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REVIEW ARTICLE

Advances in hybrid phase change materials for thermal energy storage: A systematic review toward sustainable energy systems

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Abstract - Phase Change Materials (PCMs) have excellent energy density and reliable temperature control which enables them to store thermal energy with a prominent efficiency. But, challenges like low thermal stability, phase separation, leakage during phase transition, and low thermal conductivity limit their broader use in thermal energy storage (TES) systems. The development of PCM composites, enabled by integrating PCMs with nanomaterials, mitigates the problem of low thermal conductivity; however, a low thermal stability issue persists. To tackle this issue, the strong tendency of nanoparticles to form robust intermolecular bonds with PCMs is addressed by combining nanoparticles with PCMs. Consequently, review provides a comprehensive analysis of TES and the classification of PCMs, highlighting specific enhancements in thermal and mechanical properties achieved through the use of hybrid and other nanomaterials. These enhancements, including increased thermal conductivity, mechanical robustness, and shape stability, lead to more efficient heat transfer and improved thermal performance in TES systems, thereby addressing thermal stability issues that degrade after multiple thermal cycles. Additionally, the review examines the preparation methods of PCM composites by dispersing various hybrid nanomaterials and bio-derived carbonaceous substances. Authors observed that maximum augmentation in thermal conductivity of a hybrid PCMs is 900 %. Moreover, emerging applications based on the thermos-mechanical properties of the PCMs are comprehensively discussed. At last, the limitations of hybrid particle-dispersed PCM composites are evaluated, along with current challenges and future research prospects.

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1. Introduction

Solar energy is a suitable option for transitioning from fossil fuel-based energy sources, providing an alternative to petroleum, coal, natural gas, and wood [1]. However, large-scale adoption of solar energy is limited by the fundamental mismatch between energy production and consumption, since it is only available during daylight hours. At the same time, no sunlight is available at night [2]. These time-based limitations are needed to advance operational thermal energy storage (TES) technology and ensure a reliable, steady supply to meet demand. Furthermore, TES has emerged as a cost-effective and reliable method for mitigating intermittency in solar energy systems [3]. TES systems are vital for stabilising energy output and balancing supply and demand by storing thermal energy in a solid container with negligible temperature instability [4]. TES technologies are classified into thermochemical, sensible, and latent heat storage. Sensible heat storage requires a temperature difference in a material when heat is present, whereas latent heat storage involves phase transitions that occur at approximately constant temperature [5]. Among all methods, phase change materials (PCMs) have attracted significant interest owing to their isothermal latent-heat storage [6]. During phase changes such as solid-to-liquid, liquid-to-solid, or gaseous-to-solid, thermal energy is either absorbed or released due to changes in molecular structure. PCMs have been considered as functional materials for emerging thermal energy storage applications [7]. Moreover, PCMs are categorised into eutectic, organic, and inorganic types, each with distinct advantages and drawbacks. The inorganic PCMs exhibit a high degree of supercooling, low thermal stability, phase separation, and low thermal conductivity [8], whereas eutectic systems offer only limited relief of these issues. On the other hand, organic PCMs are composed of hydrocarbon compounds that exhibit diverse thermal properties and are typically classified as paraffin or non-paraffin materials [8]. Organic PCMs are well-defined by the C_nH_{2n+2} formula, which consists of mixtures such as heptadecane ($C_{17}H_{36}$), hexadecane ($C_{16}H_{34}$), and n-eicosane ($CH_3(CH_2)_{18}CH_3$), which create suitable melting temperatures and latent heat capacities for low- to medium-temperature range TES applications [9]. PCMs show non-corrosiveness, low supercooling, cost-effectiveness, and chemical stability. But PCMs' wider use is limited by characteristic limitations, such as low thermal conductivity (0.1–0.4 (W/m·K)), leakage problems during phase transitions, and very low volumetric energy storage capacity [10]. PCMs are considered promising candidates for efficient TES due to their high latent heat capacity and isothermal phase-change behaviour. However, their practical application is significantly constrained by inherent drawbacks, including low thermal conductivity and insufficient thermal and mechanical stability during repeated melting and solidification cycles [11].

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In prior studies, Liu et al. [12] developed three types of n-eicosane@TiO_2 microencapsulated PCM composites, such as tubular, octahedral, and spherical, through an emulsion interfacial polycondensation method. The research results confirmed different correlations among microstructure, morphology, and functional performance. Encapsulation efficiencies were 27.1%, 48.9%, and 75.7% for tubular, octahedral, and spherical configurations, respectively, with the spherical structures showing the highest TES and release capacity. Overall, tubular MPCMs exhibit higher thermal conductivity (up to 1.216 W/m·K) and a lower subcooling of 5.2 °C. These MPCMs were developed using tetrabutyl titanate via a sol–gel in situ method with fluorine-ion-induced polymerisation, which showed stable temperature cycling, integrity, effective photocatalytic and antibacterial properties, and robust thermoregulation. Similarly, Liu et al. [13] experimentally developed n-docosane@Fe_3O_4/$CaCO_3$ MPCMs using a non-aqueous emulsion self-assembly method to advance solar photo-thermal energy utilisation. The results of the experimental work demonstrate that the composite achieved a TES capacity of approximately 140 J/g, an encapsulation efficiency of 59%, and a thermal conductivity of 0.795 W/m·K, which is higher than that of the base PCM. Furthermore, the developed composites demonstrated higher thermal reliability and leakage resistance, and a 47.9% improvement in photo-thermal conversion efficiency compared to Fe_3O_4, suggesting improved overall thermal stability. Asadi et al. [14] conducted experimental investigations into the feasibility of integrating microencapsulated PCMs into cement mortar to enhance thermal regulation, while rigorously assessing the resulting mechanical and physical consequences. Mortar combinations were formulated by using cement-sand ratios and varying volumetric fractions of MPCMs, with their renewed and toughened properties being critically measured. The research assessed compressive strength, water absorption, workability, bulk density and thermal conductivity to determine the effect of adding MPCM to mortar. The results demonstrated that adding MPCMs to the mortar increased its TES capacity, thereby enabling current control of temperature changes during the absorption and release of latent heat. But this thermal advantage came at a cost of significant drops in mechanical performance of the mortar.

As the amount of MPCM increased, it reduced the workability, so the water-to-cement ratio had to be increased up to 0.68. This produced a density drop up to 18.3%, and a compressive strength drop up to 46.3 %. Moreover, an X-ray microstructural analysis revealed a more porous internal architecture and an irregular distribution of MPCM. The result highlights the inherent trade-off between thermal efficiency and structural integrity when MPCMs are integrated into cementitious composites, which highlights the need for mix design in functional construction materials. Yang et al. [15] examined the performance of a PCM–based battery thermal management system (PCM-BTMS) for a six-cell lithium-ion battery module under mechanical vibrations similar to those encountered during electric vehicle operation. Their results show that vibrational effects are minor at low discharge rates but become pronounced above a threshold. The mechanical vibration lowered the module's peak temperature by about 2.28 K at 8 C. The research showed that vibration-induced improvement in thermal absorption occurs when a PCM layer is thicker than the thickness, and larger PCM volumes benefit more from vibrational mixing. Increasing the vibration amplitude improved thermal performance up to a point, after which further increases yielded no additional benefit. On the other hand, increased vibration frequency improves heat absorption over a particular range. Hence, the research demonstrates the importance of accounting for vibrational effects in the design of PCM-BTMS and supports their use in lithium-ion battery systems operating at high discharge rates.

Based on the literature, to address the PCM's low thermal conductivity, researchers have investigated the use of nanoparticles in PCMs, which improves heat transfer rates within the PCM matrix during nanoparticle dispersion [16]. Notwithstanding thermal conductivity enhancement, a low thermal stability problem remains a challenge. The addition of single nanoparticles can sometimes result in phase segregation and agglomeration over time [6]. So, to address these issues, researchers have developed hybrid nanoparticles composed of two or more distinct nanoparticle types. The hybrid nanoparticles exhibit stronger intermolecular bonding with PCMs [17]. To improve interaction and advance thermal conductivity, increasing the overall thermal stability, material strength, load-bearing capacity, and durability of the PCM composites. These methods aim to minimise mechanical wear while maintaining thermal performance, providing a comprehensive framework for designing PCM composites for applications that demand both thermal and mechanical performance, including energy storage, electric vehicles, and innovative building materials. This will facilitate future advancements in emerging PCM-integrated applications. These assessments are characterised by examinations of the thermal and mechanical properties of PCMs in innovative TES applications. This type of viewpoint has not been addressed in prior research. Prior research has studied mechanical properties; however, these analyses were often superficial and did not provide any systematic assessment for real-world TES applications. Up-to-date assessments primarily highlight thermal performance, latent heat retention, and energy efficiency. The discussion lacks sufficient information regarding the impact of PCM integration on structural integrity, load-bearing capacity, and long-term material durability in practical applications. This review systematically addresses a research gap by providing a timely and thorough assessment of the thermo-mechanical properties of PCMs and highlights the relationship between their thermal regulation effectiveness and mechanical integrity. This review offers practical insights for designing and optimising PCM composites by correlating material properties with real-world applications, including innovative building materials, BTMS, and advanced TES devices. It emphasises methods to achieve an equilibrium between thermal efficiency and mechanical integrity, which facilitates the reliable and versatile integration of PCM. Hence, the review work offers an in-depth analysis of PCM behaviour under concurrent thermal and mechanical loading, which helps guide future research and innovation in the development of robust, high-performance PCM-integrated applications.

Additionally, the review offers a timely and detailed overview of the classification of hybrid PCMs and nanoparticles, methods for preparing hybrid PCM composites dispersed with nanoparticles, and a thorough assessment of their thermophysical properties [18]. This work stands out from the existing literature by uniquely compiling and comparing different synthesis methods, dispersion techniques, and the mechanical and thermal behaviours of nano-enhanced PCMs. Afterwards, thermal and mechanical properties of the PCMs are discussed in detail. As follows, an emerging thermomechanical application based on PCMs is critically presented. Additionally, the review paper presents well-structured recommendations for future research directions. It highlights potential challenges in TES systems and mechanical properties of PCMs for sustainable energy solutions and several emerging applications.

2. Thermal Energy Storage Technology

A cost-effective way to reduce pollution and greenhouse gas emissions is to enhance energy efficiency. This promotes eco-friendly energy for various applications. Solar applications and building thermal energy conservation are of utmost importance nowadays. As a result, TES reduces expenses and enhances energy efficiency, helping maintain peaceful conditions. Two forms of thermal energy are stored by PCMs, as illustrated in Figure 1. The first is sensible heat, and the second is latent heat. The goal of a technique known as TES [19] is to store thermal energy in materials for later use at different temperatures. A TES system is comprised of three primary components: the heat storage medium, which is responsible for storing energy in the form of latent or sensible heat; the energy transfer mechanism, which is responsible for releasing and absorbing the required quantity of heat; and a control system, which is responsible for providing adequate insulation and is sealed against leaks [20]. The amount of heat transferred into or out of a substance is represented by its sensible heat. When a phase shift occurs at a constant temperature, the term “latent heat is used to describe the quantity of heat absorbed by or released from the substance. This near-isothermal storage technology offers far lower temperature fluctuations and more storage density than conventional storage methods. In addition, latent heat storage can maintain a heat-of-fusion temperature that is either constant or nearly constant, depending on the phase transition temperature (PTT) of the PCM. With the help of TES, storage facilities can make more efficient use of solar energy. Additionally, it eliminates the intermittent nature of solar power, thereby resolving supply-and-demand imbalance [21]. Sensible heat storage occurs when an external heat source alters the temperature of materials such as water, air, concrete, ceramics, sand, brick, bedrock, and cast iron [22]. Solids become liquids during melting and freezing, gases during evaporation and condensation, solids become gases during sublimation and deposition, and solids become liquids again through a change in crystalline structure [23].

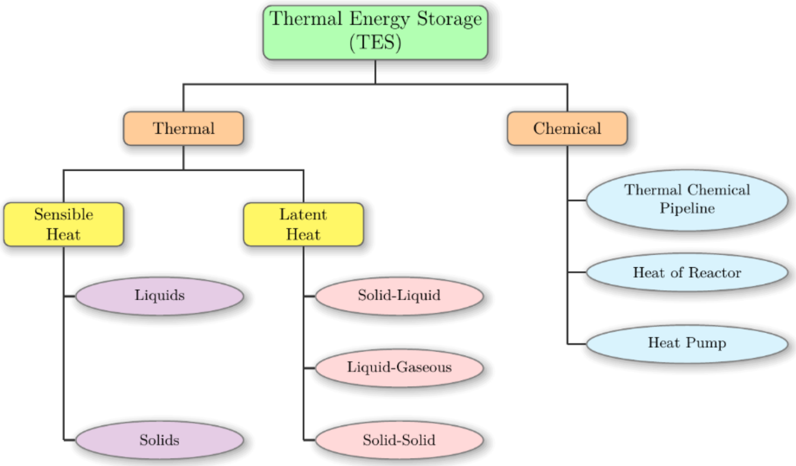

Figure 1. Classification of thermal energy storage

During phase transitions, such as melting and vaporisation, intermolecular bonds are disrupted and re-established. This induces significant alterations in the substance’s internal energy and enthalpy. The microscopic structure of a substance can be altered by harnessing the heat released during a phase transition. The middle-of-the-road heat absorbed by a solid during melting is used to break the bonds between its atoms. A negligible fraction of the heat is converted to work (PdV, where P denotes pressure and dV denotes the volume change). For this reason, the frequency with which chemical bonds are broken correlates strongly with the potential for latent heat release. Due to the significant volume shifts that occur during phase transitions from solid to gas and from liquid to gas, higher latent heat is available during these transitions. This is because closed storage vessels are required during these transitions [24]. Technology for releasing and absorbing heat during an isothermal phase change is well developed in PCM, making it a viable material for TES [25]. They have reached a pivotal development point in the past decade: they can be used in various contexts. The solid-liquid phase transition PCM is the most popular type. As shown in Figure 1, there are numerous essential implications when TES is implemented using PCM. Both domestic and commercial settings extensively use thermal energy to heat their buildings. Observing PCM integration for TES is fascinating, where PCM is filled within a storage system. They transport fluids at high temperatures through the storage system’s pipeline. The high-temperature fluids provide PCM with the thermal energy it needs to undergo a complete phase transition from solid to liquid. During periods of high thermal energy demand, low-temperature fluids are circulated through the storage system, where the PCM releases heat, warming the fluid. A storage system is included with PCM TES to facilitate its integration.

2.1 Classification of Phase Change Materials

Figure 2 categorises PCMs into three main groups according to their arrangement and thermophysical properties. The PCM categories include organic, inorganic, and eutectic PCMs. Organic PCMs contain paraffins, alkanes, and fatty acids, which are known for their chemical stability and even melting points. On the other hand, inorganic PCMs comprise materials such as metals, salts, salt hydrates, and alloys, which have superior thermal conductivity and latent heat storage capacity compared with other PCMs. The last group, eutectic PCMs, comprises mixtures of two or more components that melt and solidify at a specific temperature. EPCMs are further categorised into organic-to-organic, organic-to-inorganic, and inorganic-to-inorganic eutectic PCMs. This arrangement provides a systematic framework for selecting suitable PCMs for emerging TES applications.

2.1.1 Organic phase change materials

Organic PCMs are widely employed for thermal comfort in buildings, solar energy systems, and emerging TES applications due to their superior latent heat storage capacity and suitable melting temperatures. A wide range of chemicals has been examined as organic PCMs, including fatty acids, paraffins, alkanes, and other organic compounds [26]. Nevertheless, these benefits are inhibited by their low thermal conductivity and thermal stability. Hence, to address the aforementioned problems and better align with real thermal energy needs, combinations of two or more organic PCMs with varying phase change temperatures are commonly used. This method enables the modification of latent heat storage properties and transition temperatures. For example, definite organic PCM products derived from long-chain fatty acid esters have displayed better thermal performance [27]. Hence, these materials have demonstrated stable thermal properties after 1000 thermal cycles, signifying noteworthy consistency for low-temperature TES applications. Moreover, commercially available compounds have significant potential as PCMs for low-temperature TES applications, particularly several conventional materials in terms of thermal efficiency. Their beneficial behaviours make them remarkably capable of improving the effectiveness of TES applications [28].

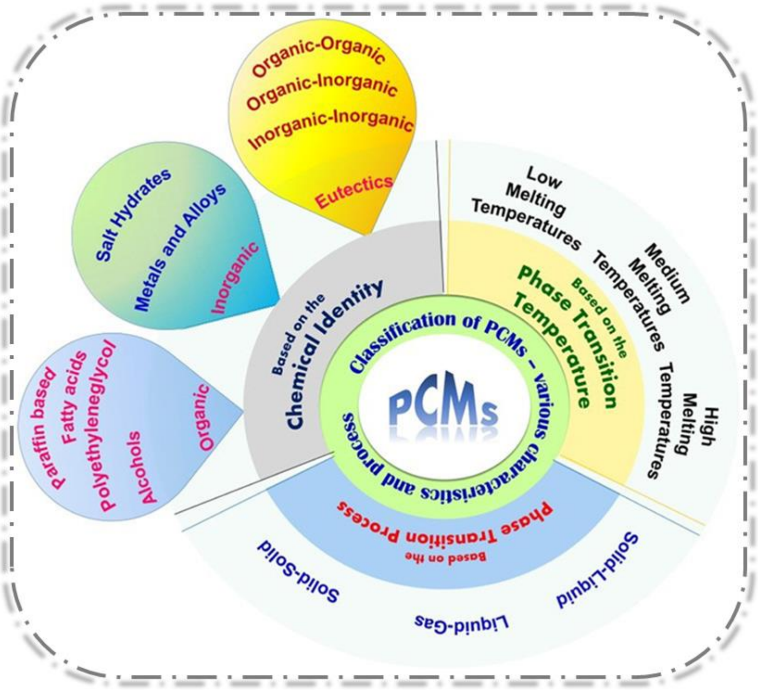

Figure 2. Schematic diagrams of different types of PCMs are based on the chemical identity, various characteristics, and [29]

2.1.2 Inorganic PCM

Inorganic PCMs, including salt hydrates, metals, molten salts, and their alloys, offer noteworthy benefits for TES applications. Also, their volumetric heat storage capacity is approximately twice that of the organic PCMs. Moreover, inorganic PCMs are cost-effective and exhibit improved thermal conductivity and energy storage capabilities. Their ability to operate at high temperatures makes them suitable for elevated-temperature TES applications. Thus, inorganic PCMs are observed as promising options for emerging TES applications [30].

2.1.3 Eutectic phase change materials

Eutectic PCMs were engineered as composite systems consisting of two or more constituent PCMs that recrystallized during solidification into a combined crystalline framework. As mentioned, PCMs like organic, inorganic, or hybrid combinations. Such eutectic or mixed crystalline structures undergo phase transitions without significant segregation of components, thereby ensuring compositional stability across repeated thermal cycles [31]. As a result, the option of phase separation remains insignificant. During melting, the phase transition occurs reliably, with the PCMs undergoing a simultaneous change from solid to liquid.

2.2 Commercialise and Bio-Waste Additives

Nanoparticles measuring 1 to 100 nm have attracted significant attention in recent years due to their diverse practical uses. Further, based on morphology, composition, characteristics, and dimensionality, nanoparticles are approximately categorised. Also, based on composition, metallic, carbon-based, ceramic, and bio-based nanoparticles are further classified. Metallic nanoparticles frequently contain elements like copper, gold, silver, and aluminium, while ceramic nanoparticles are mainly composed of aluminium nitride, which also includes boron nitride. Bio-waste-derived particles are sourced from eco-friendly biomaterials, such as agricultural byproducts and usual waste. From an operational viewpoint, nanoparticles are divided into 0-D, 1-D, 2-D, and 3-D arrangements based on their geometry. Bio-waste-derived particles were synthesised by pyrolysis and facile methods in a tube furnace under an inert gas atmosphere. During heat treatment, the precursor material undergoes dehydration and devolatilization, resulting in a spongy internal structure as gases are released [32]. The rheological characteristics of the resulting biowaste-derived material were familiar, with the dispersion temperature modifiable. Subsequently, the carbonised material undergoes crushing, followed by dry/wet ball milling, to reduce particle size to the desired nanoscale. Characteristic sources of bio-waste particles included lotus shells, coconut shells, bamboo, wheat husk, walnut shells, rice husks, and orange peels. Moreover, Figure 3 shows the arrangement of commercial nanoparticles and bio-waste-derived particles by size.

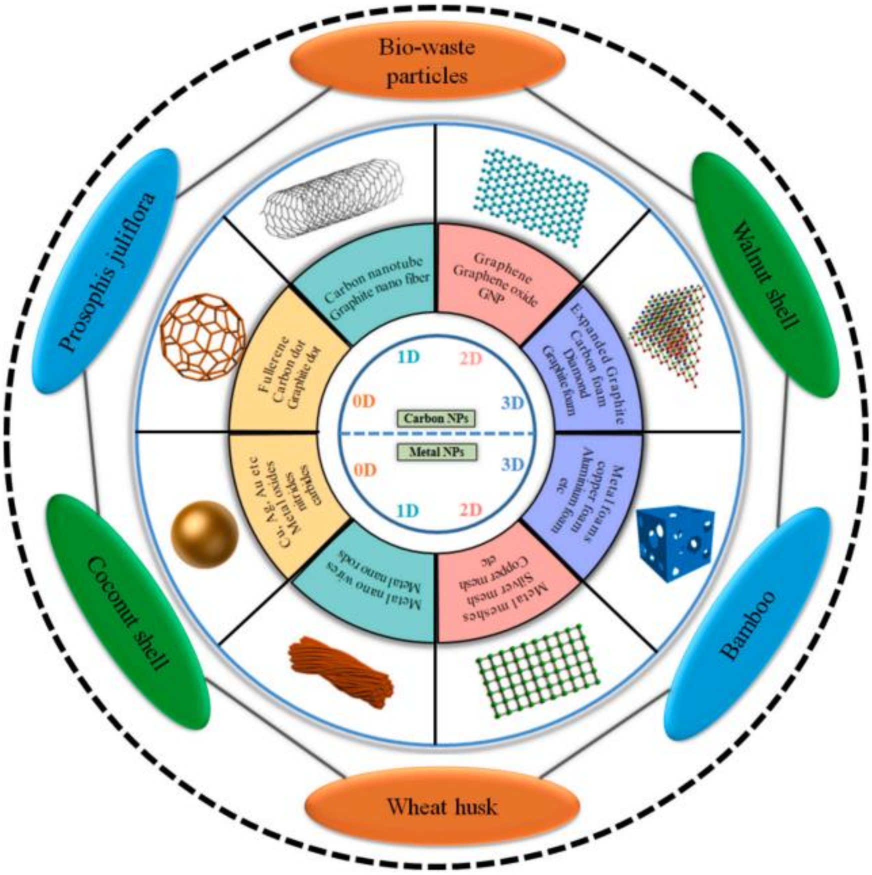

Figure 3. Types of nanoparticles based on the dimensions [33]

2.3 Nano-Enhanced Organic Phase Change Materials

Nano-Enhanced Phase Change Materials (NePCMs) are advanced thermal storage materials comprising conventional PCMs embedded with high-conductivity nanoparticles (e.g., Al_2O_3, SiO_2, CuO, CNTs). These nanoparticles significantly enhance the thermal conductivity, latent heat capacity, and energy storage–release rates of PCMs, enabling their application in thermal management systems, building cooling, and renewable energy storage. NePCMs exhibit reduced thermal stability after repeated phase-change cycles due to intermolecular bonding between the dispersed nanoparticles and the PCM matrix, leading to nanoparticle agglomeration, phase separation, and degradation of thermophysical performance over time. To address the thermal instability of NePCMs, a hybrid nanoparticle mixture comprising two or more nanomaterials (e.g., graphene/Al_2O_3, CNT/SiC) is proposed as a cutting-edge additive. Hybrid nanofillers demonstrate a vital effect by combining the thermal conductivity of one component with the surface compatibility of another. This mixture can improve the dispersion rate within the PCM matrix. Enhanced interfacial bonding and reduced agglomeration in PCM composites improve thermal reliability, latent heat retention, and cyclic durability. This hybrid approach confirms sustained development in thermophysical properties after multiple thermal cycles, making these materials appropriate for efficient, stable TES systems.

2.4 Preparation of Hybrid Particles Dispersed Phase Change Materials

To address the low thermal conductivity and thermal stability issues of O-PCMs, researchers have developed advanced synthesis methods to produce O-PCM composites. An advanced technique aims to improve its practical use in real-world scenarios. This section discusses significant preparation techniques for nanoparticle-dispersed PCM composites. Scientific methods, such as sonication, stirring, vacuum impregnation, and in situ polymerisation, are also discussed in detail based on the suitability of the intended PCM composite. [34] A PCM composite of CuO and TiO2, formulated as hybrid nanoparticles with RT-42 as the base PCM, was experimentally developed. The vacuum infiltration technique was employed to fabricate the PCM composite, as illustrated in Figure 4(a). In this study, the authors analysed the effect of hybrid nanoparticles dispersed in the base PCM on the composite's thermal properties. [35] Conducted an experiment in which the paraffin wax was used as a base PCM with different loading levels (0.5 %, 1 %, and 2 %) of hybrid nanoparticles Al_2O_3 and ZnO. Figure 4(b) shows the ultrasonication methods used to fabricate the PCM composite. The main aim of the current study is to develop hybrid nanoparticle-dispersed PCM composites and check their effects on the thermal properties and performance of photovoltaic-thermal (PVT) systems. Bhutto et al. experimentally developed an h-BN and graphene hybrid nanoparticle-dispersed PCM composite to analyse its effect on the thermophysical properties. Figure 4(c) shows the ultrasonication methods used to fabricate the PCM composite. Additionally, the authors examined the nanoparticle's effect on the composite's chemical stability and thermal reliability after 500 heating-cooling cycles. [36] A study focused on developing a composite material comprising silver-graphene hybrid nanoparticles dispersed in a PCM. An ultrasonication method for fabricating PCM composites is illustrated in Figure 4(d). Furthermore, the authors analysed the thermal properties of the developed composite by incorporating the hybrid nanoparticles. It is also essential to assess the composite's chemical stability and thermal reliability after 500 heating-cooling cycles.

In summary, hybrid composites incorporating nanoparticles dispersed in PCMs have significantly improved thermal conductivity, stability, and overall performance in real-world applications. The research highlights a preparation method, such as vacuum infiltration and ultrasonication, which is tailored to specific combinations of PCMs and nanoparticles. Nassar et al. demonstrated that adding copper oxide (CuO) and titanium dioxide (TiO_2) to the RT-42 PCM via vacuum infiltration significantly improved its thermal properties. Likewise, Kibaria et al. and Bhutto et al. efficiently dispersed hybrid nanoparticles comprising aluminium oxide (Al_2O_3), zinc oxide (ZnO), hexagonal boron nitride (h-BN), and graphene into paraffin wax and other PCMs via ultrasonication. This method improved thermal conductivity, chemical stability, and reliability during thermal cycling. The results show that the efficiency of hybrid nanoparticles in improving the thermal performance of PCM composites supports the development of challenging applications, such as photovoltaic-thermal systems. Ongoing advances across multiple studies confirm that selecting appropriate synthesis techniques and nanoparticle types is essential to exploit the thermophysical properties of PCM composites. These developments open opportunities for broader use of the PCM composites in TES applications.

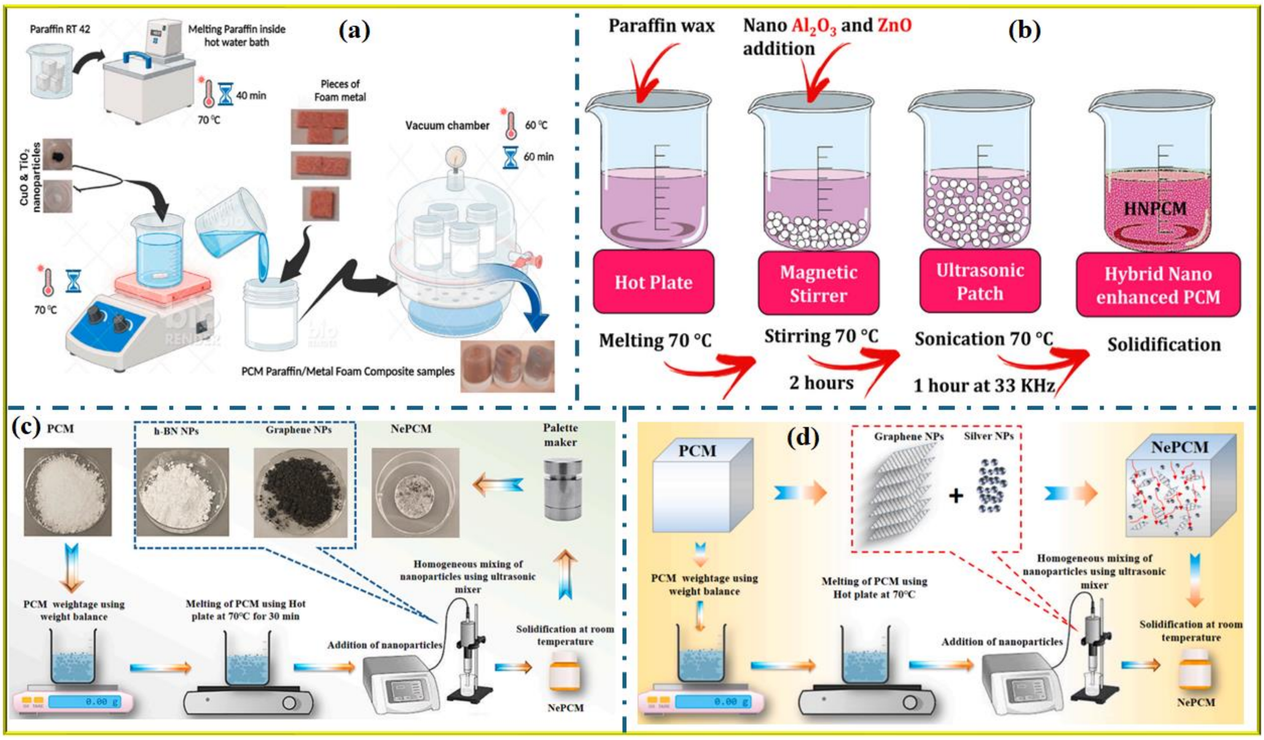

Figure 4. Preparation methods of hybrid nanoparticle-dispersed PCM composites: (a) Vacuum impregnation methods (RT-42/CuO-TiO_2), (b) ultrasonication method (Paraffin/Al_2O_3-ZnO), (c) Sonication method (PCM/h-BN-graphene), and (d) ultrasonication method (PCM/graphene)

2.5 Thermal Properties of Nano-Enhanced Phase Change Materials

Improved overall thermal properties of O-PCMs have been achieved through the nano-enhancement technique. This section discusses research on the thermal properties of nano-enhanced PCMs, providing a proper justification for whether thermal properties have increased or decreased. Some fundamental limitations include latent heat, PCM type, phase-transition point, loading, and filler type. Such parameters play a crucial role in determining the eventual probability of employing NePCM composites in TES systems [37]. A synthesised NePCM (PEG/carbon fibre) was used to determine the thermal conductivity of a composite [38]. A vacuum impregnation method was used to develop NePCM composites. A study found that NePCM had a thermal conductivity of 0.68 W/m·K, which was 223.8% higher than that of pure PEG-PCM. The composite had lower latent heat and melting point than PEG-PCM, at 156.3 J/g and 52.2 °C, respectively. This was primarily due to MWCNT nanoparticles, which are ideal thermally conductive fillers due to their high aspect ratio, large specific surface area, and excellent thermal properties. However, interweaving distributed MWCNTs creates a uniform heat-conduction network, thereby improving the thermal conductivity of the NePCM composite. Likewise, a study [39] experimentally analysed the thermal properties of NePCM by grafting MWCNTs dispersed in Paraffin with organic montmorillonite. Results revealed that the thermal conductivity of NePCM composites (OMMT/Paraffin/MWCNT) was 0.301 W/m·K, 34% higher than that of OMMT/Paraffin, because MWCNT was dispersed in a well-distributed interlayer with Paraffin, thereby increasing the thermal conductive path. Similarly, [40] experimentally developed a binary BPCM composite consisting of n-dodecanoic acid as a base PCM and fly ash (FA) as a supporting material, according to a PCM to FA ratio of 1:1. The result of the research work demonstrated that the thermal conductivity of the PCM composites was 0.172 W/mK and a latent heat capacity of 68.93 J/g. The dispersion of FA recognised a thermally conductive path, dense, advanced heat transfer during charging and discharging processes, by developing well-organised nucleation paths. So, the developed PCM composite's thermal conductivity was improved by 9 %, compared with n-dodecanoic acid PCM. In related work, [41] evaluated thermal properties of a foam-stabilised PCM composite containing eutectic capric acid–palmitic acid (CA–PA) base PCM and delignified wood (DW) as a scaffold thermal properties enhancer. The PCM composite was developed via the vacuum impregnation method. Graphene nanoparticles were dispersed in the CA–PA PCM to enhance its thermal properties. Based on the results, the composite's thermal conductivity increased to 0.49 W/mK at 1 wt.% graphene, which is higher than that of the base PCM (0.21 W/mK).

Additionally, the DW scaffold showed a reduced thermal conductivity of 0.12 W/mK, which confirms the vital role of graphene in enhancing the heat transfer rate within the developed composites. The main reason for the increase in thermal conductivity is that graphene particles create a thermal pathway due to their high thermal conductivity. Additionally, the latent heat of a foam-stable BPCM (94.4 J/g) was improved as compared with base CA-PA (71.8 J/g). The latent heat of the foam-stable BPCM increased because DW has higher phase-change properties than wood. As a result, hydrogen bonds formed between DW and CA-PA, and DW could adsorb CA-PA into its microscale pores. The thermophysical characteristics of BPCM utilising dodecanol as the base PCM and wood flour as a strengthening agent are investigated. The melting and freezing values for BPCM were 27.2 °C and 11.3 °C, respectively. Based on experimentation, [42] examined the thermal performance of BPCM at 1, 3, and 5 wt.% of exfoliated graphite nanoplatelets xGnP & CNT. The investigation focused on enhancing the thermal conductivity and latent heat of a BPCM using xGnP & CNT nanoparticles. According to the experimental results, the maximum thermal conductivity of a BPCM composite was 0.670 W/m·K at 5 wt.%.% xGnP nanoparticles and 0.536 W/m·K at CNT nanoparticles. The xGnP and CNT nanoparticles, with their higher thermal properties, develop well-established thermal pathways. Hence, thermal conductivity improves. In another study, the development, thermal characteristics, and blending of a shape-stabilised PCM composite consisting of modified graphene (GN-16) are reported. The study analysed the effect on the thermophysical properties, including thermal conductivity and latent heat capacity, of dispersing nanoparticles at loadings from 0 to 9 wt.% GN-16 into the base PCM. Results show that the composite achieved a peak thermal conductivity of 1.32 W/m·K at 9 wt.% GN-16, and the maximum latent heat was 103 J/g at 5 wt.% GN-16, suggesting an ideal concentration for TES effectiveness [43]. Moreover, Table 1 provides detailed information on the thermophysical properties of a nanoparticle-dispersed PCM composite.

2.6 Thermal Properties of Hybrid Particles-Enhanced Phase Change Materials

The hybrid nanoparticles have been integrated with the organic PCM to compensate for the low thermal conductivity and enhance the TES management heat transfer rate. Some relevant studies have focused on enhancing the thermophysical properties of PCMs by using hybrid nanoparticles to improve energy storage rates and thermal performance. Some studies have experimentally demonstrated that incorporating hybrid nanoparticles into organic PCMs improves their thermal properties and enhances thermal stability after multiple cycles. [60] Experimentally investigated the thermal properties of a macro MaPCM consisting of RT-65 paraffin as a core material and five different-sized (550–270μm, 270–180μm, 180–150μm, 150–106μm, and <106 μm) dendritic copper powder-sintering frame as a shell material. The vacuum impregnation method was used to fabricate the MaPCM by embedding Paraffin within the copper powder-sintered frame (CPSF). They found that the thermal conductivity and latent heat of MaPCM varied from 17.18 W/mK to 156.30 W/mK and from 32.69 J/g to 11.61 J/g, respectively, as porosity increased from 47% to 74%. The thermal conductivity of the MaPCM increased with increased porosity, as porosity stores more latent heat. [61] A MaPCM was synthesised utilising PEG-SiO2 as the matrix and Cu and Al_2O_3 nanoparticles as the reinforcement. MaPCM was ultrasonicated and evaluated for its thermal properties.

Table 1. Summary of the thermophysical properties of bio-based PCMs via the dispersion of bio-waste and commercialized particles, emphasizing PCM ratio, supporting

LA-SA	Al_2O_3	Ceramsite	Vacuum impregnation	0.2843	133.4	22.5	-	76.25	-35.21	5.63	[44]
CA	DOPO (d)-CNT	RPUF	In-situ polymerization	-	103.2	31.14	-	-	-33.16	2.36	[45]
Paraffin	Al_2O_3	(PMM-MA)	Ultra-sonication	0.3816	75.40	22.96	-	80.85	-56.41	-17.17	[46]
Paraffin	TiO_2	-	Ultra-sonication	0.449	100.24	60.69		65.68	-50.41	-2.049	[47]
n-hexadecanol	Hydroxylated (CNT)	MF	In-situ polymerization	0.3598	155.6	35.6	164	19.85	-34.97	-21.41	[48]
n-dodecanol	GO	MF resin	In-situ polymerization	0.2790	170	35.6	-	115.27	-17.23	64.13	[49]
Nextek 37D	Cement paste	Melamine-formaldehyde	In-situ polymerization	0.44	197.3	36.4	-	-53.26	3.84	-1.62	[50]
PEG-10000	MWCNT	CPC	Vacuum impregnation	0.494	149.4	63.7	230	129	-20.32	-2.0	[51]
PEG-4000	MC_4P_4-MF (MWCNTs)	PPy, MF	In-situ polymerization	-	165.1	62.1	44.4	-	-7.66	3.5	[52]
Nonadecane	Activated carbon	Expanded graphite	Vacuum impregnation	0.84	173.11	29.84	165	100	-25.34	-0.830	[53]
Glutaric acid	-	Expanded graphite	Ultra-sonication	3.10	167	96.5	220	900	-12.15	-3.045	[54]
Beeswax	Bentonite	Graphite	Ultra-sonication	0.78	105.06	57.11	600	271.4	-60.14	-7.288	[55]
Methyl palmitate	expanded waste glass	Carbon nanofibers	Vacuum impregnation	0.51	96.7	26.92	227	112.5	-60.20	-1.715	[56]
Paraffin	-	Polypyrrole	Vacuum impregnation	0.79	72.2	26.1	-	295	-43.37	3.984	[57]
PEG-6000	SiO_2/MWCNT-COOH	-	Sol-gel method	0.48	116.3	58.5-60.5	370	108.7	-45.34	-4.72	[58]
PEG-2000	CNT	GF	Impregnation method	0.665	128.7	50.31	-	118	-26.70	-1.56	[59]

Results demonstrate that MaPCM's latent heat and thermal conductivity were 124 J/g and 0.398 W/m·K, respectively, at a 3.3 % weight concentration of Al_2O_3. At 2.1 wt.% Cu nanoparticles, PEG-SiO_2 exhibited a thermal conductivity of 0.414 W/mK and a latent heat of 112 J/g. This surpasses (PEG)/SiO_2-Al_2O_3 by 38.1 %. MaPCM with Al_2O_3 exhibited superior thermal conductivity compared to CuO due to the enhanced agglomeration of Al_2O_3 nanoparticles. CuO nanoparticles enhance PCM more effectively than Al_2O_3. An experimental study revealed that dispersing mono- and hybrid nanoparticles in PCMs significantly improves their thermal properties. The dispersion of CuO nanoparticles at 0.5 to 2.5 wt.% into paraffin wax-based PCM results in a peak thermal conductivity enhancement of 28.11 % at 2 wt.% concentration. Furthermore, the dispersion of CuO together with graphene nanoplatelets (GnP) produced a noteworthy increase, reaching 150.69% at a GnP loading of 1.5 wt.% due to synergistic effects, as shown in Figure 5(a) [62]. Furthermore, hybrid silver–graphene dispersed PCM composites displayed a 53.8 % improvement in thermal conductivity at 0.8 wt.% loading, accompanied by a negligible reduction in latent heat (3%), signifying an irrelevant interference with phase transition behaviour as illustrated in Figure 5(b) [63]. Another study of eutectic capric–myristic acid PCMs, with a dispersion of Ag–GnP hybrid nanoparticles at 1 wt.%, results in an 18.26% improvement in thermal conductivity and a rise in latent heat from 154 to 158 J/g, thereby confirming improved energy storage with negligible effect on phase transition enthalpy [64]. Moreover, PEG composites contain hexagonal boron nitride (h-BN) and graphene nanoplatelets (GNP) as thermal-property enhancers. Results show that thermal conductivity improved significantly by up to 336% at 30 wt.% h-BN and 1 wt.% GNP, and latent heat reduced by 32 %, and a minor change in melting temperature was observed due to the filler loading [65]. In another study, a lauric acid-based PCM composite with h-BN and multiwalled carbon nanotubes (MWCNTs) showed a 52% enhancement in thermal conductivity at a nanoparticle concentration of 0.8 wt.%, along with a 7% reduction in latent heat (241 J/g compared to 225 J/g for the base PCM). The developed composite retained thermal reliability, with less than a 10% reduction in latent heat after 500 heating and cooling cycles, as shown in Figure 5(c) and Figure 5(d) [66].

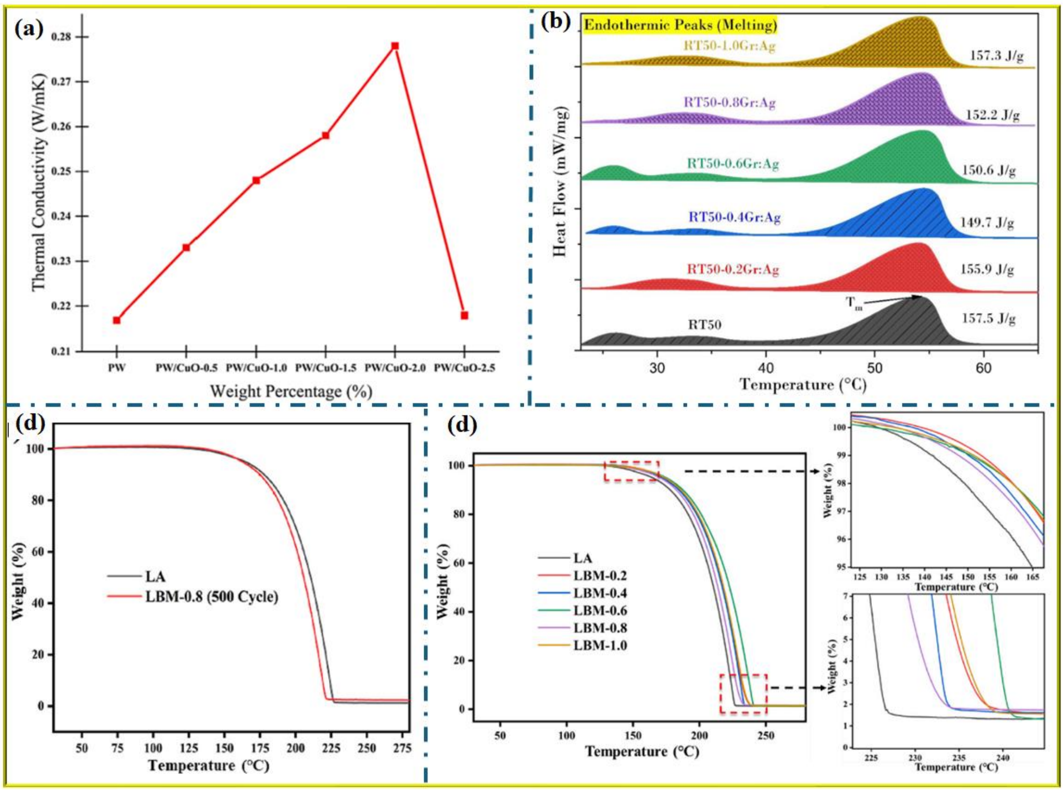

Figure 5. Schematic diagram of the hybrid nanoparticle dispersed composite: (a) thermal conductivity [62], (b) latent heat [63], (c) thermal stability before thermal cycles, and (d) thermal stability after thermal cycles [65]

In summary, incorporating hybrid nanoparticles into organic PCMs significantly enhances their thermophysical properties, thereby improving thermal conductivity and energy storage efficiency. Research shows that adding nanoparticles such as CuO, graphene nanoplatelets (GnP), silver-graphene, and hexagonal boron nitride (h-BN) can increase the thermal conductivity of base PCMs by 18.26% to 336%. These enhancements are critical for optimising TES systems. Moreover, while the thermal conductivity of these nanocomposites is greatly improved, the reduction in latent heat is minimal, typically less than 3%. This means that the phase transition characteristics remain largely intact. Additionally, the remarkable durability of these nanocomposites, even after numerous thermal stress cycles, underscores their suitability for long-term use in TES systems. According to the research, careful selection and application of hybrid nanoparticles can lead to optimised PCM composites that offer high thermal conductivity while maintaining stable latent heat. Consequently, these materials are appropriate for a variety of thermal management applications, including building materials and energy storage systems.

3. Mechanical Properties of Nano-Enhanced Phase Change Materials

Nano-enhanced PCMs integrate latent heat storage with mechanical strength, making NePCMs suitable for load-bearing thermal management components [67]. Researchers' analysis shows that incorporating high-aspect-ratio, high-modulus nanofillers (graphene, carbon nanotubes, and metal oxides) into organic or inorganic PCM matrices enhances thermal conductivity and improves the stiffness and impact resistance of the resulting composites. The nano additives improve interfacial load transfer rate and offer nano-reinforcement. The advantages of PCMs make them more effective as both thermal buffers and structural components in thermo-mechanical applications [68]. The dispersion of nanoparticles, along with hybrid networks comprising metal foams or fibrous scaffolds, reduces thermal gradients during phase transitions, thereby reducing induced stresses and cyclic fatigue in composite assemblies. So, a significant advantage for battery packs, photovoltaic modules and building envelope components subjected to repetitive loading [69]. Further, microencapsulation and shell-reinforcement methods preserve latent heat capacity while restoring the compressive strength and ductility diminished by the incorporation of the base PCM into the supporting matrix [70]. Empirical and modelling studies indicate that optimal nanoparticle loadings and morphology can be modified to improve mechanical integrity while reducing latent heat. The integration of engineered supports, such as foams and fins, improves effective heat transfer without causing mechanical degradation [71]. Together, these enhancements make NePCMs advantageous for various mechanical applications requiring energy storage, dimensional integrity, and thermal cyclical durability [72].

Insufficient research on the enhancement of mechanical properties of PCMs through the dispersion of nano-additives. Gencel et al. [73] experimentally examined PCM-integrated composite concretes by incorporating PCM into highly porous pumice aggregates, followed by the application of a cement slurry coating to mitigate PCM leakage and improve interfacial adhesion within the cementitious matrix. The newly developed composites were assessed using tests of thermal conductivity, ultrasonic pulse velocity, compressive strength, and dynamic thermal regulation, and their performance was evaluated under simulated solar radiation using infrared thermal imaging. Results showed an improvement in thermal stability. When heated, the PCM-based specimens (MAL-2) had surface temperatures approximately 5 °C lower than those of the reference concrete (MAL-K) because the PCM absorbed latent heat. On the other hand, MAL-2 showed long-term temperature deterioration during the cooling phase, maintaining a surface temperature roughly 1 °C above that of MAL-K due to measured latent heat emission. From a mechanical and physical standpoint, the PCM impregnation ratio was accompanied by a decrease in overall sponginess from 13.55% to 7.87%. As a result, compressive strength improved from 12.7 MPa to 16.81 MPa, as represented in Figure 6(a), due to a higher pore volume and advanced interfacial bonding between the total and the cementitious matrix. Figure 6(b) shows that thermal conductivity increased from 0.5706 to 0.7058 W/m·K, while the ultrasonic pulse velocity (UPV) rose from 2.49 to 2.58 km/s, together suggesting a denser, mechanically higher matrix structure. This prior study established that PCM-impregnated pumice aggregates improved thermal regulation and mechanical performance, highlighting their potential as energy-efficient and sustainable construction materials. Mostofinejad et al. [74] experimentally analysed a ground-breaking study on enhancing lightweight concrete with superior thermal and mechanical properties by incorporating PCMs. In their research, PEG-600 and PEG-1000 were incorporated into lightweight expanded clay aggregates (LECA) to harness latent heat storage in warm, humid conditions.

A comprehensive experimental plan was devised to encompass assessments of thermal behaviour, thermal conductivity, water absorption, and mechanical properties, as well as simulated exposure to solar radiation and humidity. The results of the study indicated that increasing the LECA replacement to 75% enhanced water absorption by 119% (as shown in Figure 6(c)). This happened due to LECA's high porosity. Nonetheless, the incorporation of PEG-based PCMs increased to 58 % by occupying pore spaces and restricting capillary ingress. As the replacement level of normal aggregates with LECA increased to 25%, 50%, and 75%, the compressive strength decreased to 35, 33, and 29 MPa, reflecting decreases of 12.5%, 17.5%, and 27.5%, respectively. This underscores the inherent trade-off between reduced density and mechanical performance in LECA-based concrete. Figures 6(d-e) show the inclinations for PEG-600 and PEG-1000 PCMs. The well-known reduction in strength is attributed to the improved porosity of LECA, which compromises interfacial adhesion between aggregates and the cement matrix, thereby diminishing load-bearing capacity. Additionally, thermal conductivity was reduced by up to 63 % with the addition of LECA, followed by a further reduction of around 70 % with the addition of PCM. This is because lightweight aggregates serve as effective insulators, while PEG can retain latent heat. The authors developed a novel thermal conductivity model predicated on the quantity of lightweight aggregate to address the issue of unreliable predictive tools. The thermal conductivity model aligned effectively with experimental data and established design codes, providing a robust foundation for enhancing PCM-based LWC systems. Sheikholeslami et al. [75] experimentally investigated the thermophysical properties of a solar collector combined with a TES unit to advance charging efficiency and thermal stability, as represented in Figure 6(e). The system utilised buoyancy-driven circulation. The radiative heat transfer in the evacuated region near the absorber was simulated using the Surface-to-Surface (S2S) radiation method, which reduced convective losses. A PCM tank was combined into the upper storage unit, and both circular and elliptical versions were observed at various inclination angles. RT31 was selected as a phase-transition material, and its low thermal conductivity was enhanced by incorporating Ag–SiO_2 hybrid nanoparticles at a volume fraction of 0.02. Furthermore, validation of the model against independent experimental data established a robust correlation, confirming the accuracy of the figures. The inclusion of the evacuated zone increased the PCM liquid fraction by 9.17%, as shown in Figure 6(f). This was due to reduced heat loss and enhanced radiative absorption. Hybrid nanoparticles reduced the melting time of a container by 5.46% by enhancing its effective thermal conductivity. The elliptical container inclined at 135 °C showed the fastest melting rate, demanding 6402.7 seconds for wide-ranging dissolution. This happened due to higher natural convection and heat distribution. Incorporating additional porous metal foam into this optimised configuration reduced the melting time by 53.06 % due to enhanced heat transfer area and the inhibition of thermal stratification. The study establishes the combined benefits of geometry optimisation, NEPCM enhancement, and porous media integration for advanced solar TES systems.

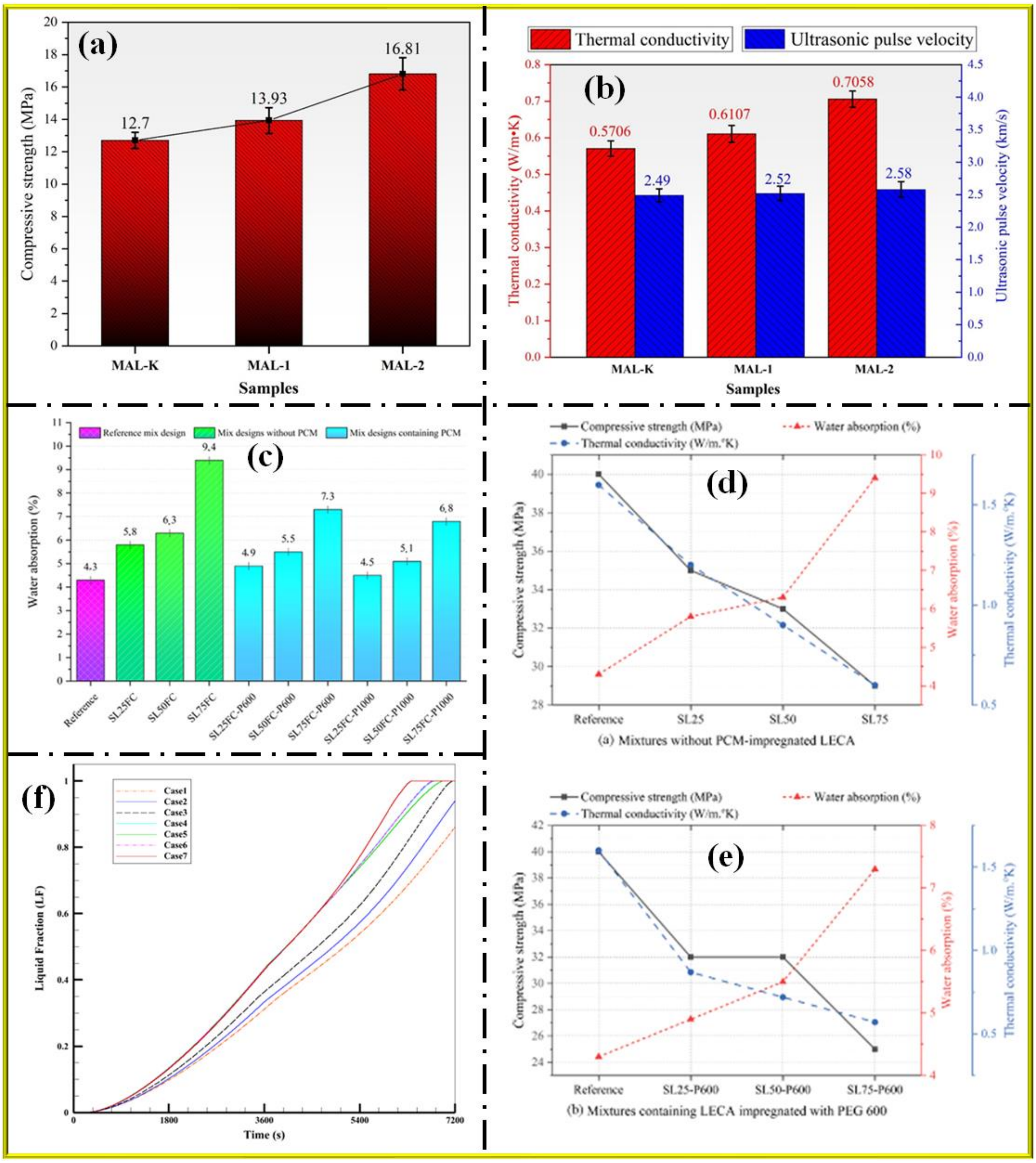

Figure 6. (a) Compressive strength and porosity of pumice aggregates impregnated with PCM. (b) Changes in UPV and thermal conductivity with PCM concentration. (c) How LECA and PEG affect the absorption of water. (d–e) Compressive strength trends for PEG 600 and PEG 1000 mixes. (f) Using evacuated zone and hybrid nanoparticles in a thermosyphon TES system to increase the PCM melting fraction

Moreover, reviewed studies indicate that PCMs can be engineered to enhance thermal regulation and provide effective mechanical performance when carrier systems and structural designs are implemented. The addition of PCM into the highly porous aggregates, such as pumice or LECA, demonstrates that mechanical degradation is not certain. As an alternative, it is significantly affected by pore architecture, interfacial adhesion, and matrix compaction. Pumice-based PCM composites showed reduced porosity, improved compressive strength, and improved ultrasonic pulse velocity, representative of a more robust matrix and improved load-transfer efficiency. On the other hand, LECA-based systems strike a balance between strength and weight reduction. An increased porosity reduced their capacity to withstand pressure, despite significant gains in thermal insulation. Furthermore, numerical examinations of PCM-integrated solar collectors at the system level show that structural improvement techniques, such as nanoparticle reinforcement, optimised geometry, and porous metal foams, improve mechanical stability by reducing thermal gradients. Overall, these findings indicate that the mechanical efficacy of PCM-based systems is influenced by design and can be enhanced to enable enduring, adaptable use in energy-efficient architecture and TES.

4.4 Application of Phase Change Materials Based on The Mechanical and Thermal Properties

PCMs are vital for mechanical engineering subjected to cyclic thermal loading, improving the efficiency, durability, and stability of components [76]. From an engineering viewpoint, PCMs serve as dynamic thermal regulators that interact with structural constraints, stress fields, and heat transfer pathways in mechanical assemblies [77]. During phase transitions, the volumetric expansion and contraction of PCMs produce thermally induced stresses that affect the surface adhesion, encapsulation, and long-term fatigue performance of components that use PCMs. The phase transition kinetics, thermal conductivity, and heat storage density collectively affect system-level performance metrics such as temperature standardisation, thermal response time, and energy efficiency in TES applications, including BTMS, heat exchangers, electronic cooling modules, and building-integrated mechanical systems [78]. Furthermore, the recurrent solid–liquid cycling of PCMs under practical conditions requires a comprehensive assessment of their thermomechanical stability and leakage-proof capabilities, all of which are critical for mechanical design [79]. Incorporating PCMs into engineering components requires a Multiphysics design framework that accounts for solid mechanics, heat transfer, and material degradation. This will confirm that PCM-enhanced systems achieve better thermal performance and structural integrity throughout their operational lifespan, as shown in Figure 7.

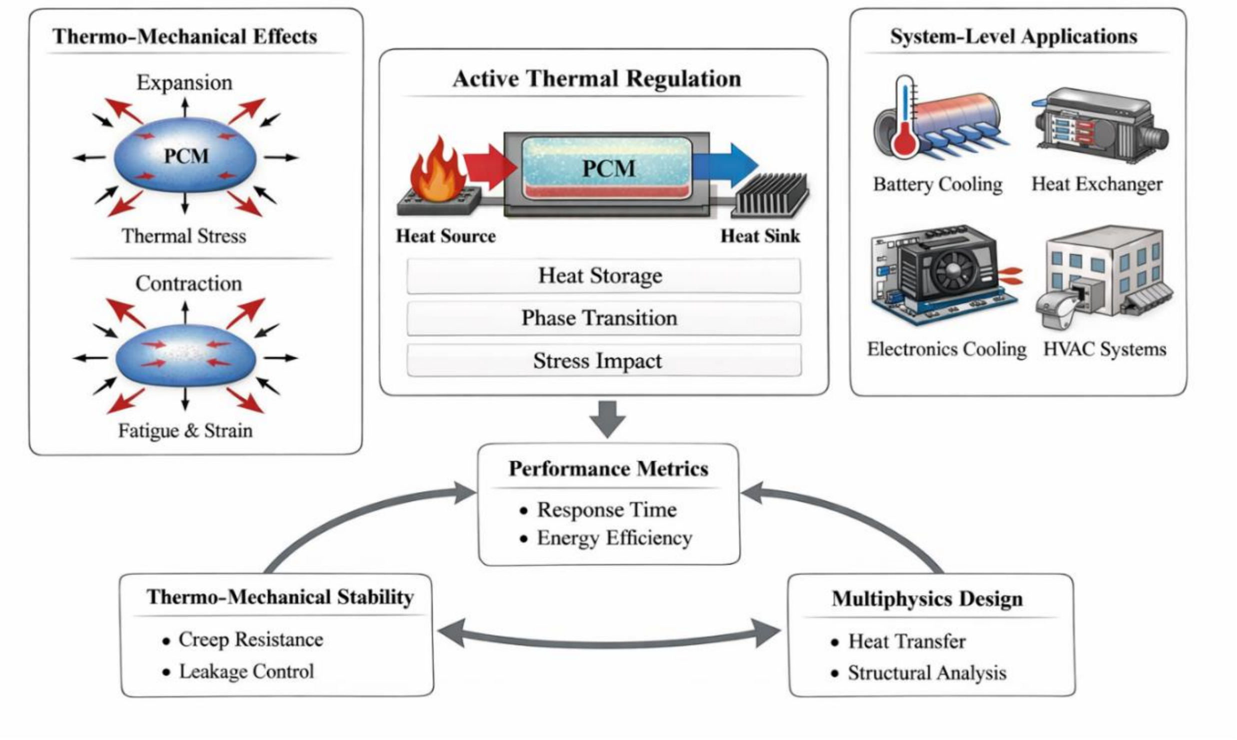

Figure 7. Multiphysics interactions of PCMs show the relationship of thermally induced stresses, heat transfer, phase transition, and structural integrity within mechanical systems

Mostofinejad et al. [80] experimentally study three methods to improve the thermal efficacy of lightweight concrete (LWC) comprising PCMs while justifying the connected reduction in mechanical performance. The research showed a reasonable analysis of three methods for integrating PCM microencapsulation, vacuum impregnation into lightweight expanded clay aggregates (LECA), and distribution within micro silica at diverse LECA replacement ratios, engaging polyethylene glycol (PEG) as the latent heat storage medium, as shown in Figure 8(a). A general experimental framework was advanced that integrates conventional mechanical and thermal assessments with simulations of solar irradiation and humidity to reproduce humid operational conditions. The experimental results demonstrated that PCM impregnation into LECA yielded the ideal overall performance. It retained 82.5% of its compressive strength due to superior PCM containment within the porous combined structure. It achieved a 55% reduction in thermal conductivity through more effective use of latent heat and improved thermal resistance, as shown in Figure 8(b). The rise in water absorption was only 4.7 %, which is negligible. This is due to a PCM being excellently encapsulated within the LECA pores. On the other hand, the dispersion of PCM in micro silica provides optimal thermal insulation. Yet a 62.5% reduction in compressive strength results from matrix cracking and reduced load-transfer effectiveness. Microencapsulation exhibited intermediate performance, yielding moderate insulation improvements while preserving stability at an adequate level. The research work identified the factors influencing fluctuations in thermal performance, which can inform the design of structurally robust and thermally adaptive PCM–LWC systems for building applications. Zhao et al. [81] presented a bioinspired method for developing multilevel carbon-based porous frameworks to mitigate PCM leakage and enhance thermal conductivity while maintaining sustainability and cost-effectiveness, as shown in Figure 8(c). SiC ceramic frameworks were synthesised using residue apple-derived carbon (CNA) as a biological template to replicate and enhance the essential hierarchical microstructure; however, the inherent limitation of extreme porosity (80 %) limits improvements in thermal conductivity. The authors demonstrated that interfacial effects influence the heat transfer rate in porous composite PCMs through computational modelling and experimental validation.

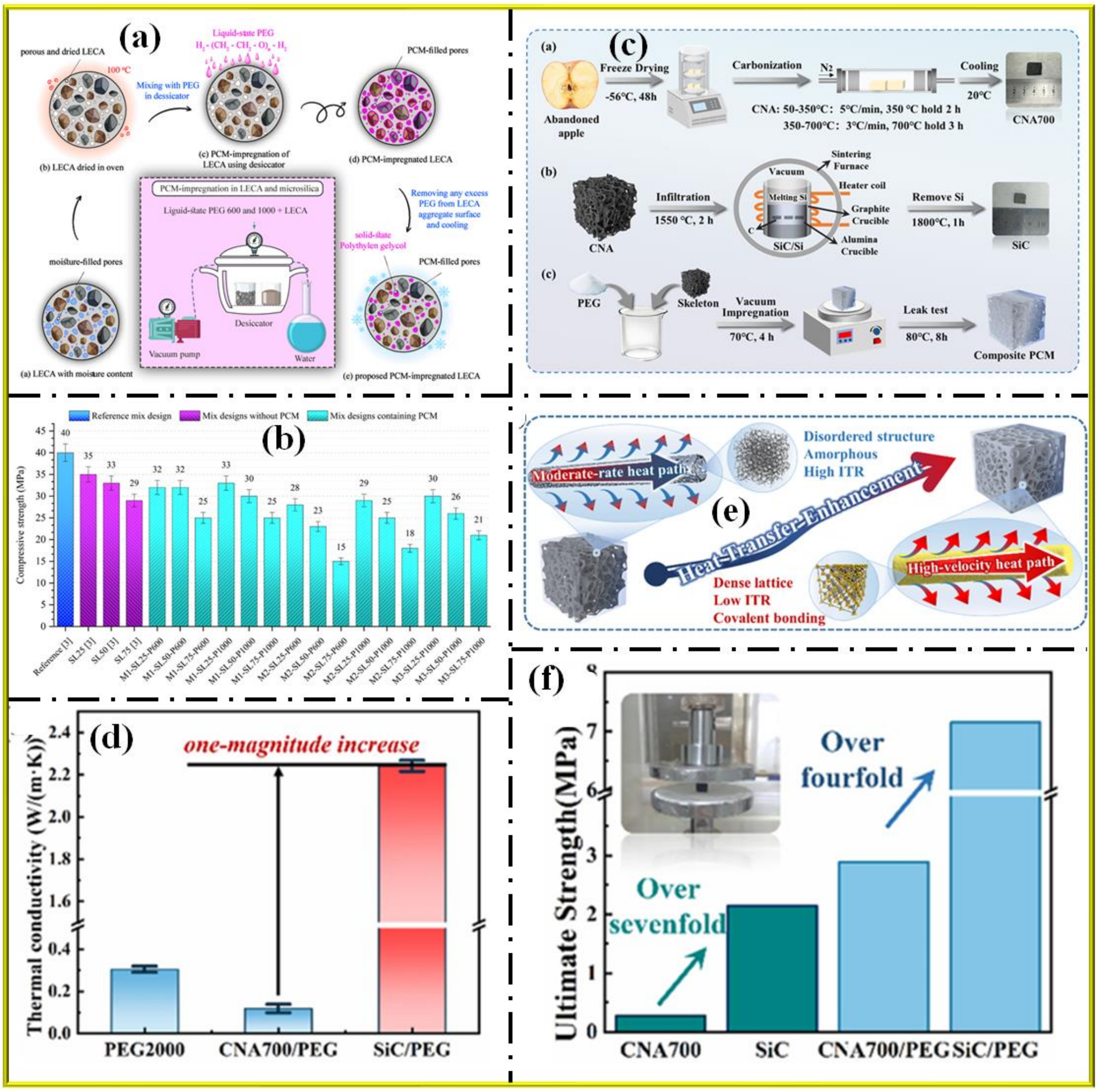

Figure 8. (a) Methods for integrating PCM into LWC with PEG at several LECA ratios. The mechanical and thermal properties of PCM–LECA composite concrete. (c) Developing a SiC porous framework was achieved using standard strategies. Improved thermal conductivity and storage capacity of SiC/PEG. (e) An efficiency of a PCM composite in the heat transfer rate. An assessment of the compressive strength of frameworks developed from CNA and SiC

The robust C–Si covalent bonds, arranged in SiC grains, facilitated thermal conductivity across the interface and enhanced mechanical interlocking. The following are the major reasons for the enhancement in thermal performance. The SiC/PEG composite showed a 13 % increase in PEG encapsulation, increased thermal conductivity of 2.242 W/(m·K), and a 10% enhancement in thermal storage density, as represented in Figure 8(d). This represents a noteworthy improvement as compared with base PEG. Figure 8(e) represents the thermal transfer capabilities of the developed PCM composite. The compressive strengths of SiC and SiC/PEG were evaluated at 2.13 MPa and 7.15 MPa, respectively, which are about 7 times and 4 times greater than those of CNA700 and CNA700/PEG (0.27 MPa and 1.35 MPa), as shown in Fig. 8(f). This remarkable enhancement results from the high-temperature melting of silicon. At the interfaces of the carbon template and silicon particles, partial fusion results in a diamond-like β-SiC crystalline structure composed of alternating carbon and silicon atoms, as shown in Figure 9(a). The strong covalent C–Si bonds ease load transfer and improve resistance to compression. CNA700/PEG is appropriate for lightweight structures, while SiC/PEG is suitable for difficult aerospace and automotive applications. Interfacial wetting assessments, as shown in Figure 9(b), demonstrated that PEG readily infiltrated both structures shown in Figure 9(c-d), with more rapid penetration into carbon due to elevated interaction energy, as shown in Figure 9(e), and its oxygen-rich surface chemistry. The composites demonstrated excellent solar absorption and photothermal conversion (Figure 9(f-g)), achieving 92% efficiency, thermal regulation exceeding

1750 seconds (Figure 9(h)), and consistent cycling performance (Figure 9(i)). This indicates their technical robustness and scalability.

Jahangiri et al. [82] conducted research on integrating PCMs with thermoelectric generators (TEGs) as a feasible approach to waste heat management, aiming to mitigate the intrinsic limitations of TEGs due to inadequate heat transfer rates and insufficient temperature changes. Further, two systematic configurations of PCM–TEG were studied: (i) PCM located between two concentric copper tubes, and (ii) PCM limited within an inner copper tube, as shown in Figure 10(a–b). An experimental design based on Taguchi methodology was conducted to estimate the effects of key effective parameters, including air temperature, air velocity, PCM type, PCM mass, and the number of thermoelectric generator (TEG) modules. The experimental results showed that the arrangement with PCM between the copper tubes produced the highest electrical power output. This enhanced convective heat transfer and maintained the temperature differential across the TEGs. In this configuration, incorporating an additional TEG unit enhanced power generation. On the other hand, when the PCM was confined to the smaller tube, the system's performance showed improved sensitivity to outdoor air temperature and velocity. This showed that heat exchange was constrained and the thermal driving force was diminished. The noted performance improvement was attributable to improved thermal regulation and reduced heat dissipation by the PCM. On the other hand, the deterioration in thermal performance was attributable to airflow condensation and reduced heat-transfer effectiveness.

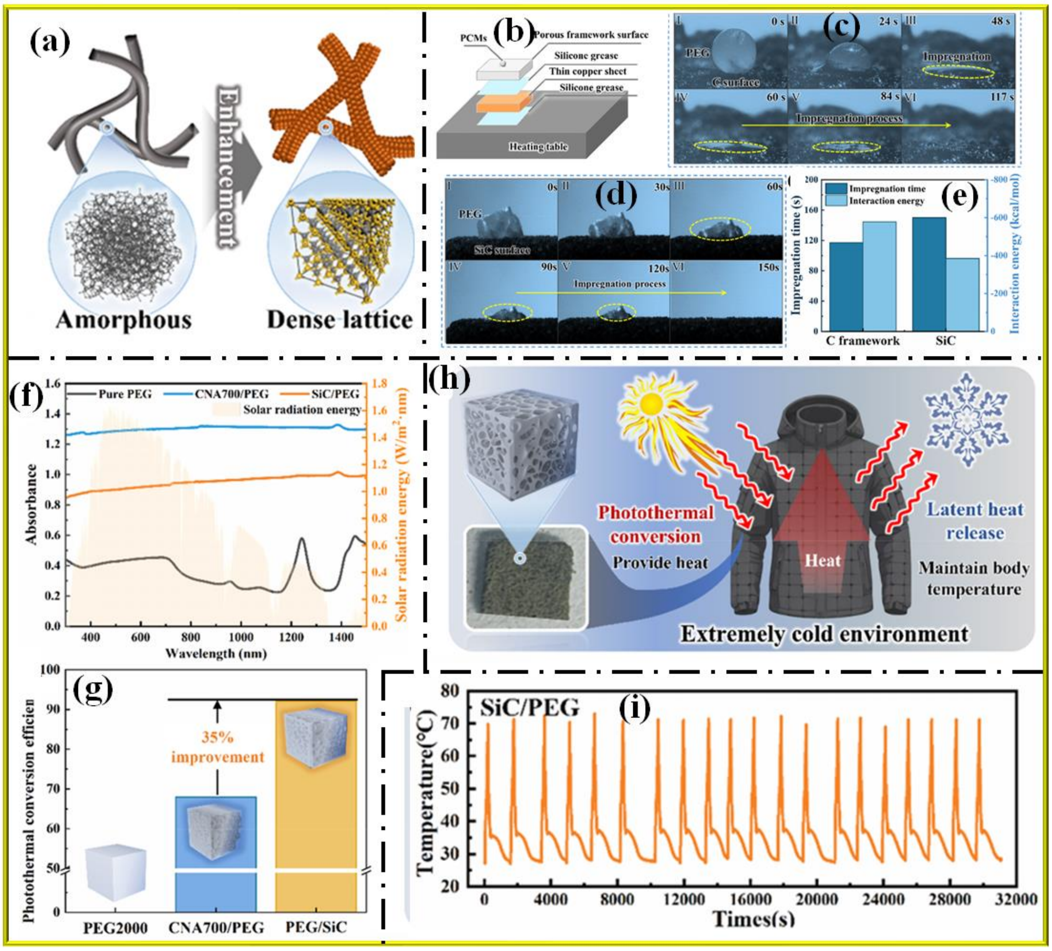

Figure 9. Representation of a development of β-SiC at carbon-silicon boundaries using high-temperature fusion. (b) A mechanism by which PEG wets the surface. PEG integrated in carbon and SiC matrices (c–d). Investigation interaction energy. Absorption of solar energy and its conversion to thermal energy. Period of thermal regulation

This study delivers a serious insight for enhancing the PCM-TEG composite for well-organized waste heat recovery applications. Rana et al. [83] demonstrated a novel fins-enhanced PCM-based BTMS to moderate warmness in lithium-ion batteries used in electric vehicles which operates under high-temperature conditions as shown in Figure 10(c). The research documented the low thermal conductivity of conventional PCMs as a significant limitation. It incorporated metallic fins within the PCM domain to improve heat transfer and improve heat extraction from the battery surface. Both experimental measurements and numerical simulations presented that the proposed passive BTMS kept the battery temperature within the optimal functioning range. The fins-enhanced PCM system concentrated the maximum average temperature by 6 % relative to base PCM cooling and by 20.53 % related to fin-only cooling at a 3C discharge rate, as shown in Figure 10(d). This was mainly due to a synergistic effect of improved conductive heat transfer rate and latent heat absorption. Furthermore, parametric investigations indicated that the system provides suitable thermal regulation, even at a high discharge rate of 5 °C. Increasing the intercellular distance increased the maximum average temperature through reduced thermal exchange between cells. However, the system is less costly. The PCM’s melting temperature was recognized as a noteworthy factor. Optimal thermal performance was observed when the melting point exceeded the board battery management temperature by about 3 °C, especially when external temperatures remained below 35 °C.

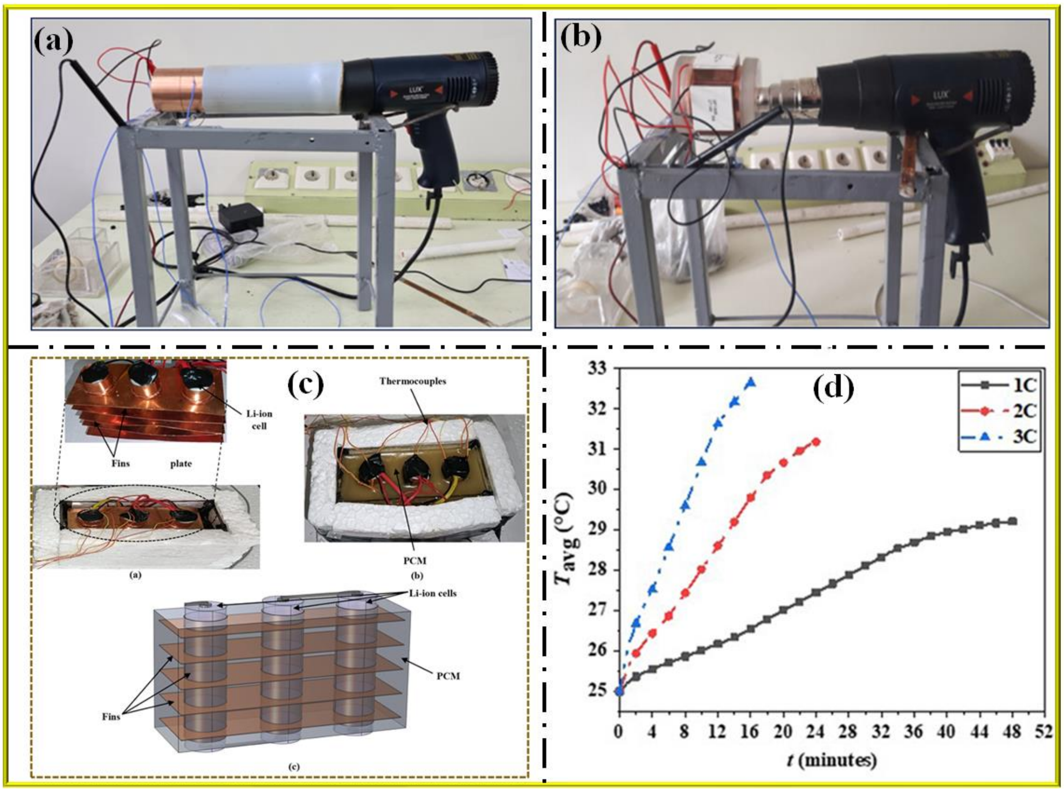

Figure 10. (a–b) An experimental PCM–TEG arrangement with PCM between two concentric copper tubes and an inner copper tube for waste heat collection. BTMS diagram with fins to advance PCM. (d) Thermal performance comparison presentation of cooling approaches to reduce the peak battery temperature

The present review reports that PCMs have advanced from simple thermal bumpers to integral components of numerous systems, where their thermal and mechanical properties enhance the thermal performance of engineering systems. PCMs proficiently control temperature by storing latent heat. PCMs influence interfacial stability, structural integrity, and cyclic durability. Further, PCMs are employed in several applications, including BTMS, waste heat recovery, and energy-efficient construction materials. Thermal enhancement techniques, such as fins, porous structures, and optimised encapsulation, reliably advance heat transfer, temperature uniformity, and energy efficiency. On the other hand, mechanical performance is determined by interfacial effectiveness, interfacial bonding, and microstructural continuity. The study specifies that poorly integrated PCM can negotiate and rigidify structures, whereas well-designed architectures can improve compressive strength, leakage resistance, and thermomechanical stability concurrently. Together, these findings establish the need for a synergistic thermomechanical design approach, in which the choice of PCMs, geometry, and encapsulation is optimised to ensure the dependable and effective performance of next-generation energy and mechanical systems under various thermal cycling and mechanical loading conditions.

5. Conclusions

This review highlights the role of hybrid nanoparticles, which, due to their cooperative effects and diverse functionalities, improve thermal conductivity and strong intermolecular interactions within the PCM matrix. These relations improved thermal stability, reduced supercooling, and enhanced latent heat retention across several thermal cycles. The dispersion of bio-waste-derived particles with hybrid nanostructures offers an eco-friendly and sustainable approach to enhancing the thermal and mechanical properties of PCM composites. An in-depth investigation of synthesis techniques, dispersion methods, and the characterisation of progressive PCM composites requires significant advances in thermophysical properties. Challenges such as nanoparticle agglomeration, scalability, economic viability, and long-term durability remain uncertain. Consequently, future research should focus on forward-looking, eco-friendly, scalable fabrication techniques, enhancing nanoparticle surface functionalization to improve dispersion stability, and conducting comprehensive thermal cycling investigations to enable the practical application of hybrid nanomaterial-enhanced PCM in next-generation thermal energy storage systems for renewable and sustainable energy applications.

Future recommendation

a) Future research should focus on identifying optimal concentration and ratio groupings for hybrid nanoparticles to improve thermal conductivity while preserving latent heat capacity.

b) Extended thermal cycling tests with more than 500 heating and cooling cycles are optional to assess the long-term durability, thermal degradation, and phase stability of nanocomposite phase change materials under representative operational conditions.
c) Further research should examine innovative dispersion techniques, such as surface functionalization or in-situ synthesis, to improve nanoparticle distribution uniformity, reduce agglomeration, and optimise thermal performance.
d) Future research should tailor the use of hybrid nanoparticle-enhanced phase change materials for emerging TES applications, photovoltaic-thermal systems, building envelopes, and electronic cooling, and evaluate their effectiveness across diverse environmental and operational conditions.
e) Future research should focus on advanced encapsulation methodologies, nano-reinforced PCM composites, and integrated thermomechanical models to support design decisions in mechanical engineering applications.
f) Prior to system integration, future research should define the energy balance, heat-transfer pathways, and charging and discharging kinetics to establish a clear coupling framework between solar thermal input and PCM storage.

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Conflict of Interests

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

Authors’ Contribution

G. Navindran: Methodology, Conceptualisation; Writing – original draft,
Aman Yadav: Writing – revise & review; Conceptualisation;
M. Samykano: Validation, Supervision, Funding acquisition, Conceptualisation, Writing – review & editing
M. M. Rahman: Analysis; Writing – revise & review; Funding acquisition.
A. K. Amirruddin: Writing – review & editing, Supervision, Conceptualisation

Availability of Data and Materials

Data will be made available on request.

Ethics Statement

This is the review manuscript did not involve any human participants or animals. SO, an ethical approval was therefore not required.

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Nomenclature

Phase change materials	PCMs	One-dimensional	1D
Phase transition temperature	PTT	Two-dimensional	2D
Thermal energy storage	TES	Polyethylene glycol	PEG
Battery thermal management system	BTMS	Lightweight concrete	LWC
Organic phase change materials	O-PCMs	Lightweight expanded clay aggregates	LECA
Nano-Enhanced Phase Change Materials	NEPCMs	Thermoelectric generator	TEG
Photovoltaic-thermal	PVT	Bio-based phase change materials	BPCMs
Multiwalled carbon nanotubes	MWCNTs	Phase change materials	PCMs
Fly ash	FA	Phase transition temperature	PTT
Delignified wood	DW	Thermal energy storage	TES
Thermal conductivity	K (W/m·K)	Battery thermal management system	BTMS
Latent heat	LH (J/g)	Organic phase change materials	O-PCMs
Melting point	Tm (˚C)	Nano-Enhanced Phase Change Materials	NEPCMs
Graphene nanoplatelets	GNP		