam/porous matrix in a composite phase change material (CPCM) serves as a support to prevent the leakage of PCM and maintain the form (shape) of the CPCM, even when it is heated above the melting temperature [44].

To create a shape-stable PCM (SSPCMs), a mixture of paraffin and high-density polyethylene (HDPE) was made [45]. An overview of the synthesis, use, and thermal management of various FSPCMs was given [46]. The methods for using nano-porous supporting materials in PCMs with stable shapes were examined [47]. Vacuum impregnation method recommended as compared to the other preparation methods due to its higher PCM absorption capacity [48]. For applications involving TES, several SSPCMs with porous support were examined. Discussions on the behaviour of SSPCMs included the effects of surface modification, pore size, interaction forces, geometry, and compositions. The potential and efficient porous material designs were also discussed [49]. By combining the developments in molecular dynamics modeling and prediction, an effort was made to pinpoint the favourable factors influencing the interaction between the skeleton and PCM. A thorough explanation of the problems with stable shape PCMs (SSPCMs) and how to resolve them was provided [50].

Recent reviews, such as, [51] discuss the various models and numerical methods used to study the thermal behaviour of these materials and compare the results of different studies. The paper concludes that using porous foams with PCMs can significantly enhance heat transfer and suggests that further experimental validation is needed. In another review, the author discusses the various mechanisms by which metal foams can enhance heat transfer, such as increased surface area and improved mixing, and summarizes the results of different studies [52]. Some authors highlighted the various factors that can affect the performance of these materials, such as foam type, PCM type, and filling fraction, and summarized the results of different studies. These papers conclude that metal foam-phase change material composites can provide high thermal energy storage densities [21]. Furthermore, some review work also discussed the application of foam based PCM composites in the built environment. Also, FSPCM can significantly benefit energy efficiency and thermal comfort [22].

While previous research has mainly concentrated on determining the methods to enhance the thermo-physical properties of FSPCM, there remains limited research in critically classifying and analysing FSPCM in terms of temperature range and foam material type. Therefore, it is necessary to classify PCMs according to the transition temperatures from a solid to a liquid state because the type of PCM used depends on the application. For instance, PCMs with a melting range of 30 to 65°C are required for cooling applications of electronic devices, while PCMs with a melting point below 40°C, are essential for storing heat in air conditioning applications. Furthermore, absorption in refrigeration requires PCMs with a melting point greater than 90°C [53]. Many authors have discussed the thermal conductivity of FSPCM [33,54] their orientation, and morphological characteristics [55] although different FSPCM applications have been discussed in other works. This demonstrates that PCM melting temperature is crucial when choosing a PCM for a specific application. However, the classification of PCMs according to their melting points; low, medium, and high temperatures has not yet been extensively addressed. Table 1 highlights the different ranges of temperatures that authors used to classify the PCM as low, medium, and high temperatures. It is clear from Table 1 that different researchers categorize the temperature of PCM differently. There is no standard classification of PCM as per the temperature range. In this review, we are classifying the PCMs as low temperature (up to 40°C), medium temperature (40-100°C), and high temperature (above 100°C) due to the varying temperature ranges used in previous studies, as well as the convenience and clarity provided by this classification scheme for comparison and analysis of different PCM types and applications.

Table 1: Classification of PCM as per their temperature ranges [11]

Low temp:	Medium temp:	High temp:
<227°C	227 – 427°C	>427°C
<20°C	20 – 250°C	>250°C
<100°C	100- 250°C	>250°C
<220°C	220-420°C	>420°C
<80	80-200°C	>200°C
<40°C	40-100°C	>100°C (This work)

Fig. 1 breaks through the limitations traditionally imposed by earlier studies and establishes a new standard for improvements in this field. This study introduces a novel perspective by analysing the use of metal foams and carbon-based foams in conjunction with PCMs at low, medium, and high temperatures. This review investigates in-depth the applications of foam materials as a solution to the leakage problem and to improve the thermal properties of PCMs. According to our knowledge, this is a novel review article that investigates the potential of metal foams and carbon-based foams with PCMs across a wide range of temperature ranges. By investigating emerging applications and discussing their implications, this study fills a crucial knowledge void and provides valuable insights for PCM technology researchers and industry professionals pursuing innovative solutions.

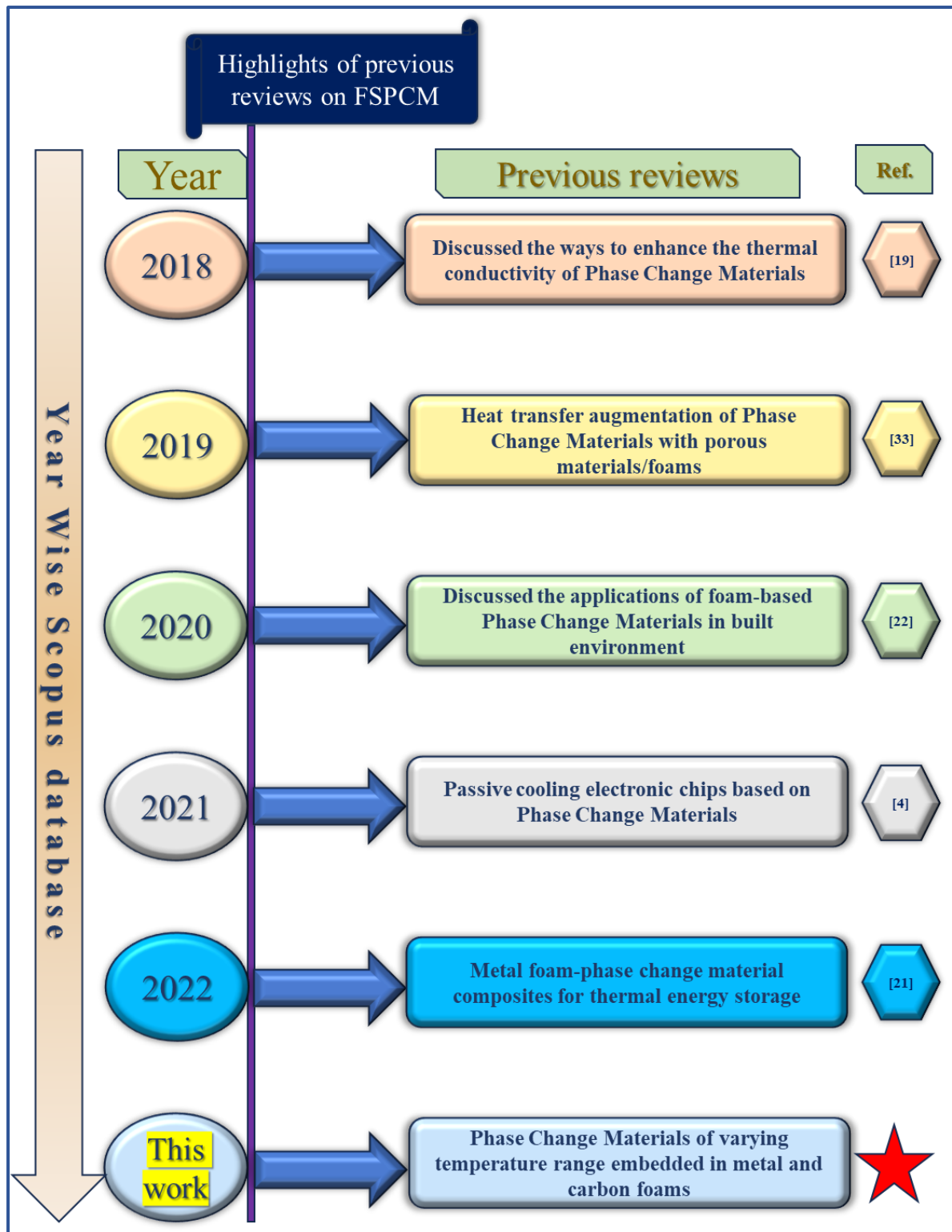


Fig. 1. Year wise Scopus database for previous FSPCM published papers

2. Foams used in low temperature PCMs

2.1. Carbon foam based low temperature PCMs

The use of carbon-based foams plays a significant role in the advancement of FSPCMs, which are classified based on their structure, characteristics, and fabrication methods. Fig. 2

(a) and (b) shows the different types of carbon-based allotropes that have been used for foam-stable PCM. Fig. 2 (c) show the preparation process of FSPCM composite by vacuum-assisted method. Fig. 2 (d) shows the SEM images of carbon foam (CF) carbonized at different temperatures, where CF-1200, CF-1300, and CF-1400, referring to the carbonization temperature at 1200°C, 1300°C, and 1400°C respectively. Some common carbon-based supporting materials for developing FSPCMs include; carbon aerogels as lightweight, highly porous materials with a low density and have significant surface area. These materials are made from carbon precursors subjected to a sol-gel process followed by supercritical drying, resulting a sponge-like structure. Notably, they possess a good thermal conductivity making them as supporting material for PCMs to enhance their thermophysical properties [56]. Other notable carbon-based materials used as supporting materials for FSPCMs include carbon nanotubes, which are nanoscale-diameter cylindrical tubes with micrometre-scale lengths. Carbon black, another carbon-based foam, emerges as a fine, black, amorphous form of carbon produced from the incomplete combustion of hydrocarbons. Graphite is a form of carbon with a layered crystal structure. It possesses a good thermal conductivity ($25\text{--}470\text{ W m}^{-1}\text{ K}^{-1}$) [57] and mechanical strength [58]. Graphene is a two-dimensional material composed of a single layer of carbon atoms that are structured in a hexagonal lattice.

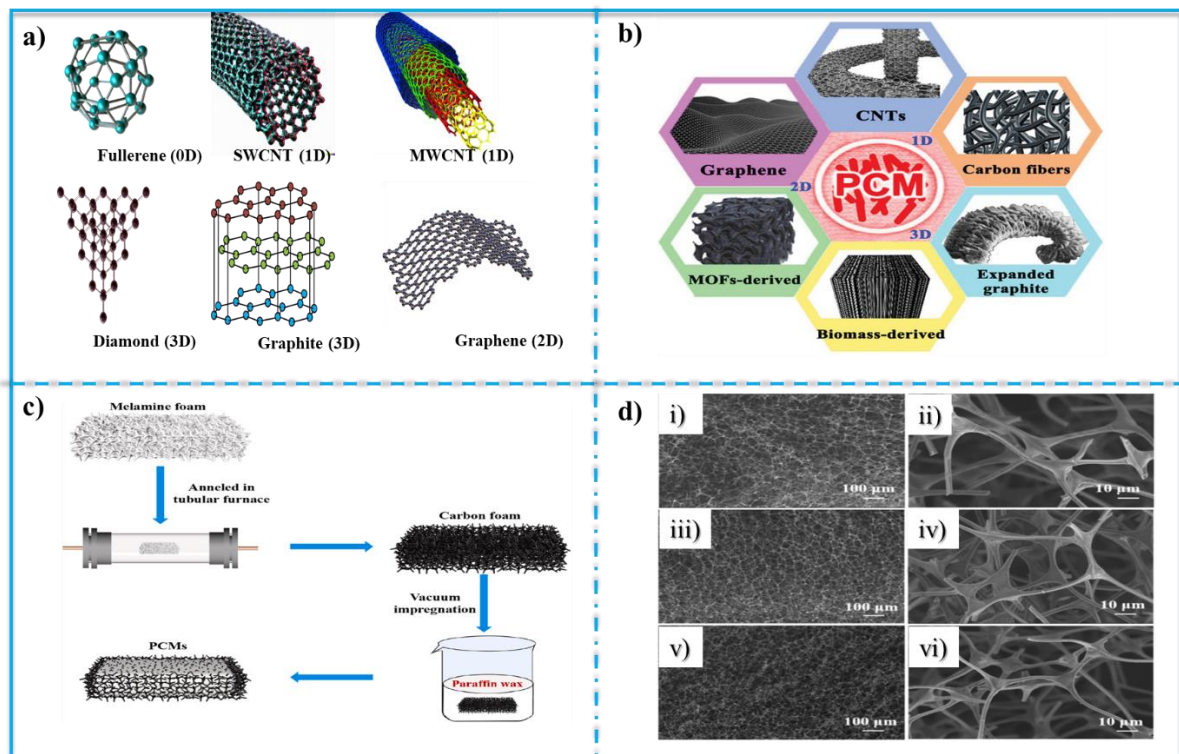


Fig. 2. (a) Different types of carbon derived materials for FSPCM (b) Various types of porous carbon materials used with PCM [59] (c) The preparation flow diagram of composite PCMs [60] (d) SEM images of CF-1200(1, 2), CF-1300(3, 4), and CF-1400(5, 6)[60]

The carbon aerogels, carbon nanotubes, carbon black, graphite, and graphene serve as foam matrices or supporting materials to improve the thermal conductivity of base PCMs along with solving the leakage issue due to their high thermal conductivity [61–64]. These materials are incorporated into PCMs in the form of foams or vice versa to create FSPCMs allowing it to efficiently store and release thermal energy. The enhancement of thermal conductivity of FSPCMs depends on the properties of the PCM and the supporting material such as the melting point (T_m), thermal stability and latent heat. Moreover, the fraction (weight %) of PCM in the supporting material has a significant effect on the latent heat of the final composite.

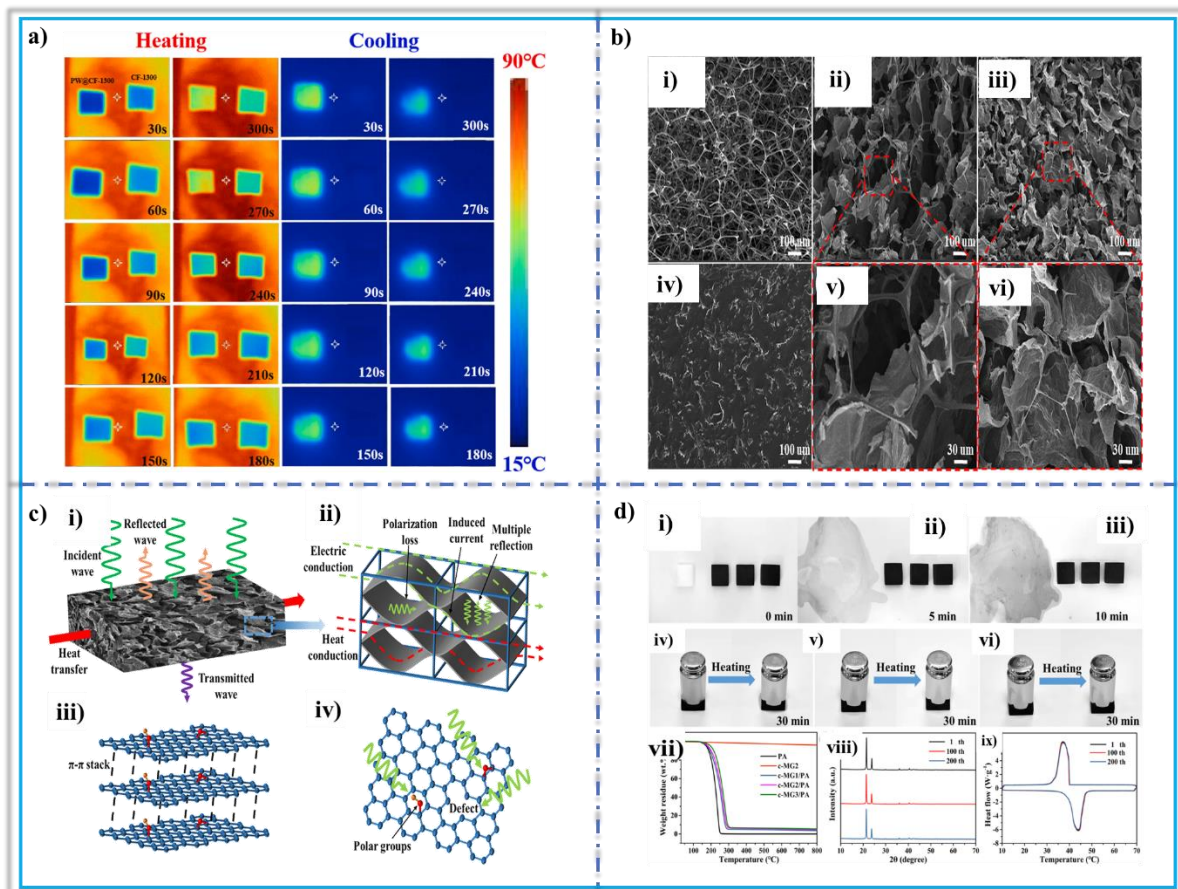


Fig. 3. (a) Infrared thermal images of CF-1300 (copper foam-1300) and PW@CF-1300 (paraffin wax embedded in copper foam-1300)[60]. (b) SEM images of (i) MF (Melamine foam); (ii) MG (Melamine graphene); (iii) c-MG (Melamine reduced graphene); (iv) c-MG/PA (Melamine reduced graphene/paraffin). Partial enlarged SEM images of (v) MG and (vi) c-MG [65]. (c) (i) Electromagnetic shielding and heat transfer diagram of c-MG/PA. (ii) Electromagnetic shielding and heat transfer mechanism of dual cross-linking network of c-MG. (iii) Interface polarization loss mechanism of graphene network. (iv) Dipole polarization loss mechanism in a network of reduced graphene oxide (rGO) [65]. (d) (i-iii) Shape stability of PA and c-MG/PA at 80 °C. The stability of (iv) c-MG1/PA, (v) c-MG2/PA and (vi) c-MG3/PA after heating at 80 °C for 30 min under 50 g weight load. (vii) TG curves of PA, c-MG2 and c-MG/PA. XRD patterns (viii) and DSC curves (ix) of c-MG/PA before and after 100 and 200 cycles [65]

The hexagonal crystal structure of graphite suggests high thermal conductivity which is crucial for efficient heat transfer during phase change [33]. To investigate the graphitization degree of carbon foams, their Raman spectra were recorded and analysed [66]. The structural and morphological properties of the graphite material, as determined by the X-ray diffraction, [67]. SEM imaging including grain size and orientation, can help identify potential defects or impurities in the material that could affect its performance as a phase change material [68], a finer microstructure generally indicates higher thermal conductivity [69]. SEM images can also be used to analyse the surface chemistry of the graphite (carbon foam), which can reveal any impurities present on the surface [70]. Additional layering can affect the thermal conductivity and stability/leakage of the foams requiring careful consideration in FSPCM design[49].

Fig. 3 (a) shows the temperature distribution of CF-1300 (carbon foam carbonized at 1300 degrees) and PW@CF-1300 (paraffin wax incorporated into carbon foam carbonized at 1300 degrees) samples during the cooling process, emphasizing the enhanced heat transfer properties of the composite material resulting from the addition of carbon foam to paraffin wax and lead to a more uniform temperature distribution. Fig. 3 (b) illustrates the SEM images that reveals the morphology of the materials: Fig. 3 (b-i) shows the MF (Melamine foam), (b-ii) MG (carbon foam/reduced graphene oxide composite), (b-iii) c-MG (carbon foam/reduced graphene oxide composite), and (b-iv) c-MG/PA (paraffin incorporated carbon foam/reduced graphene oxide composite). (b-v) The partially enlarged SEM images of MG and (b-vi) c-MG reveals the layered structure of the carbon foam/reduced graphene oxide composite material. Lightweight carbon foams exhibit excellent electromagnetic interference (EMI) shielding properties due to their three-dimensional (3D) network structure that enhances the multiple reflections of incident electromagnetic waves and improves the microwave absorption [71–73]. As shown in Fig. 3 (c), diagrams (i), (ii), (iii), and (iv) illustrate the electromagnetic shielding and heat transfer mechanisms of the carbon foam/reduced graphene oxide/paraffin composite material. Fig. 3 (c-i) shows that adding paraffin to the carbon foam/reduced graphene oxide composite (c-MG/PA) enhances its electromagnetic shielding and heat transfer properties. Fig. 3 (c-ii) explains the dual cross-linking network of the modified carbon foam/reduced graphene oxide composite (c-MG), which involves chemical and physical bonding mechanisms. Fig. 3 (c-iii) shows the interface polarization loss mechanism of the graphene network, which is due to the repeated alignment and realignment of graphene sheets in response to the electromagnetic field. Fig. 3 (c-iv) illustrates the dipole polarization loss mechanism of the reduced graphene oxide (rGO) network, which is caused by the interaction

between the electric field and the polar functional groups on the rGO sheets. Fig. 3 (d i-iii) shows the images for the shape stability of pure paraffin (PA) and the carbon foam/reduced graphene oxide/paraffin composite (c-MG/PA) at 80°C. The composite material exhibits better shape stability than pure paraffin at this temperature. Fig.3 (d iv-vi) show the stability of three different samples of c-MG/PA after heating at 80°C for 30 minutes under a 50g weight load. The samples maintain their shape without any visible deformation, indicating good shape stability and mechanical strength. Fig.3 (d-vii) shows the thermogravimetric (TG) curves of PA, carbon foam/reduced graphene oxide composite (c-MG2), and c-MG/PA. The TG analysis reveals that adding carbon foam and reduced graphene oxide improves the thermal stability of the composite material. Fig.3 (d viii-ix) present the XRD patterns and DSC curves respectively, of c-MG/PA before and after 100 and 200 thermal cycles. The results indicate that the composite material retains its crystal structure and phase change properties after repeated thermal cycling, demonstrating good thermal stability and reliability.

Low-temperature PCMs are particularly interesting for building insulation and other thermal management applications [74–76] due to their ability to store and release large amounts of thermal energy over a narrow temperature range. The thermal conductivity of PCMs can be improved by adding other supporting materials with carbon foams such as polymethyl methacrylate (PMMA) [77], Polypropylene (PP) [78], Polyethylene [79] and others, to create shape stable FSPCM composites. Meanwhile, several studies have investigated the use of different porous carbon-based supporting materials in low-temperature PCM composites and the effect on the thermal conductivity of the composite [32,47,80]. Umair et al., [81] developed paraffin ($T_m=40^\circ\text{C}$) based FSPCM composite using a carbon foam scaffold derived from biomass, which was demonstrated to be stable with no leakage issues. In a previous work [82], researchers prepared paraffin composites with carbonized cotton foam and evaluated their thermal properties and leakage. With the inclusion of carbon sponge support, the thermal conductivity is elevated to $0.434\text{ W k}^{-1}\text{m}^{-1}$, representing an approximate 1.7 fold increase compared to the original paraffin wax (PW). Leakage tests were conducted on phase change composites (PCCs) and PW at 80°C . The findings showed that pure PW blocks exhibited leakage, while PCC samples supported by carbon sponges demonstrated no leakage. The leakage test procedure is shown in Fig. 4 (a), following a 15-minute duration, pure PW liquefied and spread onto the filter paper, while in case of the developed PCC liquefied PW remained confined within the carbon sponges. This phenomenon can be ascribed to the adsorption effect of hollow carbon fibre sponges, effectively preventing PCM leakage.

Lu et al. [83] prepared the paraffin wax/carbon nanotube sponge (PW@CNS) composite using the vacuum impregnation technique. The results shows that the thermal conductivity of the composite reached to $1.85 \text{ W k}^{-1}\text{m}^{-1}$, which is about 11 times that of pure PW. Fig. 4 (b-i) illustrates the morphology of CN sponge and the impregnation of PW into the carbon sponge. Fig 4 (b-ii) shows the morphology of the prepared PW@CN sponge, it is clear that PW is uniformly distributing throughout the carbon nano sponge (CNS) foam. In addition, it exhibits great performance in the leakage test of the PW@CNS composite, even under 50 g load (about 162 times the PW@CNS weight), as illustrated in Fig. 4 (b-iii) [84,85]. In comparison to pure paraffin wax (PW), the inclusion of carbon nanotubes (CNTs) in PW, denoted as PW@CNTs, significantly enhances the heat transfer rate without compromising the stability or compatibility of the resulting composite [86]. L. Chen [87] examine using paraffin/ carbon nanotube sponge (CNS) composites as FSPCM for LHTES (latent heat thermal energy storage). CNS serves two functions: it acts as a flexible scaffold for wax encapsulation and preserves a conductive network throughout phase change, encompassing both solid and liquid states. The seamless interpenetration of the nanotube network and paraffin wax, characterized by a strong affinity, improves phase change enthalpy and thermal conductivity relative to pure paraffin wax.

Another study conducted by Sari et al., [88] found that by incorporating 20 wt% of EG into the fatty acid, the thermal conductivity of the composite increased, and melting time decreased. The reduction of melting time, exhibits an elevated rate of heat transfer and improved thermal conductivity. The latent heat shown a reduction of 28%, 22.3%, and 22.2% in the case of capric acid/EG, lauric acid/EG, and myristic acid/EG, correspondingly. It is observed that these results indicate the potential for improved thermal conductivity in fatty acid/EG composites.

A research investigation by Cui et al.,[89] has been carried out to examine the potential of utilizing carbon nanotubes (CNT) and carbon nanofibers (CNF) as porous support materials, in conjunction with paraffin wax as the PCM-filled phase change material, to enhance their thermal conductivities by 28% and others, from $0.369 \text{ Wm}^{-1}\text{k}^{-1}$ to $0.469 \text{ Wm}^{-1}\text{k}^{-1}$. A composite material made of paraffin wax and carbon nanotubes (PW@CNS) was successfully created using a vacuum impregnation method [90]. This composite material has both good thermal conductivity and high electrical conductivity, making it useful for thermal management and electromagnetic interference (EMI) shielding in electronic devices. The material's thermal reliability and reusability were also tested by subjecting it to 100 thermal cycles. It was found to have similar latent heat values before and after the cycles, indicating

good thermal performance. Overall, the PW@CNS composite has the potential for use in thermal management and EMI shielding for electronic devices. The use of paraffin/carbon-coated nano scroll (CAN) composite PCMs for thermal energy storage has also been investigated [90]. Adding a carbon coating to the nano-scrolls is intended to improve the thermal conductivity of PCM. The authors report that the carbon-coated nano-scroll PCM composite has a higher thermal conductivity than pure paraffin, which allows it to transfer heat efficiently. This is likely due to high thermal conductivity of carbon, which allows efficient heat transfer by the movement of heat-carrying phonons through the material. The carbon coating also helps to increase the contact area between the PCM and the heat transfer fluid, which can further improve the heat transfer rate.

Maleki et al., [91] prepared a cost-effective porous carbon foam, derived from melamine, was employed as a support material for polyethylene glycol PCM. The results reveal that PEG exhibited leakage at 30°C, whereas the PEG composite remained stable without leakage at the same temperature. At 37°C, PEG spread on the hot plate, but CF/PEG displayed minimal leakage over time, as illustrated in Fig. 4 (c). The treated materials exhibit good shape stability, indicating they are suitable for practical thermal management systems. In another study [92], the researchers investigated composite phase change materials (CPCM) made of cellulose acetate (CA) and Di isobutyl phthalate (DI) or reduced graphene oxide (rGO)-modified DI (CA/rGO-DI). They found that when the CA content reached 65wt%, the CPCM agglomerated, indicating poor dispersion. Heating experiments showed that at 55wt% and 60wt% CA content, mass loss during heating was negligible. However, a significant mass loss of about 10wt% occurred at 65wt% CA content, indicating leakage. Thus, the optimum CA content without leakage was determined to be 60 wt%. Fig. 4 (d-i) illustrates the macroscopic photographs of CA/DI and CA/rGO-DI-2 composite phase change materials (CPCM) with varying cellulose acetate (CA) contents. The exudation stability of the composite was investigated by subjecting CA/DI and CA/rGO-DI-1 composite phase change materials (CPCM) to heating at 80°C for 0-2 hours. The Fig. 4 (d-ii) depicts shows the residual quantity of CA/DI and CA/rGO-DI-1 CPCM during this heating process.

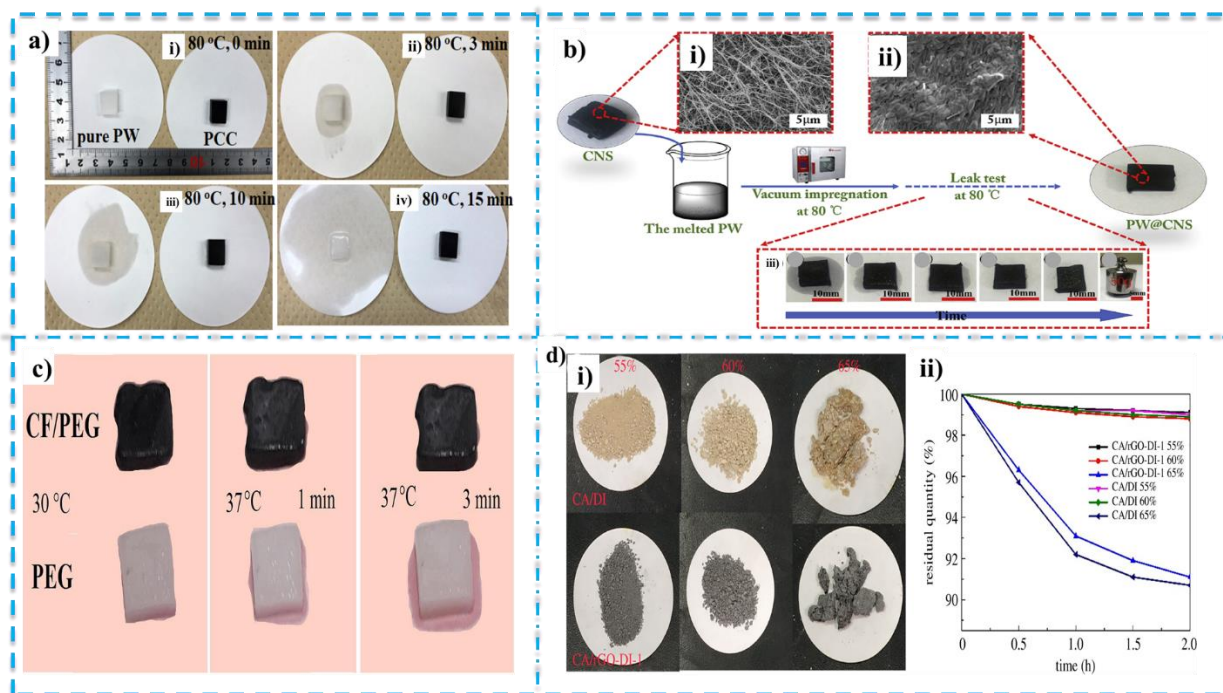


Fig. 4. (a) Leakage test after different durations of heating at 80°C comparing a typical PCM with carbon sponge as a supporting framework to pure paraffin wax (PW) [82]. 4(b) PW@CNS preparation process; CNS morphology, PW@CNS morphology, Leakage test: PW@CNS, no leakage observed [83]. 4(c) The photographs illustrate pure phase change materials (PCMs) and their corresponding composites at different temperatures [91]. 4 (d-i) photographs of CA/DI and CA/rGO-DI-1 composite phase change materials (CPCM). 4 (d-ii) displays the residual quantity of the composite PCMs during the heating process [92].

The results presented in Fig. 4, demonstrate the effectiveness of various composite materials, including paraffin wax/carbon nanotube sponges, paraffin/carbon-coated nano scrolls, and PCM/carbonized foams shape-stabilized phase change materials, in improving the thermal conductivity and shape stability thereby preventing the leakage issue of these composite. The enhanced thermal conductivity is attributed to high thermal conductivity of carbon nanotubes, carbon coating, and expanded graphite, as well as the improved dispersion of these materials (PCM) in the composite matrix. These advancements can lead to more efficient heat transfer and improved thermal management systems performance. The literature supports the notion that incorporating low temperature PCM into a foam matrix or vice-versa addresses leakage issue while increasing thermal conductivity and thermal stability.

However, carbon foams may endure contraction or other deformations at low temperature due to thermal expansion and contraction. Temperature-induced contraction causes volume reduction in carbon foam, leading to internal stresses, which causes deformations or even structural damage. However, polymeric carbon foams exhibit inherent flexibility and resilience, providing greater mechanical stability compared to other carbon foam types. This

mechanical stability helps mitigating potential structural integrity issues in low-temperature PCM applications, making polymeric carbon foams a promising solution for addressing the mechanical stability challenges in such systems.

2.2. Metallic foams based low temperature PCMs

Metals or metal alloys, known as "metallic foams," have a porous, sponge-like morphology; they have a range of unique properties, including a high strength-to-weight ratio, low density, and good thermal conductivity. These properties make metallic foams attractive for various applications, including energy absorption, heat transfer, and structural support. Researchers have recently explored using metallic foams as PCMs for thermal energy storage. By incorporating metallic foams into PCMs, it is possible to create materials with improved thermal conductivity and stability, making them practical for thermal management applications. Metallic FSPCMs are composite materials with a metallic foam matrix infused with a PCM. Metallic FSPCMs have several potential applications in thermal management, including in buildings, vehicles, and electronic devices. They effectively store excess heat generated by these systems and release it as needed, helping maintain a uniform desired temperature and improve energy efficiency. In addition, the high thermal conductivity of metallic foams facilitates efficient heat transfer between PCM and the surrounding environment, further elevating the material's performance consequently, enhancing the thermal management systems [93].

The selection of metallic foam for the usage in FSPCMs depends on the application's specific requirements; including the temperature range, load-bearing capacity, and cost constraints. Various types of metallic foams have been used to develop FSPCMs, such as Aluminium (Al), Copper (Cu), and Nickel (Ni). Al foams are lightweight and have good thermal conductivity, making them popular for FSPCMs. They are relatively inexpensive and easy to process, thus, practical across diverse applications [94]. Copper foams boast higher thermal conductivity and weight, compared to aluminium foams. Also, they are expensive than Al foams however this high cost is justified by enhanced performance in specific applications.

Meanwhile, Ni foams have good strength and thermal conductivity [95], making them well-suited for high-temperature applications. They are also corrosion-resistant [96], making them a viable option for corrosive environments. Materials with low thermal conductivity could excel in heat insulation and storage. It is crucial to consider the material's strength to withstand potential structural stresses. The metallic foam should be compatible with the PCM, ensuring the foam does not react with or contaminate the base PCM. The cost of the material

is also an essential factor in determining its suitability as a foam for the required application. It is also important to consider the specific application and requirements of the PCM system in which the foam will be used. Table 2 illustrates the properties of some commonly used metallic foams.

Table 2: Different properties of these metallic foams

Material	Density (kg/m³)	Young's Modulus (GPa)	Thermal Conductivity (W/mK)	Strength (MPa)	Reference
Aluminum	2700	69	237	300	[97]
Copper	8940	110-128	401	369	[98]
Steel	7850	---	---	---	[99]
Titanium	4540	116	21.9	830–3420	[100]
Magnesium	1740[101]	---	160[102]	---	---

From Table 2, the density of aluminium is relatively low, which makes it a good candidate to be considered as foam in PCMs. Although copper has a high thermal conductivity, its high density makes it less suitable for use as foam in PCMs. The strength of steel is relatively high, making it a good candidate for use as foam in PCMs in applications with high structural support. The density of titanium is relatively high, which makes it less suitable for use as foam in PCMs. Conversely, magnesium has a relatively low density and high thermal conductivity rendering it favourable options in PCMs where high heat transfer is required.

Wang et al. [103] developed a novel passive thermal management system (TMS) using a copper foam and paraffin composite PCM. The study investigated the thermal performance of the composite integrated with a battery through experimental and numerical analysis. The composite exhibited a significantly higher thermal conductivity of $5.28 \text{ W m}^{-1}\text{K}^{-1}$ compared to base paraffin. The findings demonstrated that the passive thermal management system (TMS) allowed for up to three cycles of 4C charge and discharge at a temperature of 35°C , all while keeping the maximum temperature of the battery pack below 52°C . Another study [104] investigated the influence of copper porous foam (CPF) on heat transfer within a cylindrical thermal energy storage system involving solid/liquid phase change. The CPF, with 95% porosity, is combined with 99% pure eicosane as the PCM. Detailed experimental and analytical analyses are conducted, revealing a thermal resistance layer that reduces heat transfer between the container surface and the phase change front. The CPF significantly

enhances the effective thermal conductivity from $0.423 \text{ W m}^{-1}\text{K}^{-1}$ to $3.06 \text{ W m}^{-1}\text{K}^{-1}$. Shang et al., [105] developed modularized thermal storage unit (MTSU) that overcomes heat dissipation bottleneck. MTSU consists of paraffin encapsulated with epoxy resin, thermally enhanced by copper or nickel foams. Theoretical and experimental validations show a 376% increase in effective thermal conductivity with 95.52% porosity copper foam, and a 205% increase with 95.61% porosity nickel foam due to the relatively lower skeleton thermal conductivity of nickel foam [105]. To examine the impact of different parameters, including the dimensions and configuration of the pores in the copper foam and the melting point of the paraffin wax, the copper foam was synthesized by simple solution combustion using copper nitrate and starch [106]. The authors claim that using paraffin waxes in metal foams can improve the thermal storage capacity of the material and found that the size and shape of the pores in the copper foam have a significant effect on the phase change behavior, with smaller pores leading to a higher storage capacity [106].

Another study conducted by [107], the authors suggested that the use of PCMs in metal foams with heat pipes is an effective way to improve passive cooling, thermal storage, and thermoelectric energy generation capabilities of the system and that the size of the metal foam pores and the type of PCM can be manipulated to optimize the performance of the system. Furthermore, the authors in [108] also highlighted that the size of the metal foam pores and the type of PCM could significantly affect the system's performance, and that careful selection of these parameters can optimize the system's performance. Wang et al., [109] studied a composite PCM with paraffin filled with copper foam. Results showed that copper foam improved internal heat transfer uniformity, reduced paraffin's heat storage time by 40%, and improved the relationship between phase transition time and heating boundary temperature.

Yao et al., [93] conducted a comprehensive experimental investigation on a composite material consisting of metal foam and paraffin. The findings indicate that a reduction in pore-density led to an improvement in thermal diffusion, acceleration of the phase interface, synchronization of the phase change, and uniformity of temperature in the metal foam-paraffin composite. In a study by Lafdi et al., [110] explored the porosity and pore size of aluminium foam while melting a composite PCM comprising of paraffin wax and aluminium foam as the support structure. The findings indicate that selecting the appropriate foam porosity and pore size is crucial in enhancing the thermal performance of composite PCM. Another study involved the utilization of a vacuum assistance process to fabricate composite PCMs comprising paraffin and metal foam, specifically nickel and copper foam [111]. A notable improvement in thermal conductivity and a minor alteration in phase change temperatures

have been detected. The findings indicate a reduction in latent heat by 22-24% and 26-30% for composites of nickel and copper foam, respectively has been observed. The authors in [112] also noted that the aforementioned increase resulted in a notable enhancement of the effective thermal conductivity within the porosity of the metal foam. Atal et. al., [113] studied the impact of porosity on the charging and discharging rates of PCM composites. The findings indicate that a reduction in porosity leads to an acceleration of the charging and discharging processes. Huang et al., [114] produced a composite material consisting of myristyl alcohol and metal foam, utilizing nickel and copper foams with varying degrees of porosity, as illustrated in Fig. 5. The findings indicate that a greater enhancement in thermal conductivity was observed for pore sizes that were comparatively smaller. Moreover, the incorporation of metal foams resulted in a reduction of latent heat of the base PCM.

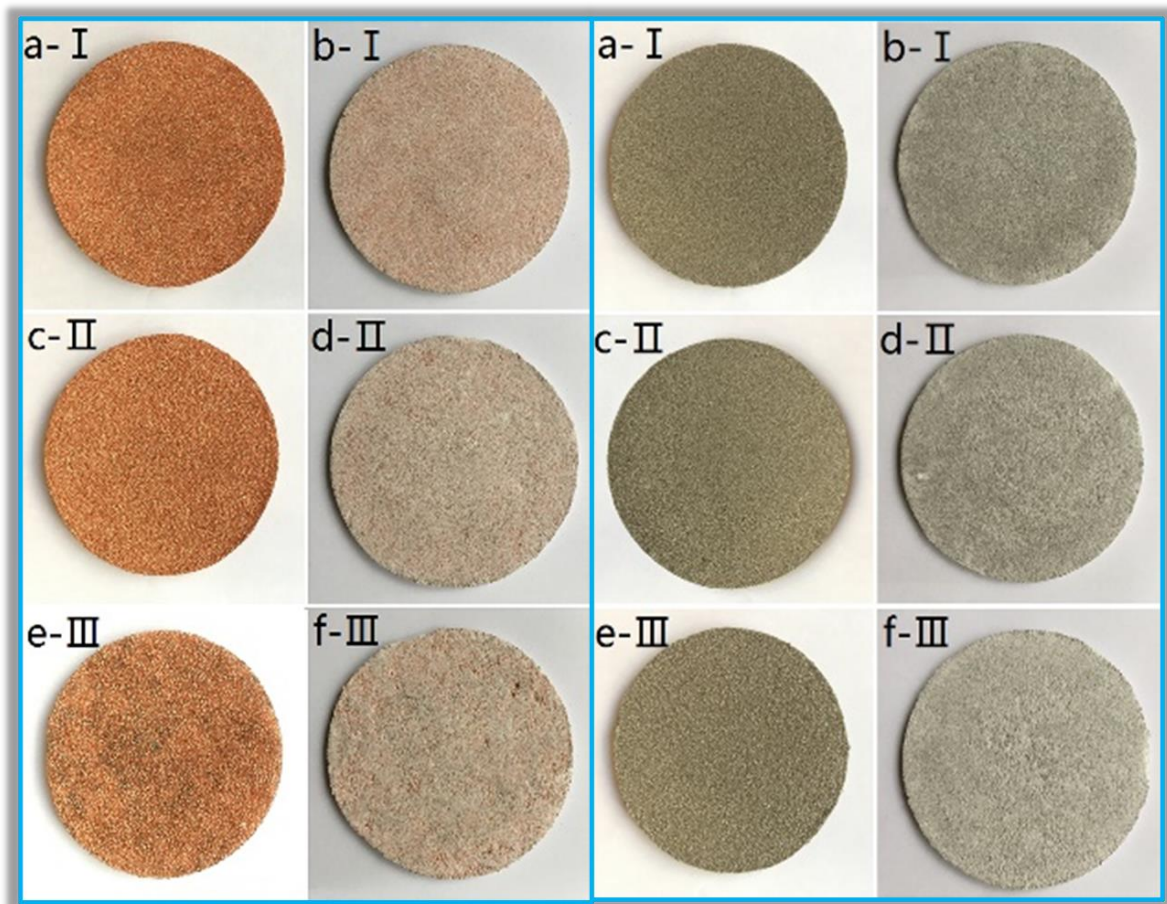


Fig. 5. The visual representation depicts the nickel and copper foam prior to and subsequent to preparation, exhibiting a distinct variation in pore size (I: 40 PPI, II: 70 PPI, III: 90 PPI)[114] .

The existing literature highlighted that, apart from solving the issue of leakage, the use of metallic foams in PCMs can also enhance the thermal conductivity of material. The inherent high porosity and substantial surface area-to-volume ratio of metallic foams facilitate more

efficient heat transfer within the material. Additionally, the use of metallic foams can improve the thermal stability and durability of PCMs, as the foam structure provides mechanical support and can help prevent sintering and other degradation processes. Some experimental studies have shown an increase in the thermal conductivity of PCMs when metallic foams are incorporated into the material [115–117]. The authors have also discussed the underlying mechanisms that contribute to enhanced thermal conductivity, such as increased convective heat transfer and reduced thermal resistance within the porous structure of the foam. However, it is important to note that the specific performance improvements will depend on the specific characteristics of the metallic foam and the PCM, as well as the operating conditions and application requirements. The high porosity of the foam allows for a reduction in the volume of the PCM, which can be beneficial in situations where space is limited or weight is a critical factor.

However, there are also some potential disadvantages to using metallic foams with low-temperature PCMs. One disadvantage is that low-temperature PCMs may have lower latent heat of fusion [118,119], which can limit their ability to store a large amount of thermal energy. Additionally, low-temperature PCMs may be more prone to crystallization or solidification over time [120], which lead to a decrease in the material's ability to store and release heat as intended. Potentially reducing the efficiency of the system in which the PCM is being used and accordingly affect the performance of the material. The suitability of metallic foams with low-temperature PCMs for a particular application depends on the specific requirements of the application and the trade-offs between the various advantages and disadvantages of the material.

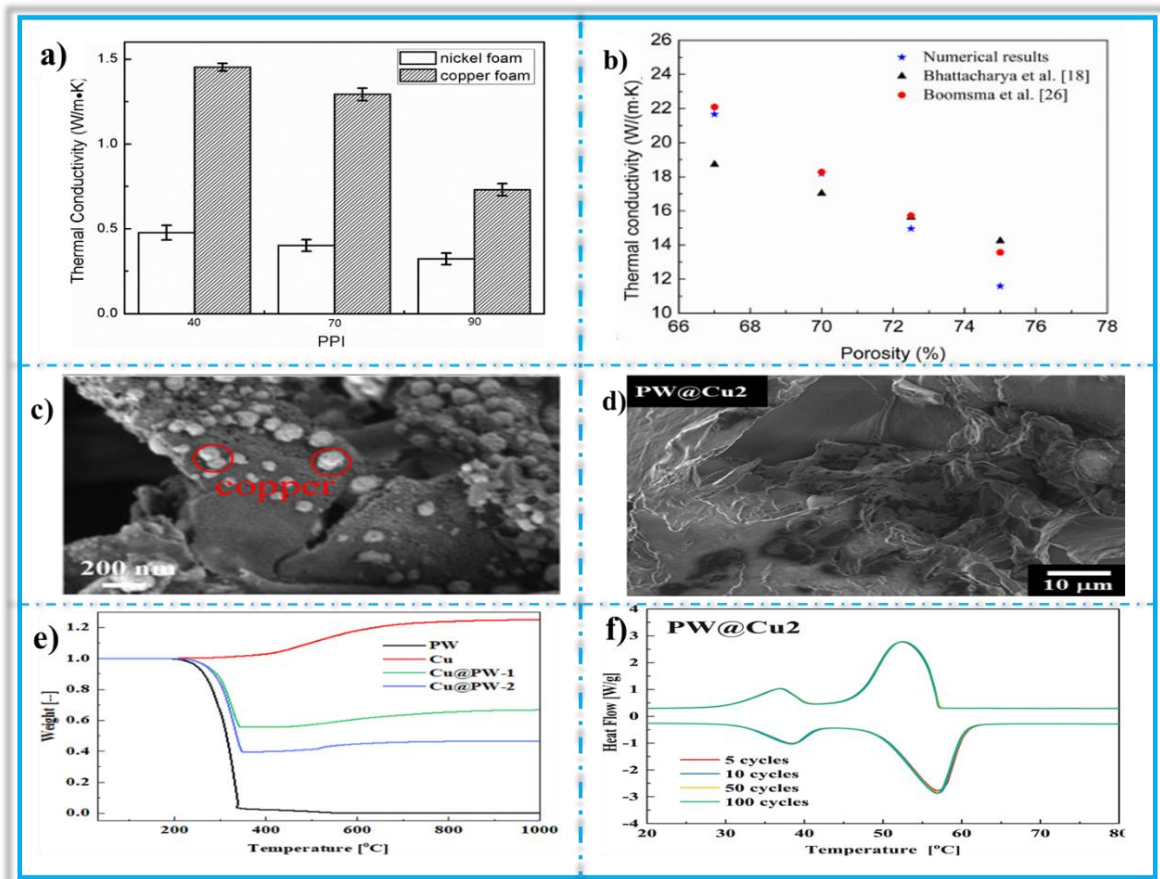


Fig. 6. (a) The thermal conductivity of composites made from MA (melamine foam) and nickel foam or copper foam with varying pore sizes [114] (b) comparison of effective thermal conductivity of composite PCM [36]. (c) SEM images of the copper samples obtained after SCS under Ar gas (d) SEM images of the annealed copper foams filled with paraffin. (e) TG curves under air flow for PW, Cu, and PW@Cu (f) DSC measurement results for the composites and PW [121].

Fig. 6 (a) and (b) present the results of a study on the thermal conductivity of composite materials made of low-temperature PCMs infused into low-porosity metal foams. The thermal conductivity of composite materials was found to decrease as the number of pores per inches (PPI) increases. Also, it was found to be positively related to the metal/PCM mass ratio of the composites, in a certain range, however, it does not have a linear relation with the metal/PCM mass ratio of composites. Hence, incorporating metal foam into a PCM can significantly increase the thermal conductivity of the composite material.

Fig. 6 (c) shows SEM images of copper samples post-Supercritical Fluid Sintering (SCS) under argon (Ar) gas, revealing a porous structure with interconnected pores beneficial for enhanced thermal transfer. This arrangement offers ample surface area, boosting PCM thermal conductivity. Further, Fig. 6 (d) illustrates another SEM image of the annealed copper foams and the foams filled with paraffin, revealing that the copper foams retain their porous structure after annealing and that the paraffin is well-dispersed within the foam's pores. Fig. 6 (e) presents the thermal gravimetric analysis (TG) curves under airflow for PW, Cu, and Cu@

PW. The graph shows that the PW's thermal stability is improved when encapsulated within the copper foam, indicating that the copper foam can act as a protective barrier for the PCM. Fig. 6 (f) presents Differential Scanning Calorimetry (DSC) measurement results for the composites and PW. The DSC curves show that the composite thermal properties do not undergo any significant changes even after 100 thermal cycles when encapsulated within the metal (Cu) foam, indicating that the metal foam can effectively transfer heat to and from the PCM.

In conclusion, using metallic foams such as copper foams as supports for low-temperature PCMs such as PW and PEG can provide several advantages. However, a disadvantage could be the cost and complexity of the synthesis process. The selection of a metallic foam should be considered concerning the specific thermal energy storage application [122,123]. Due to the different thermal expansion coefficients of the foam and the PCM, mechanical compatibility of metallic foams at low temperatures might be a challenge. Mechanical stress may be induced on the metallic foam structure due to phase change expansion and contraction of the PCM. This strain may cause the foam to distort or even break if it is too great for its mechanical strength. The mechanical compatibility of metallic foams is essential in low-temperature PCM applications because the discrepancy in thermal expansion coefficients between the two materials might amplify these mechanical stresses. In addition, the long-term composite performance may be hampered by the corrosive nature of these metallic foams.

3. Foam-based medium temperature PCMs

Medium-temperature PCMs typically have a higher operating temperature range between 40-100°C. Thus, the materials used as medium-temperature PCMs must withstand higher temperatures and pressures without deforming or degrading. Developing medium-temperature FSPCMs, such as carbon-based and metallic foams, presents this as one of the main challenge. Generally, medium-temperature PCMs require higher thermal conductivity and heat storage capacity to match the increased demands of the higher operating temperature range. Due to their high surface area-to-volume ratio, mechanical strength, and excellent thermal conductivity, carbon-based foams are suitable for this application. These properties allow them to efficiently transfer heat and store more thermal energy per unit volume, making them suitable for medium-temperature applications. Medium-temperature PCMs are commonly used in process heat recovery, waste heat recovery, and thermal energy storage. These applications often involve higher temperatures and higher heat transfer rates than low-temperature PCMs, which further emphasizes the need for materials that can withstand high

temperatures, high pressures, and high thermal conductivity. One of the main advantages of medium-temperature PCMs is that they can store a relatively high amount of heat per unit volume compared to other thermal energy storage materials, such as water or sensible heat storage materials.

Furthermore, medium-temperature PCMs can be used in various heat transfer fluids and can be solidified or melted using various heat sources. They can be used in solar thermal energy storage, HVAC systems, and industrial process heat storage. Common medium-temperature PCMs include paraffin waxes, fatty acids, and eutectic salts. These materials have high energy densities and good thermal stability, making them suitable for medium-temperature applications. Each material has different options; for paraffin waxes, there are options like low molecular weight, high molecular weight, high melting point, and low melting point.

3.1. Carbon-based foam for medium temperature PCM

Foams for medium-temperature PCMs may be made from various materials, although carbon-based polymers have garnered particular interest in recent years. Paraffin, fatty acids, and polyols are all examples of such materials. Carbon-based FSPCM have a high latent heat of fusion, which makes them useful since they can store and release much energy when they transform from solid to liquid. The ability to store energy during surplus production and release it during peak demand is a useful feature of TES systems. Carbon-based FSPCMs are widely accessible and environmentally preferable since they are non-toxic and biodegradable. The chain length, branching, degree of unsaturation, crystalline structure, etc., may be adjusted to achieve the desired melting and crystallization temperatures, the heat of fusion, and thermal conductivity. However, anticipating and managing these features may be challenging since they rely so heavily on the molecule's structure.

Xi et al., [124] prepared a super black carbon reinforced melamine foam aerogel-based medium temperature paraffin wax composite. The thermal properties get drastically enhanced with no leakage even above the melting point due to the rich pore structure of the foam. In addition, this composite shows promising thermal conductivity results with an enhancement of about 97% compared to pure PCM. Due to their porous structure, graphite foams have been used with medium-temperature PCM to make leakage-proof shape stable composites [125,126]. These foams show promising results in terms of thermal performance; e.g., [125] claimed the thermal conductivity of the composite as $1.54 \text{ W m}^{-1} \text{ K}^{-1}$, which is relatively high compared to the pure PCM. Carbon-based porous materials are considered to shape stabilizers for PCMs, due to their higher thermal conductivities (up to $2.1 \text{ W m}^{-1} \text{ K}^{-1}$) [127]. Another study

investigated improving the thermal conductivity of PCM by incorporating it into a carbon foam matrix [128]. Furthermore, the structure of the carbon foam is found to act as a thermal bridge, which reduces thermal gradients and makes the system's temperature more uniform.

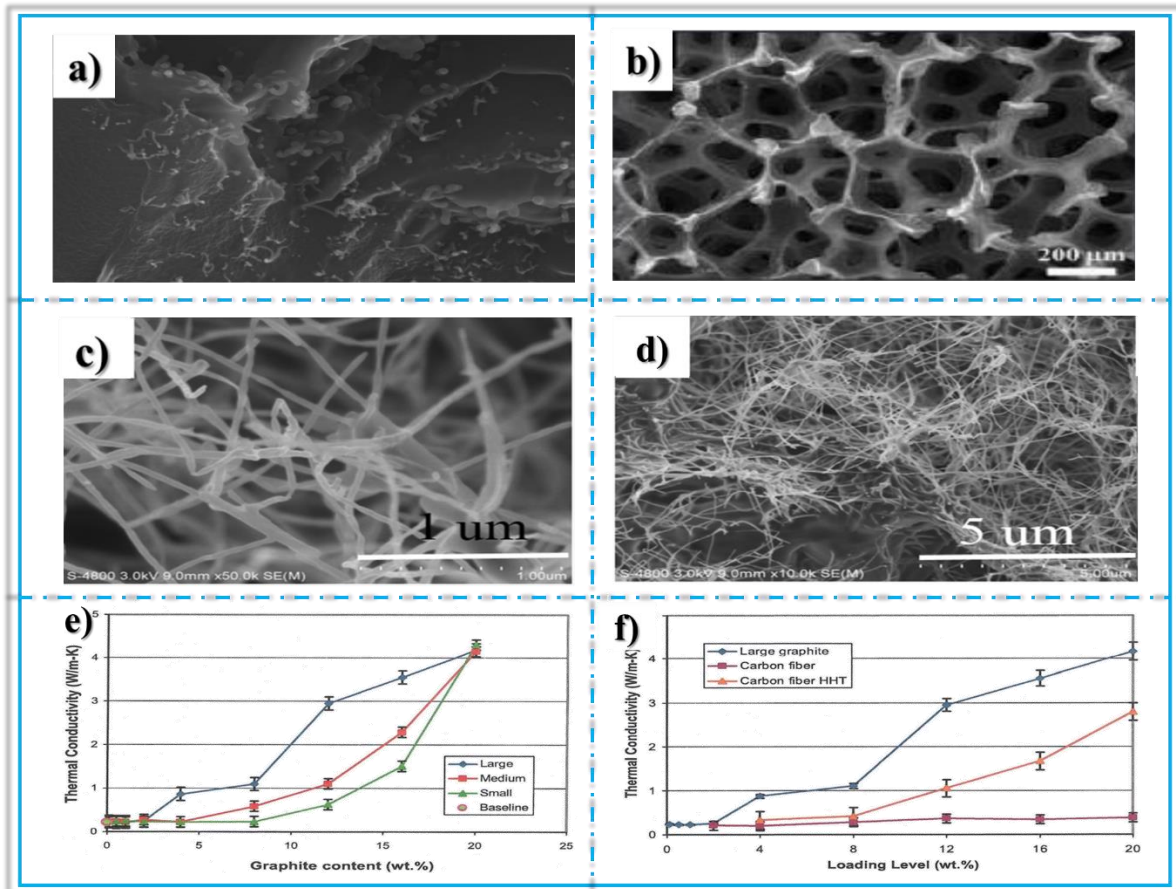


Fig. 7. (a) and (b) SEM images of NiO@CF/OD [129] (c) and (d) The SEM images of the SA/CNT sponge and CNT sponge [86] (e) Thermal conductivity of exfoliated graphite filled polymers with different graphite flake sizes as a function of the graphite content (f) Thermal conductivity comparison of graphite flake filled polymers versus carbon nanofiber and HHT carbon nanofiber composites [130]

Wang et al., [129] prepared an innovative nickel oxide (NiO) enhanced carbon foam (CF) hybrid structure with octadecanol (OD) as PCMs. The NiO@CF/OD composite PCMs show significantly enhanced specific heat capacity ($2.8 \text{ J/g}\cdot\text{K}$) and thermal conductivity ($1.12 \text{ Wm}^{-1}\text{K}^{-1}$) compared to OD alone. The morphology of the prepared composite specimen is illustrated as in Fig. 7 (a) and (b). The incorporation of NiO nano walls and CF network enables close combination and generates a semi-solid layer with improved properties. Moreover, the NiO@CF/OD composite PCMs exhibit excellent thermal reliability, thermal cycle stability, and high photothermal conversion efficiency (77.6%). Fig. 7 (c) and (d) The SEM images of the SA/CNT sponge and CNT sponge provide visual evidence of the porous structure of carbon foam-based PCMs and the excellent dispersion of PCM (SA) into CNT. The high thermal conductivity of graphite foam, as illustrated in Fig 7 (e) and 8 (f), can

enhance the thermal conductivity of the FSPCM. Graphite foam-based PCMs are suitable for medium-temperature foam stable PCM, due to the stable and porous structure of foam. This addresses heat dissipation in electronic devices by augmenting heat transfer and PCM thermal conductivity.

In order to further enhance the foam pore structure and optical characteristics, CO₂ activation was utilized to produce a super black strengthened melamine foam, referred to as activated CA/Foam (ACA/Foam) [131]. The complete procedure of preparing the composite is illustrated in Fig 8 (a). Following the vacuum adsorption of paraffin wax, the resulting paraffin wax/activated carbon aerogel/foam (PW/ACA/Foam) maintains a high thermal storage density of 143.4 J/g and exhibits outstanding thermal stability, effectively addressing the issue of PCM leakage due to its abundant pore structure. The thermal conductivity of PW/ACA/Foam is measured at 0.71 Wm⁻¹K⁻¹, marking a significant 97.2% improvement over pure PW. This material holds great potential for use in composite PCMs for solar energy utilization. Additionally, the foam has a lower thermal resistance than solid PCM, thus heat can more easily flow through the foam. This reduces the overall thermal resistance of the composite material, resulting in increased thermal conductivity.

One of the main potential problems with medium-temperature PCM is leakage [123,132,133], which can occur when the PCM is not adequately contained within the storage vessel. Leakage can result in the loss of both the PCM and the stored energy, reducing the overall efficiency of the TES system [134]. Fig 8 (b) shows the excellent shape stability results, at 80°C there were no leakage for paraffin wax (PW) impregnated carbon foam composite.

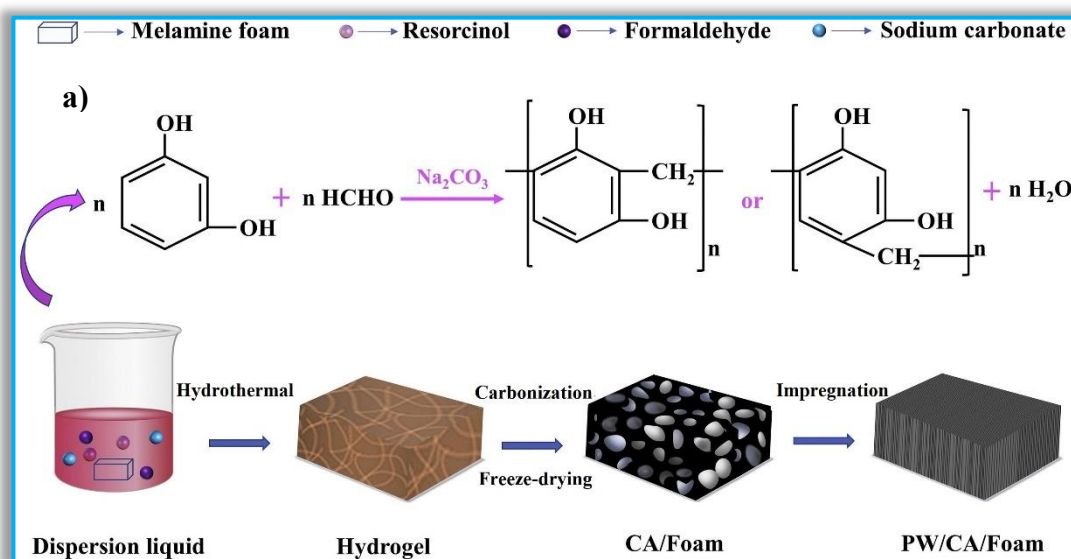


Fig. 8. (a) Schematic diagram for the preparation of CA/Foam [131]

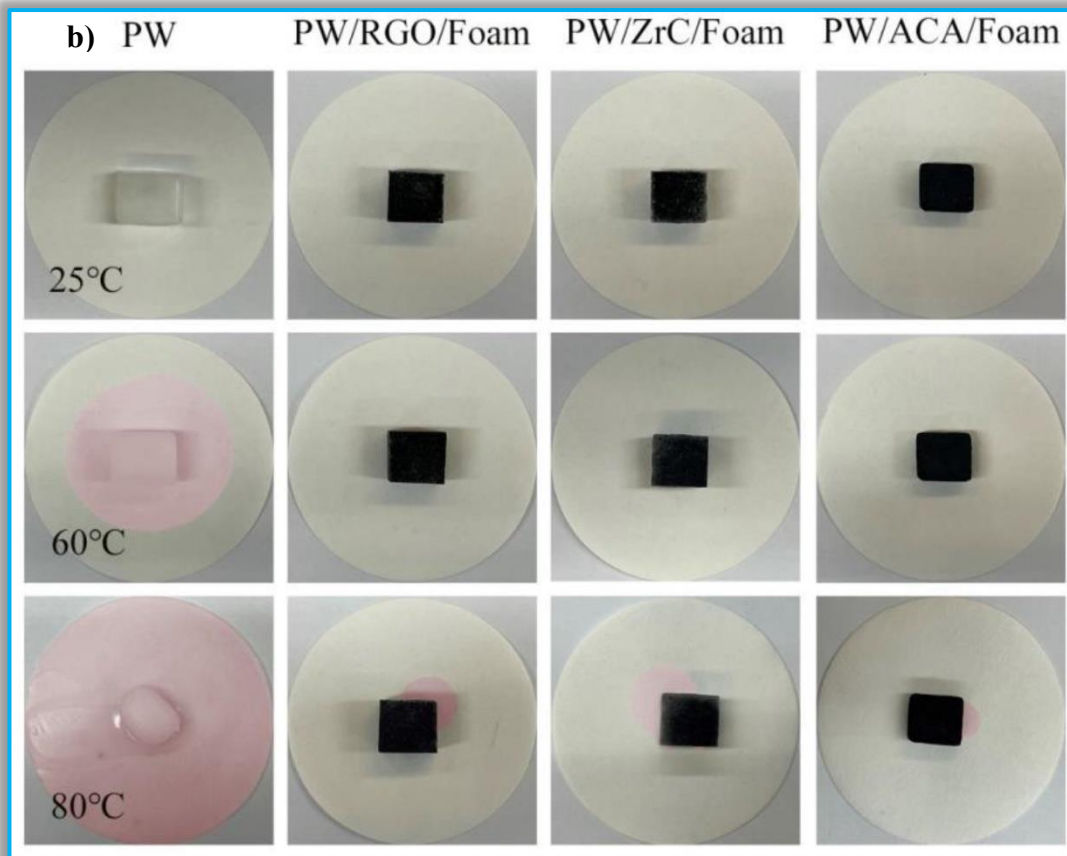


Fig. 8 (b) Leakage changes pictures of the pure PW and PW/ACA/Foam with increasing temperature [131]

Table 3: Comparison of properties for carbon-based and metallic based FSPCM for medium temperature thermal energy storage:

Property	Carbon based FSPCM	Metallic foams FSPCM
Latent heat of fusion	High	Varies
Thermal conductivity	Moderate	High
Thermal stability	Moderate	Moderate
Cost	Low	Moderate-High
Environmental impact	Low	Moderate-High
Leakage	Low	Moderate
Rate of heat transfer	High	High
Chemical stability	High	Moderate-High
Mechanical stability	High	High

Table 3 provides a direct comparison between carbon-based FSPCM and metallic FSPCM across various properties. It highlights the differences and similarities between the two

materials, allowing for a clearer understanding of their relative advantages and drawbacks. In the context of PCM with a medium temperature range (40°C - 100°C), the suitability of carbon-based FSPCM is rooted in its distinctive properties. With a high latent heat of fusion, it ensures efficient energy storage and release during phase transition. Its moderate thermal conductivity facilitates controlled heat transfer, vital for gradual temperature modulation within the specified range. The low cost and environmental impact align with the practical and sustainable requirements of medium-temperature applications. Additionally, low leakage potential, high heat transfer rates, high chemical stability, and robust mechanical durability collectively establish carbon-based FSPCM as an optimal choice for reliable and effective thermal energy storage and release in this targeted temperature spectrum. The data has been inferred from literature using carbon foam with different temperature ranges PCM. However, it is crucial to consider that these characteristics could vary based on the precise kind of carbon-based FSPCM being used.

3.2. Metallic foam based medium temperature PCM

Metallic foam-based medium temperature PCM is a composite material that combines the PCM thermal storage properties with the high thermal conductivity of metallic foam. Main advantage of using metallic foam in medium-temperature PCM is that it has low thermal resistance and high thermal conductivity [135–137] which improves the heat transfer and allows for faster absorption and release of heat energy.

The low density of metallic foam like Al also allows for more PCM in the composite material, resulting in a higher thermal storage capacity [107]. Furthermore, using metal foams also leads to an overall improvement in heat transfer, with an increase of 3-10 times based on metal foam's relative density [106]. It was also noted that metal foams with smaller pores and higher porosity resulted in improved heat transfer performance compared to those with more extensive pores and lower porosity. To further validate the heat transfer rates, the outcomes of heat transfer in PCM/copper foam composite compared to pure paraffin discussed by [138]. At the beginning of heating process, heat transfer was primarily conducted through the material, but as the paraffin began to melt, convection became dominant mode of heat transfer. However, when copper foam was present, role of convection was reduced compared to pure paraffin. The researchers compared phase change process of pure paraffin and paraffin composites with different heat flux (6.25, 12.5, and 18.75 KWm²) in medium-temperature PCM [139]. They found that the heat transfer performance was significantly improved for the copper foam/paraffin composite compared to pure paraffin. It was observed that the melting and solidification process was more uniform when copper was present in the matrix.

A study by [37] evaluated the PCMs heat transfer performance with and without metal foams. They found that the heat transfer rate was significantly improved, with an increase of 3-10 times based on the pore density of the metal foam. The cooling time was also significantly reduced, indicating a higher heat transfer rate. The research also provided an experimental setup typically used in this study, as shown in Fig. 9 (a). In a study by [140] a composite of copper foam and modified sodium acetate trihydrate (SAT) was fabricated using an impregnation technique. The study aimed to compare the effective thermal conductivity of this composite with that of pure SAT. The modification of SAT was achieved by incorporating disodium hydrogen phosphate dodecahydrate (DHPD) and carbon methyl cellulose (CMC) at concentrations of 2 wt% and 0.5 wt% respectively. The findings indicated that the modified SAT exhibited enhanced thermal stability. Moreover, when combined with copper foam at a porosity of 92.4%, the composite demonstrated a remarkable effective thermal conductivity of $6.8 \text{ Wm}^{-1}\text{K}^{-1}$, which was 11 times greater than that of pure SAT. Moreover, in the context of composite PCM, it was found that the duration required for charging was merely 40% of the time required by pure SAT. Fig. 9 (b) displays a schematic representation of the experimental arrangement.

Several studies [141–143] have been carried out to assess thermal performance augmentation and the impact of orientation on porous metal/PCM composites in medium temperature. An investigation was conducted utilizing a copper matrix with a porosity of 0.86 and 10 PPI pore density as a thermal conductivity enhancer, along with n-eicosane serving as PCM, for the purpose of thermal analysis [143]. The results showed a negligible impact of orientation on the heat transfer rate in the porous matrix/PCM-based heat sinks. Nevertheless, the enhancement ratio was found to be 7.5 at 10 W, and the maximum PCM enhancement ratio was 3 at 7 W at temperature 52°C .

A comparative analysis was conducted to evaluate the Myristyl alcohol (PCM) thermal conductivity in its pure form and in composite form with copper foam. The composite material was fabricated through the process of vacuum melting infiltration. It was observed that the thermal conductivity of the PCM/copper foam (40 PPI) composite was significantly increased by a factor of 7.51 [114]. The composite's melting temperature exhibited a marginal increase, whereas the solidification temperature displayed a minor reduction. The study observed that metal foams with larger pore sizes exhibited a decrease in heat transfer rate owing to a reduction in surface area. Additionally, the latent heat of the composite was reduced by 3-29%. A study investigated paraffin melting in paraffin-copper foam composites using both numerical and experimental methods. The melting point and latent heat of the paraffin were

determined through DSC [141] The utilization of copper foam in the paraffin composite let to a reduction of wall temperature that of the unmodified paraffin material. Increasing pore density improved thermal conductivity, interfacial area, and heat transfer during melting. However, it was observed that this increase in pore density had an adverse effect on natural convection. A decrease in porosity from 0.95 to 0.9 increased natural convection resistance and effective thermal conductivity, while lowering conductive resistance.

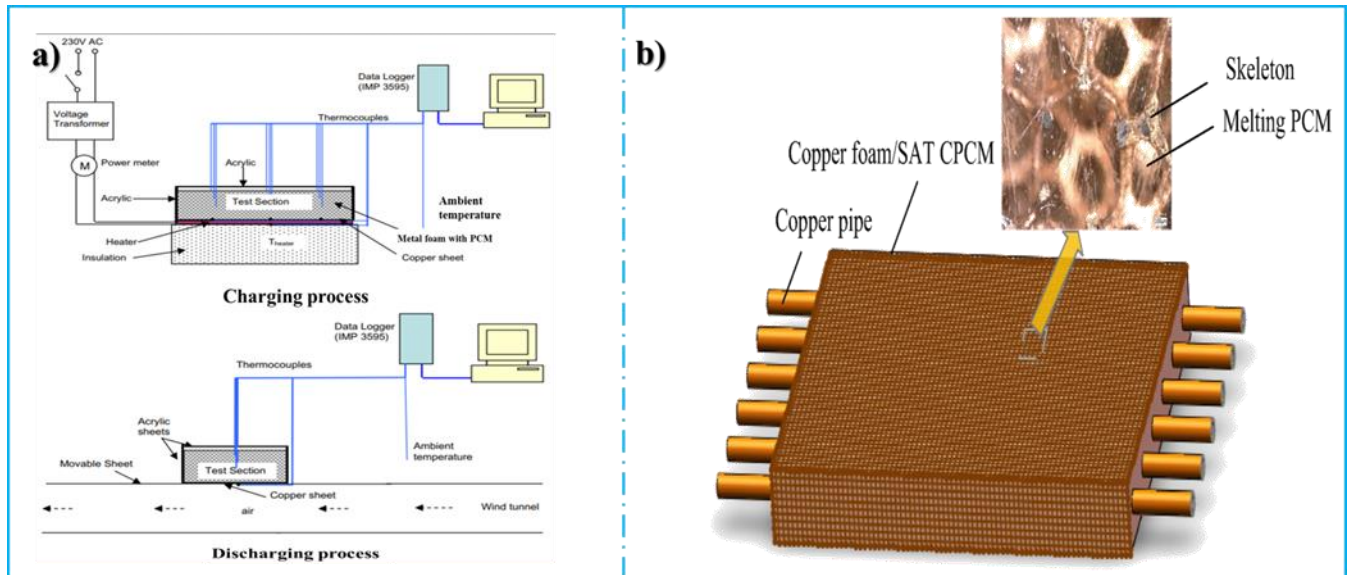


Fig. 9. (a) Standard experimental arrangement for studying copper foam/PCM composite [37] (b) Compact heat storage using copper foam and SAT composite PCM [140]

A significant disadvantage of metallic foams is their higher cost due to complex manufacturing processes, potentially impacting economic viability for PCM systems. Additionally, metallic foams operate at higher temperatures than carbon foams, leading to extended charging and discharging times and increased energy input, possibly compromising overall system effectiveness. Thus, the high cost and operating temperature of metallic foams should be carefully considered for medium-temperature PCM applications, prompting exploration of alternative solutions.

4. High temperature PCM

High-temperature PCMs also play a significant role in sustainably storing thermal energy. They have a phase change temperature range above 100°C so that these materials can store much thermal energy as latent heat at elevated temperatures, specifically for applications that have operating temperatures of more than 100°C . This section discusses the carbon foam and metal foam-based high-temperature PCMs, which have gained attention for being used as a

sustainable solution. Including the different types of materials being developed, their thermal properties, and possible uses in areas like renewable energy and industrial processes.

4.1. High temperature carbon based FSPCM

High-temperature carbon foams are designed for temperatures exceeding 100°C, offering excellent thermal conductivity, limited expansion, and mechanical strength, suitable for applications like heat exchangers. However, their use in high-temperature PCM composites has limitations. While carbon foam tolerates up to 500°C, degradation beyond that range occurs, rendering it unsuitable for very high temperatures. Brittle behavior may hinder flexible or mechanically stressed applications. Additionally, oxidation at elevated temperatures can degrade foam morphology and thermal qualities of FSPCM. However, several researchers have successfully impregnated carbon-based foams into the high temperature for a wide range of applications. A study conducted by [144] claimed that the combination of graphite foam with stable high temperatures with a melting point of 714°C-770°C inorganic salts, magnesium chloride, and potassium chloride is the best choice because it requires higher latent heat and stability, for which graphene is amongst the most preferred foam, especially in a high-temperature application. Moreover, the composites' thermal conductivity, consisting of graphite foam and the PCM, was observed to be 25 Wm⁻¹K⁻¹, indicating the significant impact of graphite foam on the thermal conductivity of the graphite-PCM composites. The increased heat transfer can be attributed to graphite foam's high thermal conductivity, facilitating efficient heat exchange between PCM and the heat exchanger, thereby enhancing heat transfer and storage in the LHTES system. A similar outcome of thermal conductivity was reported by [145], in which they incorporated KNO₃/NaNO₃ (T_m=207 °C) into graphite foam to store thermal energy at temperatures exceeding 200°C. A combination of expanded natural graphite particles and salt powder were compacted under cold conditions using the elaboration process. Results showed that cold compression was a practical way to increase salt thermal conductivity by 20 times using graphite amounts between 15 and 20 weight percent. Similarly, [146] studied the impact of graphite foam on the melting time of a PCM (T_m=306°C) called magnesium chloride in a heat exchanger. Their experimentation revealed that graphite foam improved the PCM's melting rate by twice compared to using PCM alone, indicating its potential benefit in heat exchangers. Moreover, they demonstrated that by incorporating graphite foam into PCM (MgCl₂), the heat transfer rate of the PCM was significantly improved. The thermal conductivity was found to be 10-170 Wm⁻¹K⁻¹, a significant increase from the 0.46 Wm⁻¹K⁻¹ of the pure PCM. Additionally, the number of heat

transfer tubes required was significantly reduced 11,427 to 839, which offered economic advantages.

Singh et al., [147] explored the use of graphite foam in PCMs (MgCl_2 and NaCl) found that the thermal conductivity was 44 times higher compared to the base PCM. However, the latent heat was decreased by 22%. This reduces the number of heat transfer tubes by 12 times, making the system cost-effective and drastically improved the heat transfer rate. Additionally, the system's exergy efficiency was enhanced by 47.9%. This research highlighted the potential benefits of incorporating graphite foam in high-temperature PCMs, enhancing heat transfer and energy efficiency in concentrated solar power plants. Zhong et al., [148] used EG and binary molten salts ($\text{LiNO}_3\text{-NaNO}_3$, $\text{LiNO}_3\text{-KCl}$, and $\text{LiNO}_3\text{-NaCl}$) ($T_m = 171\text{-}199.3^\circ\text{C}$) in the solution-impregnating process to make porous heterogeneous composite PCMs (PHCPCMs). The number of binary salts in the composite ranged from 77.8% to 81.5%. EG addition increased the thermal conductivity of $\text{LiNO}_3\text{-NaNO}_3$, $\text{LiNO}_3\text{-KCl}$, and $\text{LiNO}_3\text{-NaCl}$ by 6 and lowered the phase transition temperature. No chemical reactions occurred between EG and salts, preventing leakage

Lee et al. [149] highlighted the thermal conductivity and differential scanning calorimetry (DSC) of erythritol PCM and EG blends. With more space between the layers, resulting in raising the thermal conductivity to $3.56 \text{ Wm}^{-1}\text{K}^{-1}$, and the latent heat was 90% pure erythritol. A thermal cycling test was also done, and the results revealed that the system was stable when the temperature kept going up and down. Another study conducted by [150] investigated the thermal properties of FSPCM, which was made by adding succinic acid (SA) and adipic acid (AA) as eutectics to EG, resulting in improving latent heat, diffusivity, and thermal conductivity.

Recent research on high-temperature stable carbon foams composed of PCMs is summarised in Table 4. Carbon-based materials, including carbon aerogel, graphene, carbon nanotubes, carbon black, and carbon fiber, have been investigated as potential PCMs for high-temperature applications. These materials exhibit promising energy storage capability ranging from 90 J/g to 180 J/g, and working temperatures of 700°C to 1000°C . Different methods including the sol-gel method, in situ polymerization, injection moulding, compression moulding, melt blending, solution casting, hot pressing, suspension polymerization, spray pyrolysis, and electrospinning are considered potential ways to create the FSPCM. As shown here, high-temperature stable carbon-based foam PCMs may be fabricated with a wide range of characteristics, allowing for the design of materials for various applications.

Table 4: Recent studies on high temperature carbon-based foams

Reference	Material	Maximum Operating Temperature (°C)	Fabrication Method
[151]	Carbon aerogel	700	Sol-gel method
[152]	Graphene/Phenolic foam	800	In situ polymerization
[124]	Carbon aerogel/melamine foam	800	sol-gel polymerization, freeze drying and carbonization
[153]	Carbon fiber/Epoxy resin	1000	Resin transfer molding
[154]	Graphene oxide/Epoxy	800	In situ polymerization
[155]	Carbon black/Polypropylene	900	Melt blending
[156]	Carbon nanotubes/Thermoplastic elastomer	1000	Solution casting
[157]	Graphene/Polyethylene	800	In situ polymerization
[158]	Graphite nanosheets-based carbon foam (CF)	1100-1800	vacuum carbonization (nano-Al ₂ O ₃ /epoxy)

To sum up, research has demonstrated that including carbon foam in high temperature PCM may significantly improve the system's thermal performance. Carbon foam has been demonstrated in studies to increase the efficiency of PCMs by lowering melting temperatures, shortening melting times, and reducing energy consumption. It has also been discovered that combining carbon foam composites with PCMs for usage in high-temperature applications like concentrated solar power plants is particularly useful since it may significantly reduce the number of heat transfer tubes required for the system. However, challenges exist when using PCMs with carbon foams at elevated temperatures. Acquiring suitable high-temperature PCMs can be complex and costly, while carbon foam's relatively low mechanical stability and thermal conductivity pose concerns for long-term reliability and efficient heat transfer.

Addressing these issues is crucial for effective use of carbon foams in high-temperature PCM systems, necessitating further research.

4.2. High temperature metal based FSPCM

High-temperature metal foams are another FSPCM used over 100°C, and foaming metal alloys like aluminium, nickel, or copper often produce these foams. These foams can be adjusted using different fillers or coatings to enhance their thermal characteristics, like carbon-based foams. High-temperature heat exchangers, thermal management systems, and high-temperature insulation are ideal applications for metal foams. Metal foams are more costly than carbon but have superior thermal stability and endurance. Nevertheless, they have their drawbacks. Production costs can be high, particularly for larger applications. Moreover, metal foams may corrode at high temperatures, degrading thermal properties, and their relatively higher thermal expansion coefficient makes them less stable.

Waste heat recovery systems were modelled by [159] and tested in a few different methods. The authors created a heat-storing foam using erythritol ($T_m=118^\circ\text{C}$) and nickel. A mixture of PCM and foam had an effective thermal conductivity that was 16 times higher than pure erythritol. Furthermore, Tian & Zhao [106], investigated the impact of metal foam in PCM (LiCO_3 , $T_m=486^\circ\text{C}$) on the thermal energy storage (TES) system in a concentric tube and was numerically investigated. The researchers found that metal foam in the lower part of the concentric tube was most effective in increasing TES efficiency, with a savings of 28% of the porous metal. This allows for more space for the natural convection of the PCM in the upper area. In another study [160] revealed that heat storage capacity of aluminium oxide was observed to be the highest among the materials studied, exhibiting a value four times greater than that of copper foam. On the contrary, aluminium oxide exhibited the longest duration of energy storage. In terms of thermal energy storage density, silicon carbide showed better performance due to its lower density. The research also analyzed heat transfer within concentric tubes containing PCM. Findings revealed that increasing porosity linearly from the bottom to the top of the system boosted heat transfer rates. This enhancement was attributed to the moderate natural convection at the top.

Table 5: Highlights of the important parameters from previous works on metallic foams based FSPCM

Material		Thermal Conductivity ($\text{Wm}^{-1}\text{K}^{-1}$)		Heat Capacity C_p ($\text{JKg}^{-1}\text{K}^{-1}$)		T_m (PCM)	Reference
Foam	PCM	Foam	PCM	Foam	PCM		
	Paraffin	380	0.3	386	230	---	[161]
	Li_2CO_3 - K_2CO_3	400	0.6	383	1600	485.85	[162]

Copper	Ternary nitrate	398	0.379~0.378	386	1510	170	[163]
Nickel		91.4		444			
Steel		81.1		455			
Zn-Al	Paraffin	110.0 – 115.0	0.15-0.3	---	---	---	[164]
Stainless steel wall	56% Li ₂ CO ₃ + 44% Na ₂ CO ₃	20.1	0.77	559.9	1945	496	[165]
Aluminum foam	Water	30	0.6	---	4210	---	[135]

Table 5 summarizes current research on high-temperature metal foam stability. Aluminum, copper, nickel, stainless steel, and other materials indicated in the table have been used as foams in thermal energy storage due to their thermal stability and energy storage capability. These materials may be used at more than 100°C and have >300 JKg⁻¹K⁻¹ of heat capacity. High-temperature thermal energy storage, metallic FSPCMs are better than standard PCMs due to their relatively high thermal conductivity ranging from 10 and 400 Wm⁻¹K⁻¹ [166]. Materials with high thermal conductivity are more efficient heat transporters and energy storage mediums. Further study has the potential to enhance and broaden their use.

The thermal properties, including thermal conductivity (K), melting temperature (T_m), and latent heat capacity (L), are crucial in determining the overall thermal performance of FSPCMs for various thermal management applications. Critical thermal characteristics of shape stable PCMs have been presented in Table 6, according to their phase change temperatures and the type of porous matrix used in each category of PCM. In addition, the change in the thermal properties after adding foam to the base PCM has also been discussed along with the percent change. The findings reveal that FSPCMs differ significantly in their thermal conductivity, melting temperature, and latent heat capacity, depending on the kind of porous support and the temperature range. The thermal conductivity of polymeric foam-based materials is most significant in low-temperature FSPCMs, whereas that of carbon foam and metallic foam-based materials is highest in medium- and high-temperature FSPCMs. In addition, it is discovered that the melting temperature and latent heat capacity of FSPCMs are very reliant on the foam type and melting temperature range. These findings stress the significance of choosing the right foam-enhanced FSPCM for various temperature ranges and thermal management tasks. FSPCMs exhibit excellent thermal conductivity, sizeable latent heat capacities, and tenable melting temperatures. In addition, it is essential to consider the

various driving factors affecting the performance of FSPCMs, such as the foam's size and morphology, thermal stability, and compatibility with the surrounding materials. Further research is needed to fully understand the mechanisms underlying the observed differences in thermal properties and to develop more effective foam-enhanced FSPCMs for various applications. In sum, the data in this table sheds light on the thermal characteristics of FSPCMs, which may be used to better construct efficient thermal energy storage systems for various purposes.

Table 6: Thermal performance comparison of across different temperature ranges

PCM			Porous Matrix	FSPCM			Change %			Reference	
PCM/Solvent	K (Wm ⁻¹ K ⁻¹)	T _m (°C)		L (Jg ⁻¹)	K (Wm ⁻¹ K ⁻¹)	T _m (°C)	L (Jg ⁻¹)	K (Wm ⁻¹ K ⁻¹)	T _m (°C)		L (Jg ⁻¹)
Cetiol MM / Teterahydrofuran (THF)	---	40	201.54 ± 5.46	Polyether polyol (Petol PZ 400-5G)	---	39.25	210.08 ± 12.25	---	1.88	4.24%	[167]
n-heptadecane	--	30.78	147.9	Polymerized high internal phase emulsion (poliHIPE) foams	---	25.17	99.6	---	-18.22	-32.65	[168]
n-hexadecane	--	20.84	254.7		---	26.36	145.48	---	26.49	-43.96	[169]
Octadecane (OD)	---	29.9	-236.5		---	33.2	-217.6	---	11.04	7.99	[170]
n-hexadecane/zinc borate	---	26.22	210		---	22.71	123	---	13.39	-41.43	[171]
n-hexadecanol (HD)	0.141	47.05	273.2	PHP/HD(80wt%)	0.157	46.67	207.4	11.35	-0.81	-24.08	[172]
				PHP@CNF(0.1wt%)/HD (80wt%)	0.168	46.45	207.1	19.15	-1.28	-24.19	
				PHP@CNF(0.6wt%)/HD (80wt%)	0.172	46.46	207.3	21.99	-1.25	-24.12	
				PHP@CNF(1.0wt%)/HD (80wt%)	0.175	46.55	207.5	24.11	-1.06	-24.05	
	0.264	46.5	227.3	PoliHIPE foams	0.754	50.8	210.4	128.2	9.25	-7.44	[173]
paraffin	0.24	25.8	138.60	Polystyrene-carbon nanotubes (PS-CNT) polyHIPE	0.39	56.88	119.3	62.5	120.47	-13.08	[174]
	--	34.6	192.30	Acrylonitrile-styrene-acrylate copolymer (ASA)	---	31.9	74.24	--	-7.8	-61.99	[175]
	0.207	58.5	168.4	polypropylene (PP)	0.534	60.6	141.9	157.97	3.59	-15.74	[176]
	---	61.75	225.50	polystyrene-b-poly(ethylene-ran-butylene)-b-polystyrene (SEBS) EG 1% & 5%	0.177	61.11	167.91	---	-1.04	-25.54	[44]
				0.501	60.96	163.25	-27.61				
				1.301	60.27	146.71	-78.79				
PEG	0.45	58.8	205.7	biological porous carbon (BPC) (Potatoes and Raddish)	4.489	56.5	159.7	897.56	-3.91	-22.36	[177]
n-eicosane (70%)	0.145	36.9 ± 0.20	243.28 ± 12.16	nano-SiO2/EG	0.334 ± 0.005	37.71 ± 0.20	135.80 ± 6.79	130.34	2.2	-44.18	[178]
Rubitherm RT28	---	27.8	120.2	polyisocyanurate (PIR)	---	26.6	105.2	---	-4.32	-12.48	[179]
1-hexadecanol	0.23	48	202.4	Chitosan	0.50	48 ± 0.50	220	117.39	1.04	8.7	[180]
paraffin wax	---	54.5 - 63.0	242.6	Melamine based CF-1300 (annealing temp)	---	47.5 - 66.5	221.1	---	-12.84	9.72	[60]
	0.36	54.8	173.3	carbon aerogels reinforced melamine foam (CA/Foam)	0.71	54.8	143.4	97.22	N/A	-17.25	[124]
PEG	0.30	67.1	156.3	CF/MWCNTs	0.68	65.0	156.3	224	126,67	N/A	[181]

PEG6000	0.298	61.5	186.6	Melamine foam	---	62.6	177.3	---	1.79	-4.98	[182]	
Palmitic acid	0.233	62.5	--	MWCNT	0.289	24.03	---	24	---	---	[183]	
					0.293	25.75		26				
					0.339	45.49		46				
					0.306	31.33		32				
					0.277	18.88		19				
Stearic Acid	0.256	61.22	196.7		11.154	59.28	91.94	630	-3.17	-53.26	[184]	
Paraffin Wax/ Diatomite	1.2	26.87	89.04		1.7	27.12	89.40	42	0.93	0.4	[185]	
Polyethylene glycol	0.24	59.13	183.4		3.43	56.68	179.4	1329.17	-4.41	-2.18	[186]	
PW	0.21	58	212.4		0.24	55.7	162.2	114.3	-3.97	-23.63	[45]	
	0.35	57.85	143.7		---	---	65.29	---	12.86	---	[187]	
Erythritol	0.326	130	316		1.147	140	308	251.84	7.69	-2.53	[188]	
	0.710 ± 0.009	121	380.5 ± 2.8		3.560 ± 0.085	120.5	342.6 ± 3.4	80.06	-10	-0.41	[149]	
Tetra-decanol	0.51	35.87	236.1		2.76	35.41	202.6	441.18	-1.28	-14.19	[189]	
CA/LA	0.14	19	93.12		3.15	18.10	115.91	2150	-4.74	24.47	[190]	
Stearic acid	---	54.32	182.39		---	56.10	90.36	---	3.28	-50.46	[191]	
	0.3	59.11	245.97		0.84	59.00	180	280	-0.19	-26.82	[192]	
	0.37	133.29	222.4		5.353	128	187	1346.76	-3.97	-15.92	[193]	
Palmitic acid	0.17	59.66	209.35		0.6	60.38	203.35	252.94	1.21	2.87	[194]	
CA	0.18	31.15	190.21	Expanded Graphite/Bentonite clay	0.77	29.31	69.30	327.78	-5.91	72.33	[195]	
Octadecanol	0.4336	59.11	170.38	Expanded Graphite/EP	6.623	59.57	245.97	1427.44	0.78	44.37	[192]	
Paraffin	0.2	48–62	181	Copper	---						[196]	
	0.1–0.3	54.43–64.11	175.24									[138]
	0.25	53.46–59.31	170.7			5						[197]
	0.27	54–56	199			2.124	50.56	151.6	720	-6.11	-23.82	[40]
Sodium acetate trihydrate	1.54	56.75	271.09		6.49	60.29	250.58	321.43	6.24	-7.57	[140]	
	0.162	62.4	188	Nickel	2.268	62.4	126.34	1300	N/A	-32.8	[198]	
	0.35	58	149.27		182.35	---	44.31	51900	N/A	-70.32	[199]	

Paraffin	0.24	65	206	Graphite	2.64	---	160	1000	N/A	-22.33	[200]
	0.21	57-58	147		0.37-0.87	57.21	114.899	76.19-314.29	0.37	-21.84	[201]
	0.13	58	143.7		---	---	65.29	---	---	-54.57	[202]
Acetamide	0.34	66.95	194.92	Expanded graphite	1.7	65.91	163.71	400	-1.55	-16.01	[203]
Stearic acid	---	53.32	182.39		---	56.47	155.50	---	5.91	-14.74	[191]
	0.3	68.8	198.8		0.84	65	183.1	180	-5.52	-9.46	[204]
Myristic palmitic-stearic acid	0.25	68.54	201.8		2.51	41.72	163.5	904	-39.13	-18.98	[205]
RT-44HC	0.22	44	226.1		13.2	42.98	152.5	5900	-2.32	-32.55	[206]
Lithium carbonate	0.6	486	342	Copper	---						[106]
Paraffin	0.514	306-307	178		---						[160]
LiNO ₃ -KCl	0.93	171	193.5	Expanded graphite	5.59	167.0	142.2	501.08	-2.34	-26.51	[148]
LiNO ₃ -NaNO ₃	0.84	199.3	232.7		6.61	195.0	171.5	686.9	-2.16	-26.3	
LiNO ₃ -NaCl	0.80	229.7	305.3		4.71	224.8	204.4	488.75	-2.13	-33.05	
Erythritol	0.81	120.2	---		2.835	----		250	----		[149]
NaNO ₃ /KNO ₃	1.82	220-223	106		20	220.2 ± 0.9	86.8 ± 0.7	989.9	1.36	-18.87	[207]

5. Various factors affecting the performance.

The thermos-physical performance of FSPCMs is determined by multiple parameters, including the type of foam utilized, phase change temperature, and heat transfer rate; hence, various factors determine how effectively low, medium, and high-temperature FSPCMs work. This section discusses the different factors that affect the performance of the FSPCMs on the different types of foams, like polymeric, carbon-based, and metallic foams. In Fig. 10 (a), previous work illustrated the use of each foam type, while Fig. 10 (b) depicted the PCM amounts utilized, aligned with their respective melting points.

5.1. Low-temperature FSPCMs

In low-temperature FSPCM, the capability to retain heat over extended periods becomes particularly necessary. In general, carbon-based polymeric foams are the optimal choice for low-temperature FSPCM due to their enhanced thermal reliability, superior adherence to the PU matrix, and better thermal conductivity balance. Due to the foam's low thermal conductivity, they balance the heat lost during the phase change process, allowing the FSPCM to store heat for longer to meet the requirement of low-temperature PCM. Furthermore, the high thermal stability of polymeric foams ensures that the FSPCM maintains its shape and integrity during the phase change. Furthermore, polymeric foams are more cost-effective and lighter than metallic and carbon foams.

5.2. Medium temperature FSPCMs

The thermal performance of medium temperatures PCM is also affected by the type of foam used, the phase change temperature, and the efficiency of heat transfer (thermal conductivity of PCM and foam). Carbon foams are the optimal option for medium temperatures due to their stability at medium temperatures and high thermal conductivity. The high thermal conductivity of carbon foams facilitates the heat transfer during the phase change, ultimately enhancing system efficiency. Also, carbon foam's high thermal stability ensures that the FSPCM maintains its shape and integrity during the phase change process. Nevertheless, the cost consideration of the foam pertinent to the intended application of the FSPCM must be considered. In general, polymeric foams are affordable than carbon-based foams. However, they are not as thermally stable as carbon foams and can be degraded over multiple thermal cycles.

5.3. High temperature FSPCMs:

Several factors affect the thermal and mechanical performance of high-temperature FSPCMs, such as the type of foam used in preparing the composite, the actual phase change temperature of base PCM, and the thermal conductivity of the PCM as well as foam. Metallic

foams are the most suited for high-temperature PCM due to their stability at high temperatures without compromising thermal conductivity. The high thermal conductivity of metallic foam allows efficient heat flow during the phase change process, making the system or application more reliable and efficient. Besides, the high thermal stability of metallic foam at higher temperatures ensures that the FSPCM maintains its shape and integrity during the phase change of the PCM. However, achieving cost-effectiveness within the FSPCM is a key consideration. Therefore, the foam's cost becomes a significant determinant when selecting the appropriate application level. It's worth noting that metallic foams typically come at a higher cost compared to their polymeric or carbon-based counterparts. Additionally, considerations surrounding the flexibility of metallic foams must be weighed, as this characteristic could potentially restrict their potential usage scenarios. It is crucial to consider the foam tendency to resist corrosion, weight, and toughness while using metallic foams in high-temperature FSPCMs. Hence, it is always recommended to do a thermal analysis of the system and test different combinations of PCM and foam to find the best solution. Also, considering the trade-offs between cost and performance for each type of foam in each application can help choose the best type of foam.

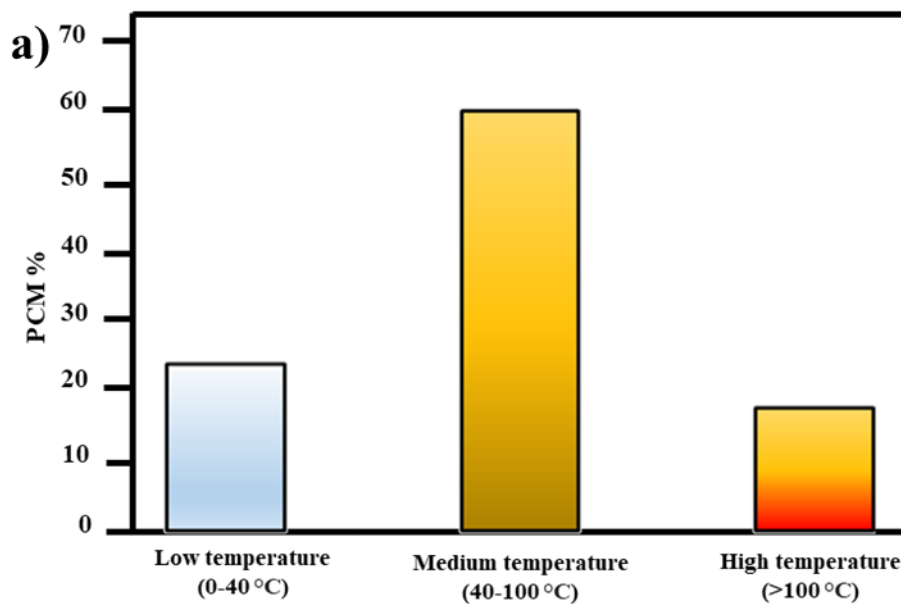


Fig. 10 (a) Illustrates the percentage of PCM across different temperature ranges that has been used by the researchers (taken from Scopus data base from 2018-2023)

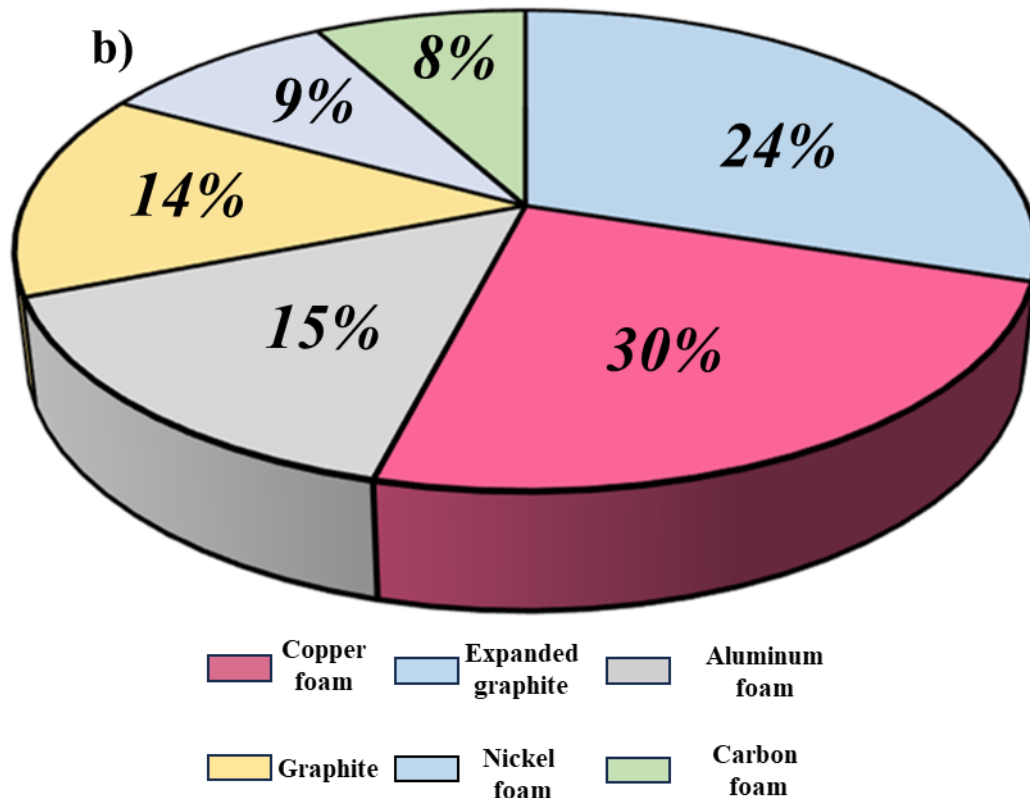


Fig 10. (b) The percentages of foams used according to their phase change temperature (taken from Scopus data base from 2018-2023)

In the pursuit of creating FSPCM, researchers have harnessed the potential of various foam types, including Copper foam (30%), EG foam (24%), Graphite foam (14%), and Aluminium foam (15%). These foams have a high thermal conductivity, which enhances the thermal characteristics of PCM. Expanded graphite foam and copper foam excel in this regard, compared to graphite foam and aluminium foam. As shown in Fig.10 (a) & (b), as per the literature, the use of the PCMs with low temperature is 23%, medium temperature is 58% and high temperature is 17%. Medium and high-temperature PCMs are used in many applications, such as power generation, HVAC and energy storage systems since they offer greater capacity for storing thermal energy per unit volume.

6. Applications of FSPCM

Over the past decade, there has been a notable shift towards adopting FSPCM systems, driven by their potential to improve the physio-thermal properties of base PCM. To ensure the optimal performance of FSPCM, it is essential to identify the appropriate type of foam/porous matrix for each application. Carbon and metallic foams are now viable options for use with low, medium, and high-temperature PCMs in applications such as thermal management for batteries, building heating and cooling, and electronic heat sinks.

6.1. Building heating and cooling

Low-temperature PCM are ideal solutions for heating and cooling buildings because of their capacity to impede heat transfer at a temperature range of around 20-25 °C, thereby maintaining a constant temperature for an extended period. Fig. 11 (a) shows Carbon foam concrete (FC) with lauryl alcohol (LA)-impregnated rice husk ash (RHA) composite PCM ($T_m = 19\text{--}25\text{ °C}$) was developed. The test chamber was used to measure the foam concrete's thermal conductivity, thermal diffusivity, and specific heat. It is equipped with a heating and cooling system to imitate the changing temperature of the walls of the building each day and sensors to measure the temperature alteration of the foam concrete. The findings of solar thermoregulation performance tests indicated that the wallboard, relative to the reference FC, provided approximately 1.29°C higher indoor temperature throughout cold climates hours. The room temperature was approximately 2.8°C lower throughout the daytime in hot climates. The image illustrates how the experiment was organized to evaluate the effectiveness of the PCM-soaked rice husk ash foam concrete to keep the temperature stable. In another study, Isa et al., (2010) established that the implementation of copper foam integrated PCM panels can offer a more comfortable indoor environment for building occupants, eliminating the need for mechanical cooling methods like air conditioning units, portable chillers, or fans. This leads to energy savings for cooling purposes and subsequently reduces CO₂ emissions, while still ensuring optimal thermal comfort for occupants [208]. Haily et al. (2023) developed a novel PCM with encapsulated fatty acids in polyurethane foam, integrated into a geopolymer mortar matrix using phosphate industry by-products. The composite exhibits an ideal temperature range (10–22 °C) for energy-efficient building design, with significant energy storage capacity ($\Delta H_f = 164\text{ J/g}$). Despite reduced compressive strength, the PU@PCM-rich composite meets concrete application requirements (29.5 MPa). Thermal analysis reveals improved heat capacity and slightly reduced thermal conductivity (1.1 J/g.°C and 0.84 W/m.°C) in the PU@PCM-rich composite. Cyclic DSC tests confirm thermal stability over 20 cycles. This composite holds potential for sustainable and energy-efficient construction due to its strong thermal performance and acceptable mechanical strength [209]. There are several studies that supports the integration of FSPCMs presents a remarkable opportunity to optimize indoor environments without solely relying on conventional mechanical systems [210,211]. These advanced composites capitalize on the efficient heat transfer capabilities of foam structures, allowing for effective temperature regulation and storage. By harnessing the latent heat capacity of PCM in synergy with the porous nature of foam, these materials enable buildings to better manage thermal fluctuations.

6.2. Battery thermal management

Carbon and metallic foams, along with low and medium-range PCM, offer effective solution for regulating the battery temperature due to their high thermal conductivity and substantial surface area that enable rapid heat dissipation in batteries. In addition, carbon foams' low density and high porosity are an effective solution to regulate the battery temperature and prevent thermal runaway, safeguarding batteries from damage and potential safety concerns [212]. Fig. 11 (b) shows the different parts of the battery module. The helix shape of the channel is meant to make heat transfer more efficient by expanding the surface area available for heat exchange. The path of the helical axis is shown in blue, which is a wireframe of the helical channel. This system uses a PCM/copper foam composite and helical liquid channel cooling. Zheng et al. (2022) developed a composite PCM (CPCM) using melamine foam, lauric acid PCM, and aluminum nitride (AlN) for enhanced thermal conductivity. With 15% AlN, CPCM reduced battery surface temperature by 24.96% and temperature difference by 83.97% during 3C discharge rate, promoting efficient thermal management for lithium-ion batteries [213]. Wang et al. (2017) prepared CF/PCM (copper foam/phase change material) for thermal management of lithium ion batteries, considering discharge rates and insulated vs. natural convection environments. Results showed improved temperature control with PCM-based battery thermal management (BTM) compared to air-based systems in an insulated environment. The CF/PCM system effectively maintained battery temperatures below 44.37 °C, 51.45 °C, and 50.69 °C for 26650, 42110, and square batteries, respectively. The passive system utilized copper foam for enhanced PCM strength during melting, showcasing its potential for effective battery thermal management [214]. Zhuo et al. (2011) investigated the heat transfer of PCM combined with metal foams and EG. Results showed that PCMs with expanded graphite or copper foam have superior transfer rates than pure PCMs. Metal foam doubled thermal conductivity for PA and tripled it for $\text{CaCl}_2\text{H}_{12}\text{O}_6$. EG improved heat transfer by 30% compared to EG metal foams, demonstrating high performance [215]. Hussain et al. (2016) utilized nickel foam-paraffin composite to keep battery pack temperature below 50 °C and maintain a temperature difference of 0.8 °C [216]. Rangappa et al. performed a numerical study using CFD to compare the thermal conductivity of different composites: pure PCM, PCM/Aluminium, PCM/Graphite, and PCM/Copper. Their findings indicated that the metal PCM composites with aluminium and copper outperformed pure paraffin and PCM/Graphite composites in terms of thermal performance [217]. Khaboshan et al. (2023) conducted a recent study to optimize a battery thermal management system (BTMS) using PCM, metal foam, and fins. They numerically evaluated

the thermal performance and energy storage of the proposed BTMSs under a 3C discharge rate. The combined PCM, metal foam, and fins BTMS exhibited a maximum temperature reduction of 3 K on the battery surface compared to pure PCM. Additionally, a 470 second delay in PCM melting was achieved [218]. These studies suggested that optimized BTMS design demonstrated foam stable PCM ensured uniform heat distribution and better thermal management between the battery and the environment

6.3. Electronic heat sink

As mentioned in section 5.3, metallic FSPCMs prove their efficiency in storing and releasing heat for high-temperature applications such as the thermal management of electronic heat sinks. In addition, they possess a satisfactory strength-to-weight ratio, positions them a prominent choice for compact and lightweight devices. Thermal analysis is highly recommended conduct prior to incorporating any PCM and foam for creating FSPCM, and subsequently integrating the prepared composite into the target application or device. Fig. 11 (c) shows a schematic of the experimental arrangement. PCM-based heat sinks with RT-64 and copper foam exhibit superior thermal performance, resulting in temperature reductions of 14% and 25%, respectively, compared to empty heat sinks [219]. In another study, Rehman et al., (2018) conducted a study on copper foam-based heat sinks with and without phase change material (PCM). The study examined the operational duration of heat in relation to specific temperatures during both the charging and discharging phases. The PCMs utilized in the investigation included paraffin wax, RT-35HC, RT-44HC, and RT-54HC. The findings showed that after a 90-minute charging period, there was a significant temperature reduction of 25% observed in the case of RT-35HC combined with copper foam at a heat flux of 0.8 kW/m², with a PCM volume fraction of 0.83. The maximum improvement in operation time was observed to be 8 times for the RT-35HC combined with copper foam and 7.7 times for the RT-44HC combined with copper foam. These enhancements were achieved at set point temperatures (SPT) of 40°C and 60°C for their respective composite materials [220]. In a recent study, Rahman et al. (2022) investigated the thermal conductivity enhancement of nickel foam-PCM composites in comparison to pure PCM. Their findings revealed that the inclusion of foam led to higher thermal conductivity in the composite. Additionally, the introduction of PCM effectively reduced the heat sink's base temperature, with a more pronounced effect observed for higher PCM fractions. The study showcased a significant maximum reduction in the base temperature by 20.47% for a PCM fraction of 0.8 at a heat flux of 2.4 kW/m². Furthermore, the temperature distribution analysis showed a maximum temperature difference of 1.13°C, emphasizing the enhanced thermal performance of the

nickel foam-PCM composite [221]. Hafiz Muhammad Ali (2022) integrated copper foam and heat pipe (HP) with PCM RT-64 for enhanced heat sink cooling. Examining various configurations, the study found that the hybrid cooling system (PCM-Cu Foam-HP) consistently outperformed others. With a cooling fan, this hybrid system reduced the heat sink's base temperature by 38% and 39% at heat fluxes of 2 kW/m² and 3 kW/m², respectively, compared to an empty heat sink. The findings underscore the effectiveness of utilizing copper foam in improving cooling performance [222]. Hayat et al. (2020) improved PCM performance by combining it with high-conductivity components. They used heat pipes and copper foam to create a hybrid system that enhanced heat transfer. The study showed significant temperature reductions of 47%, 51%, and 54% at different heat fluxes with the Foam-PCM-HP system and a fan after 6000 seconds of charging [223]. Mirshekar et al. (2023) conducted an experimental study using PCMs embedded in open-cell copper foam in a heat sink for heating and cooling processes. Paraffin RT55 was used as the PCM. Different samples were tested, considering copper foam and PCM presence, as well as thermal power and inlet air velocity variations. The results highlighted that partially filling copper foam with paraffin led to the lowest copper plate temperature during heating, with a 20.1% temperature decrease compared to other samples. In the cooling process, composite exhibited a 35.5% lower copper plate temperature [224]. In their study, Rahman et al. (2020) investigated metallic foam and PCM-based heat sinks' performance under varying heat loads. Using high-porosity copper and nickel foams with PCM (RT-54HC), they aimed to enhance heat transfer area. Copper foam consistently outperformed nickel foam in reducing base temperature across all heat loads. The integration of 0.8 volume fraction of PCM into copper foam decreased base temperature by 26% compared to nickel foam without PCM at 24 W heat load. This study highlights copper foam's effectiveness and identifies the optimal configuration for enhanced thermal management [225]. Therefore, the use of FSPCM demonstrates superior charging performance compared to commercial heat pipes. However, for effective discharging, the inclusion of a thermal conductivity enhancer becomes crucial. The foam component expedites heat transfer from the fins to the PCM, thereby diminishing the thermal resistance of the heat sink.

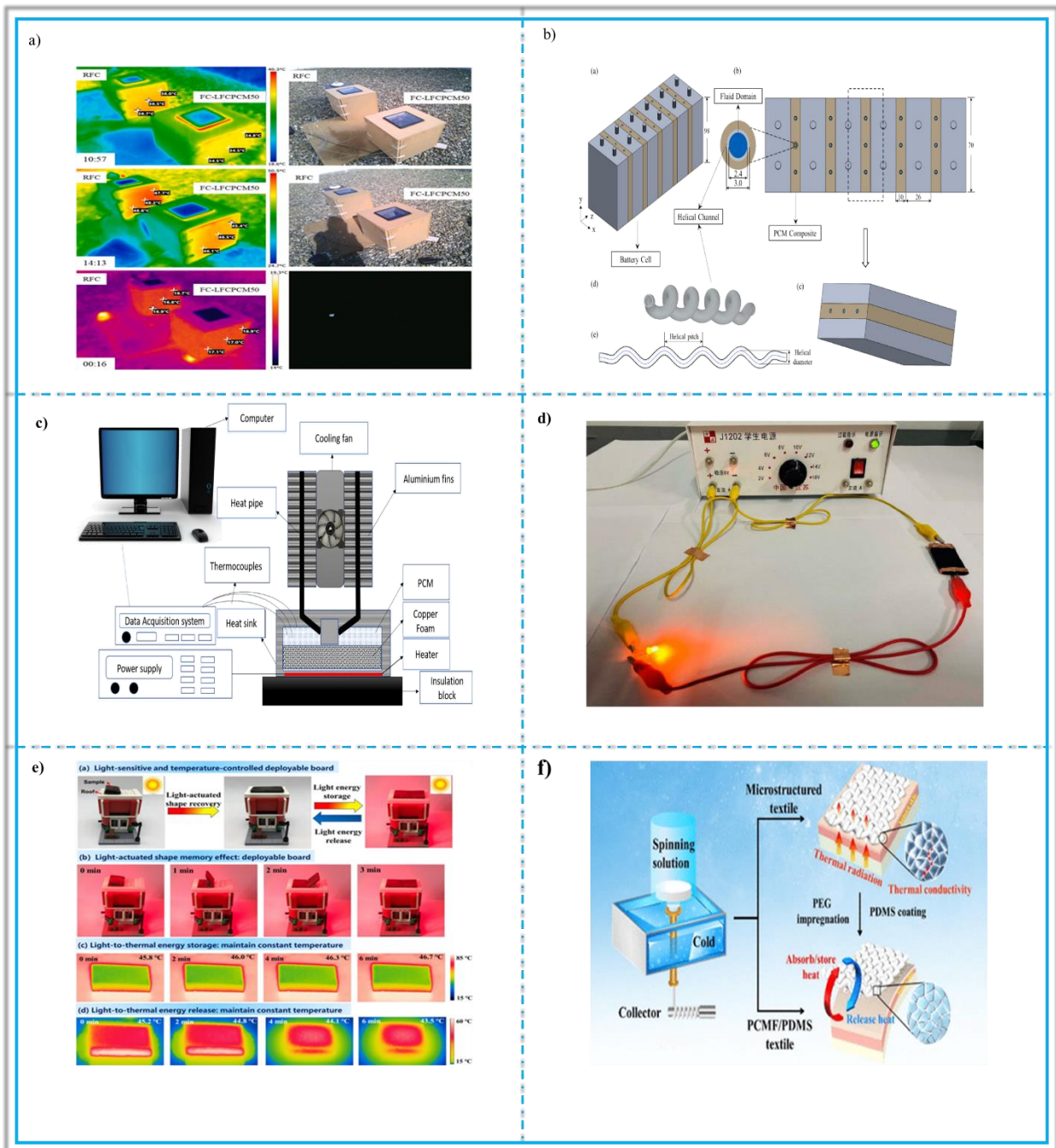


Fig. 11. (a) Illustrates the thermal imaging and of FSPCM in buildings [226] (b) The efficient use of FSPCM in thermal battery management [227] (c) shows the Heat sink for thermal management using PCM, copper foam and heat pipe [219] (d) FSPCM serves as a medium for efficient heat transfer and thermal management while enabling the diodes to emit light [228] (e) Light-sensitive and temperature-controlled deployable board using MF/RGO-1/PW PCM composite for roof temperature maintenance, showcasing shape recovery and constant surface temperature under infrared and light irradiation [229] (f) Thermo-regulation of textiles by incorporating the fibres of textiles with PCM. Reprinted (adapted) with permission from {ACS APPL. MATER. INTERFACES 2020, 12, 16, 19015–19022}. Copyright {2023} American Chemical Society [230]

6.4. Light/electric-to-thermal energy conversion

Flexible and highly thermally conductive FSPCMs with 3D conductive networks have garnered significant attention due to their unique properties and versatile applications. These FSPCMs exhibit flexibility, allowing easy integration into various systems. The presence of a

3D conductive network enhances their performance by facilitating rapid heat/electrical conduction and promoting light/electric-to-thermal energy conversion [231]. A digital photograph was captured to demonstrate the light-emitting behavior of diodes connected to a flexible, highly thermally conductive FSPCM [228]. The FSPCM serves as a medium for efficient heat transfer and thermal management while enabling the diodes to emit light. Fig. 11(d) visually showcases the practical application and versatility of FSPCMs in facilitating light-emitting capabilities through diode integration. The multi responsive nature of FSPCMs makes them ideal for a range of applications, particularly in solar energy utilization. Additionally, FSPCMs hold promise in the construction of energy-saving buildings, as they can actively manage temperature fluctuations and enhance overall thermal comfort. Furthermore, the stable shape memory cyclic properties and thermal reliability of PCM composites make them well-suited for temperature control in houses and other advanced thermal management applications [229]. The composites can maintain desired temperatures by efficiently absorbing or releasing heat as needed, as illustrated in Fig. 11 (e). In a study led by Cui et al. (2022) innovatively combined modified melamine foam (MF) and graphene nanoparticles (GNP) to enhance phase change materials (PCMs) for solar-thermal systems. The resulting composite PCM, MF@PPy-PODS/GNP3/PW, exhibited improved thermal conductivity and solar-thermal efficiency. Moreover, they developed a solar-driven thermoelectric conversion system, demonstrating the potential of these composite PCMs for cleaner energy production. This study offers a valuable strategy for optimizing composite PCM performance and their application in solar thermal systems [232]. He et al. (2022) created versatile phase change material (PCM) composites using porous MXene/silver nanowire (AgNW) hybrid sponges with polyethylene glycol (PEG) encapsulation through vacuum impregnation. Melamine foams (MFs) coated with MXene/AgNW formed a continuous electrical/thermal conductive network. The resulting MF@MA/PEG composites exhibited impressive latent heat, shape memory, electrical conductivity, and notably enhanced thermal conductivity. Additionally, their electromagnetic interference shielding effectiveness (EMI SE) could be adjusted via shape memory-based compression [233]. These studies suggested that FSPCM holds significant promise for advancing thermoelectric conversion technologies, enabling efficient energy conversion and temperature regulation.

6.5. Smart textiles

Innovative smart textiles incorporating foam-based PCM offer a potent avenue for temperature control. The foam structure ensures uniform PCM distribution within the textile, thereby enhancing its overall performance. Particularly, low-temperature PCMs have melting

and solidification temperatures ranging from 20 to 40°C, prove ideally suited for clothing applications. The significance of this research in advancing smart textiles and wearable technology is highlighted in Fig. 11 (f) illustrating how these findings propel these fields forward. Another study by Niu et al. (2022) focuses on creating smart textiles with enhanced energy storage and temperature regulation. By integrating phase change materials into flexible polymer fibers, researchers developed fibers with excellent electrical conductivity, high energy capacity, and adjustable phase change temperatures. These fibers also feature hydrophobicity, self-cleaning properties, and the ability to convert electrical and photo energy into heat. This innovation holds promise for wearable devices and protective clothing systems, offering a new dimension to smart textiles [234]. In their research, Song et al. (2021) presented an innovative method to effectively utilize PCMs in textiles. PCMs have great potential for energy storage and release, but issues like deformation and leakage during phase change have hindered their practical use. The scientists developed a PCM aerogel using the Pickering emulsion templating technique. They used cellulose nanofibrils (CNFs) to stabilize the PCM within the Pickering emulsion, which was then incorporated into a 3D interconnected CNF network, resulting in a composite aerogel made of CNF and PCM. This aerogel exhibited impressive strength, capable of supporting a load over 5000 times its own weight. It also maintained its structural integrity at 80°C, remaining leak-free even after undergoing 20 heating and cooling cycles. The composite aerogel had a latent heat capacity of 173.59 J/g, approximately 84.4% of that of paraffin. Its thermal conductivity ranged from 32.0 to 37.7 mW/m·K, indicating effective thermal insulation [235]. Given its sustainability and impressive thermal regulation properties, the CNF/PCM composite aerogel holds promise for applications in smart textiles. While studies in of FSMPC for smart textiles field may be limited, the potential for enhancing energy management and thermal regulation in wearable technology makes it an exciting avenue for future research and development.

7. Conclusions and Future Recommendations

7.1. Conclusions

This critical review of literature on foam stable phase change material provides a clear understanding of the PCMs according to their different temperature ranges and the type of foams best suited for each PCM category. In addition, the review discusses the emerging applications and the combination of foam along with a particular temperature range PCM. Low-temperature PCMs, such as paraffin wax, have low melting points and commonly used in building insulation and refrigeration due to their stability at low temperature. While they

are effective at low temperatures, they may not suffice for high-heat flux applications requiring higher heat transfer. Medium temperature PCMs such as fatty acids, have higher melting points and can be used in air conditioners and heat exchangers. Their affordability is advantageous, but they often exhibit lower thermal stability compared to high-temperature PCMs. Medium-temperature PCM applications are best suited for carbon foams. Metallic foams may not be suitable for medium-temperature PCM applications due to their relatively high melting points. High-temperature PCMs, such as eutectic alloys, have the highest melting points and favoured for high-temperature PCM application due to their stability and heat transfer efficiency.

In terms of performance, carbon-based polymeric foams are optimal for low-temperature PCMs, while, carbon foams performs better with medium-temperature PCMs. Metallic foams are suitable for high-temperature PCMs. Therefore, several factors are involved in choosing the particular combination of foam and PCM. The choice of PCM depends upon the temperature range of the particular application ensuring it remains undegraded over repetitive thermal cycles. It is worth mentioning that, the selection of the foam should be according to the trade-off between thermal conductivity, thermal stability, the temperature range needed, and cost. Furthermore, the morphological characteristics of the foam, encompassing porosity and pore density, are also crucial during the selection of any particular foam.

7.2.Future Recommendation

Based on the findings of this critical review, the following recommendations for future research can be made:

- *Investigate the impact of different foam densities:* Explore how varying foam densities affect the stability and compatibility of PCMs. Assess the relationship between foam densities, PCM loading capacity, and thermal performance. This investigation will provide valuable insights into the optimal foam density for maximizing PCM stability and heat transfer.
- *Optimize foam geometry and design:* Conduct research on optimizing the geometry and design of foam structures to maximize heat transfer in PCM systems. Explore different pore sizes, shapes, and configurations to improve the thermal performance of foams. This endeavour holds the potential to furnish valuable insights for designing foam structures that enhance heat transfer and increase the overall efficiency of PCM-based thermal energy storage systems.
- *Develop advanced numerical simulation techniques:* Further develop and refine numerical simulation techniques, such as the Lattice Boltzmann method, for accurately

predicting heat transfer in systems using porous foams and PCMs. Explore the potential of machine learning and artificial intelligence algorithms to improve the accuracy and efficiency of simulations. This advancement will enable more precise predictions and better understanding of the thermal performance of PCM systems with porous foams.

- *Exploration of new foam materials:* New foams like aerogel and MXene-based foams have recently been made, showing much promise as thermal insulation materials. More research is needed to find out their potential to be used with PCMs.

By addressing these future recommendations, researchers can advance the field of thermal energy storage using porous foams and phase change materials, leading to improved energy efficiency and sustainable solutions for various applications.

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