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Enhancing the Thermal Performance of Air-Conditioning Systems Using Phase Change Materials: A Comprehensive Review

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Abstract: With the use of conventional vapor-compression heating, ventilation, and air conditioning (HVAC) systems, the air-conditioning system electrically consumes most of the electricity for the building, particularly due to peak electrical demand and greenhouse gas emissions associated with air-conditioning systems. This review describes how using thermo-responsive phase change materials (PCM) can help to enhance the thermal performance of air-conditioning (AC), as well as reduce energy consumption. The types of PCM characterised include: organic, inorganic, and composite/eutectic materials; the importance of the characteristics (phase change temperature, heat of fusion, thermal conductivity, cycling stability, and HVAC compatibility) of PCM to any HVAC application is discussed with a particular emphasis on the methods of improving heat transfer and controlling leakages through the use of nano-enhanced and encapsulated composites. Additionally, this paper covers the three strategies of integrating PCM within an AC system, PCM-enhanced heat exchangers; PCM-based thermal energy storage (TES) devices; and PCM-embedded building materials. The results from experimental, field, and numerical studies indicate that PCM integration in AC systems can substantially reduce indoor temperature fluctuations (up to 46%), reduce heating/cooling loads (up to 31%), improves the coefficient of performance (COP) for air-conditioning by 7-88%, shift as much as 89% of the cooling load to off-peak times and produce annual cooling-energy savings of 7-32% - depending on the specific climate and/or configuration types and controls. The thermophysical enhancement techniques (nanoparticle additives, porous supports/metal foams, encapsulation) have been summarized in this review along with significant reductions in CO_2 emissions e.g. in operational terms due to life cycle studies of these techniques but the payback times are dependent on weather and costs. This paper has evaluated the major technical barriers (long term stability, supercooling, phase separation, flammability and corrosion), manufacturing & scalability issues and integration with existing infrastructure along with the various economic and market barriers. Finally, we have identified emerging opportunities for the PCM -enhanced cooling systems, such as solid to solid PCMs, bio-based PCMs, multi-functional nano-composites, advanced control or optimisation (including AI-based) and coupling with renewable energy systems, and highlighted a number of research gaps that must be closed for the large scale and cost-effective deployment of PCM-enhanced cooling to be realized

Keywords: Air conditioning system; Phase change materials; thermal energy storge; PCM

1. Introduction

Heating, ventilation, and air conditioning (HVAC) systems are typically designed to provide enough capacity to meet the highest cooling requirement for occupancy during the hottest day of the year. This highest cooling requirement occurs when the highest solar radiation, the greatest amount of heat produced inside the building and the lowest outside temperature coincide (i.e., peak load). Because peak loads are two to three times higher than average cooling loads, HVAC systems are typically oversized and therefore inefficient due to the majority of their annual operating time being spent at low capacity conditions and

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having high energy use due to the lowest efficiency of vapor-compression systems occurs at partial-load conditions [1], [2].

The use of electricity produced by combusting fossil fuels to operate large, energy-consuming buildings and related systems; most buildings in the world are very large in size (and some buildings have air conditioning) . The significant and growing utilization of air-conditioned buildings will further exacerbate the strain on our electrical infrastructure during peak demand periods (usually occurring at the same time as a hurricane, weather-related event) due to population growth and additional development in tropical and subtropical areas [1], [2], [3], [4]. Reducing or decoupling the timing of peak demands for cooling (i.e., cooling loads) from the installed cooling capacity will therefore have significant impact on improving the energy efficiency of buildings as a source of greenhouse gas emissions, while at the same time, improving the stability of the electricity grid.

To accomplish a reduction in the amount of electricity a building uses for purposes of air conditioning, improve the thermal efficiency of the air conditioning system itself and the way that the system uses energy are both possible strategies for achieving this goal. Along with the use of more efficient refrigerants, hybrid systems, and controls that use intelligent technology, the development of thermal energy storage (TES) systems represent a very effective way to shift and reduce AC load risks [1], [3], [5].

Thermo-responsive phase change materials (PCMs) can release and absorb an exceptionally large amount of thermal energy due to their ability to undergo reversible phase changes (typically solid-liquid) at nearly constant temperatures. High latent heat of fusion and adequate transition temperature are the criteria for selecting PCMs used for thermal energy storage (TES) [6], [7], [8]. Most PCMs are classified into three categories based on their chemical composition (organic, inorganic, and eutectic/composite). The most important properties of PCMs used for heating, ventilation, air conditioning (HVAC), etc. include phase transition temperature, latent heat capacity, thermal conductivity, cycling stability, subcooling behaviour, compatibility with containers, and cost [5], [6], [7], [8], [9]. Generally, organic PCMs exhibit good stability, low corrosion potential but poor thermal conductivity. Inorganic PCMs are capable of storing more thermal energy by volume but can separate and corrode. Advanced composite PCMs and form-stable PCMs have been developed to overcome issues with leakage, low thermal conductivity, and mechanical performance limitations [10], [11], [12], [13], [14]. PCMs can also buffer temperature changes and decouple the time that cooling is produced from when it is used. PCMs have been successfully used for thermal management in many different applications such as buildings, HVAC systems, electronic devices, batteries, solar energy systems, textiles, etc. In buildings for cooling and air conditioning, PCMs can be utilized, for example, within walls, ceiling panels, ducts, dedicated TES tank systems, and hybrid air conditioning configurations to lower peak energy needs, improve indoor climate stability, and increase overall system efficiency [3], [5], [12], [15].

Many of the pertinent literature is limited to phase-change materials (PCM) for thermal energy storage or in building systems [5], [6], [9], [12], [15]. Reviews typically focus solely on the use of one type of PCM (i.e., either organic or inorganic) to analyze performance metrics related to heating and cooling, without considering all three types of integration (i.e., using enhanced heat exchangers, using thermal energy storage units, or embedding PCM in building materials). Furthermore, some of the literature was published prior to rapid developments occurring since 2020 that included nano-enhanced composites and AI-supported control systems. The current review article addresses these issues by evaluating the three types of PCM (organic, inorganic, eutectic/composite) in one context, comparing on an equal basis all three types of integration methods for air conditioning systems, and summarizing the quantitative information on the impact of PCM on the COP, annual energy savings, peak cooling load reduction, and load shifting, using data from experimental, theoretical, and field studies covering a time frame from 2013-2025. The review is intended to serve as an authoritative source of information for HVAC engineers interested in this technology.

The purpose of this review is to identify how the thermal characteristics of air conditioning equipment can be improved through the integration of phase change materials (PCMs). The following objectives have been established to guide the direction of this review:

1. Classifying and critically comparing the three main types of PCM (organic, inorganic, and eutectic/composite) in terms of the thermophysical properties, enhancement methods for their

performance, and the suitability of the different PCMs for HVAC applications.

2. Reviewing and evaluating the three main ways to integrate PCMs into air conditioning systems: PCM-enhanced heat exchangers, PCM-based thermal energy storage (TES) units, and PCM-embedded building materials.
3. Providing a quantitative synthesis of documented impacts of the above-mentioned use of PCMs in terms of energy consumption, coefficient of performance (COP), peak cooling load reduction, load-shifting capability, and comfort in indoor temperature; and drawing data from experimental, numerical, and field studies to do this.
4. Identifying the major factors (technical, economic, and environmental) that could limit the widespread use of PCMs and highlighting emerging research opportunities to address the issues that must be resolved to allow large-scale, cost-effective use of PCMs.

2. Methodology

2.1 Search strategy

The following academic databases were consulted during a systematic search process, in order of relevancy: Scopus, Web of Science, ScienceDirect, IEEE, and Google Scholar (this last resource also helped identify any recent publications and grey literature). The following keyword combinations were included in the search: (1) phase-change material AND air conditioning; (2) PCM AND HVAC; (3) PCM AND thermal energy storage; (4) phase-change material AND heat exchanger; (5) PCM AND building envelope; (6) PCM AND coefficient of performance; (7) nano-enhanced PCM AND cooling; and (8) phase-change material AND energy savings. The search span began with the year 2013 and ran through 2025; however, equal emphasis is given to research published from 2019 or newer. The focus of the literature review is based on current trends in research related to advances in nano-enhanced materials; bio-based PCMs; ai-assisted control systems.

2.2 Inclusion and exclusion criteria

The studies included were: (i) published in peer-reviewed journals or conference with peer-review; (ii) addressed the use of frozen water within heating, ventilation, and air conditioning (HVAC), pipes, and building thermal management; (iii) provided findings on lab tests, computer simulations, or complete reviews with numeric results; and (iv) written in English. Excluded were: (i) studies that only used frozen water for non-HVAC reasons (e.g., photovoltaic systems only (ps), only isolators (white), and those using frozen water to pack food (not pack food, i.e. only pack food); (ii) non-peer-reviewed documents (thesis, technical reports without peer assume, and conference abstracts without access to full document(s); and (iii) documents that are duplicates (the same study previously captured from another database).

2.3 Study Selection Process

The screening procedure was conducted utilising a four-phase PRISMA-type protocol for evaluation, which is outlined in Fig. 1. The first step involved identifying roughly 620 total references in all databases combined. The second step involved removing approximately 180 duplicates from these records. This left 440 unique reference documents. The next step involved screening all title/abstract documents before review. At this point, approximately 218 were excluded based on being non-HVAC-related and/or not being peer-reviewed. Subsequently, 222 of the 440 documents were reviewed using the full text of each document. From this review process, 56 documents were excluded based on the reasons provided. These included no quantitative thermal performance data; not having a direct/indirect heating/cooling relationship to PCM; and/or being a conference abstract without an associated full-text document (n = 56). The final result of the screening process was a total of 166 studies that were used as the primary evidence supporting this systematic review. Each reason for rejection was documented for greater transparency and reproducibly.

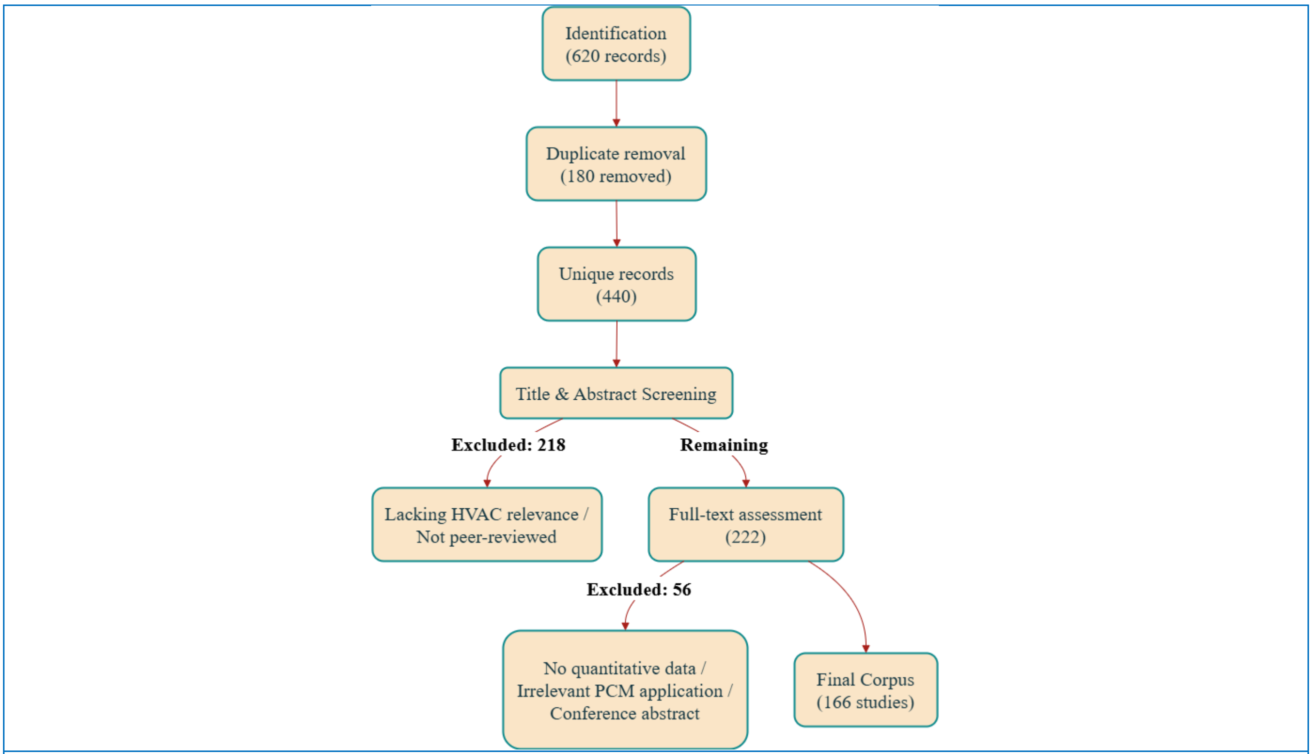


Fig. 1. PRISMA-style flowchart of the literature search and study selection process.

3. Phase change materials in air-conditioning systems

Climate control equipment has recently begun incorporating phase-change materials (PCM) as a means of providing energy storage for "cold" and smoothing out the cooling load in buildings. PCMs can be designed to create more comfortable, efficient, and manage peak heating and cooling loads through material selection, melting temperature, and configuration.

3.1 Types of PCMs used in air-conditioning

3.1.1 Organic PCMs

Organic phase change materials (PCMs) such as fatty acids and paraffins have become more prominent in thermal energy storage applications at low and medium temperatures due to their melting points being close to room or working temperature, their ability to store significant quantities of latent heat, and their high level of chemical stability.

i. Paraffin Phase Change Materials (PCMs)

Paraffin based phase change materials (PCMs) are perhaps the most common thermal energy storage media available today owing to the fact that they provide a very high latent heat of fusion, they are chemically stable/inert, they are non-corrosive, and they can be tailored for use in applications such as increasing the energy efficiency of buildings, cooling electronics and providing thermal storage for solar thermal systems by having the melting point adjust to different temperature ranges depending on the application [16], [17], [18], [19]. Paraffin PCMs, despite their beneficial thermophysical properties, have a few disadvantages, the main ones being low thermal conductivity and the potential for leakage from their containment vessels during the change from solid to liquid. Recent developments in the use of nanomaterial additives, encapsulation methods, and composite formulations using porous substrates or a metal foam have focused on overcoming these limitations and improving the thermal conductivity, cycling stability, and shape stability of paraffin PCMs. Overall, these recent developments have considerably expanded the variety of potential applications for paraffin PCMs that can help provide a more sustainable energy future [20], [21], [22], [23], [24], [25].

Fig. 2 shows a side-by-side comparison of measured latent heat values and measured thermal conductivities for several types of paraffin PCM from the previous studies. It can be interpreted that using DSC data for latent heats measured at melting points, one group of bars represents the latent heat of each material (in J/g) and the other group represents each material's thermal conductivity (in W/m·K) prior to enhancement efforts. Each bar is also referenced to a prior citation [16], [17], [20], [26]. The bar height represents the midpoint of the values within the respective reported range while the bars of error represent a full range of the reported measure. The effective conductivity produced from the use of nanoparticles added to neat paraffin (which has the highest latent heat of 150–250 J/g) improves upon the thermal conductivity of paraffin by 0.25–0.40 W/m·K, and the effective conductivity obtained by using an open-pored material (e.g., copper foam or expanded graphite) achieves the highest effective conductivity with a reduction in the latent heat required [16], [17], [20], [21], [23], [24], [25], [26], [27], [28], [29]. See Table 1.

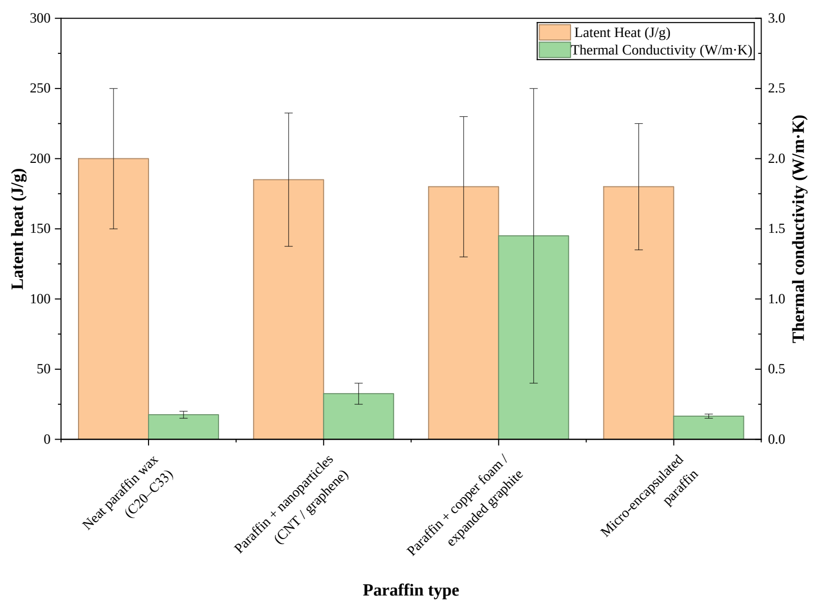


Fig. 2. Latent Heat and Thermal Conductivity Data of Paraffin-Based PCMs. Data compiled from previ ously published literature sources [16], [17], [20], [26].

Table 1: Paraffin PCMs: Latent Heat and Thermal Conductivity

Paraffin type	**Latent heat MIN (J/g)**	**Latent heat MAX (J/g)**	**Latent heat USE (midpoint)**	**Thermal conductivity MIN (W/m·K)**	**Thermal conductivity MAX (W/m·K)**	**Ref.**
Neat paraffin wax (C20–C33)	150	250	200	0.15	0.20	[16], [17], [26]
Paraffin + nanoparticles (CNT / graphene)	140	235	185	0.25	0.40	[17], [21], [23], [24]
Paraffin + copper foam / expanded graphite	130	230	180	0.40	2.50*	[20], [21], [23]
Micro-encapsulated paraffin	135	225	180	0.15	0.18	[25], [27], [28], [29]

a. Thermophysical Properties of Paraffin PCMs

Phase change materials from paraffin exhibit between 20 and 70 ˚C melting points, with associated latent heat values between 150-250 kilojoules per kilogram (kJ/kg). Paraffins retain very good cycling stability (up to 3000 times) and also generally maintain good chemical compatibility with standard encapsulation products. However, paraffins show relatively low thermal conductivity (on the order of 0.15-0.20 (W/m·K)), limiting heat transfer rates [16], [17], [19].

b. Enhancement Techniques

- ***Nanoparticle Additive Materials:*** Adding graphene nano-platelets, silica nano-particles (SiO_2), carbon nanotubes (CNT), and copper oxide CuO/magnesium oxide MgO/aluminum oxide Al_2O_3 nanoparticles to a base wire can yield a 50% or more increase in thermal conductivity, but not significantly (by 0.1) upon the addition of a base material [17], [24], [30], [31].
- ***Porous supports and metal foams:*** When paraffin is embedded in a copper foam or expanded graphite matrix, the resulting phase change material can significantly reduce melting/solidifying time, approximately 40%, and improve uniformity of heat transfer [21], [23], [32].
- ***Encapsulation:*** Micro/nano-encapsulation of paraffin using a silica shell, or other polymer matrix, substantially reduces the risk of leakage of the PCM during melting. Micro/nano-encapsulation improves durability of the PCM during repeated cycling, with reported encapsulation efficiencies of ~90% [25], [27], [28], [29].

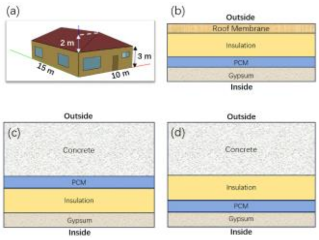
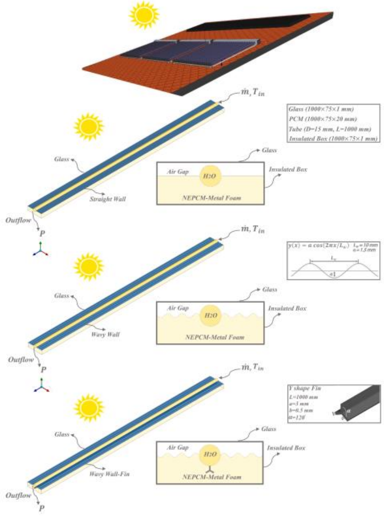
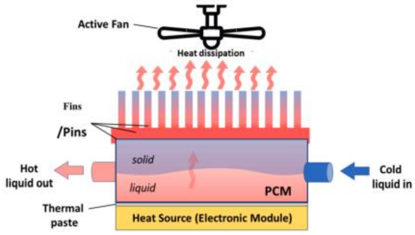
c. Applications

The applications of paraffin are listed in Table 2.

Table 2: The applications of paraffin

Applications	Building Energy Efficiency	Solar Thermal and Waste Heat Recovery	Electronics and Life Sciences
Idea	Walls and roof areas where energy-consuming devices are built-in can lower the annual consumption of energy by as much as 22% from the amount typically consumed and can reduce fluctuations in indoor temperatures by 2 to 3 degrees Celsius [26], [33].	Paraffin phase change materials (PCMs) can be found in solar collectors, as well as in systems designed to collect and utilize industrial waste heat for the effective use of latent heat [34], [35], [36] .	PCMs have the potential to be used for passive electronic/battery cooling, and for maintaining temperature in pharmaceuticals during transport, due to their biocompatibility and consistent performance characteristics [18], [37].

Table 2: The applications of paraffin

Applications	Building Energy Efficiency	Solar Thermal and Waste Heat Recovery	Electronics and Life Sciences
examples	 Walls and roof areas where energy-consuming devices [38]	 Solar Thermal and Waste Heat Re covery [35]	 Electronics and Life Sciences [37]

Research shows paraffin-based PCMs are useful for storing energy in the form of heat at medium temperatures; they have very high amounts of energy stored per unit and cycle well between solid and liquid states [16], [17]. By using some kind of enhancement techniques, especially nanomaterials (i.e., graphene, carbon nano-tubes, metal oxides), porous support structures (i.e., expanded graphite and foil) and encapsulation techniques such as capsules, the main drawbacks associated with these materials have been addressed (i.e., low thermal conductivities and high potential for leakage), thus providing advantages for improved charging and discharging speed and reliability for many different applications, including buildings, solar systems, electronic cooling, and life sciences [20], [21]. In addition to these advantages, there are tradeoffs in using fillers to improve thermal conductivity and thermal stability they may have a small negative impact on latent heat capacity and/or cost; fire resistance is still a concern for building applications [26], [37], [38]. When comparing bio-PcMs to paraffin-based PCM materials, even though paraffin-based PCM materials may offer greater long-term stability compared to fatty-based PCM materials (e.g., fatty acids/waxes), paraffin will always have a greater environmental impact as it is derived from oil, the selection process of PCM material should take application-specific factors such as cost efficiency, sustainability, and operational performance into consideration [39], [40]. The claim and evidence are shown in Table 3.

Table 3: Claims and Evidence Table

Claim	**Evidence Strength**	**Reasoning**
High latent heat storage from stable cycle latent heat storage in paraffin-based phase change materials [16], [17].	Strong	Highly reproducible enthalpy results from multiple studies show that there are no detectable changes in repeated performance (>1000 times).
Significant improvement of conductivity through the addition of nanosized/micro/nano-composites [20], [22], [23].	Strong	Fullerenes, as well as CNTs and metallic foams, provide a greater than 40% increase in thermal conductivity. This results in decreased times to melt and solidify.

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Table 3: Claims and Evidence Table

Claim	Evidence Strength	Reasoning
Encapsulation reduces leakage and increases durability [25], [27], [29].	Strong	Silica polymer shells demonstrate a greater than 80% successful encapsulation rate that can withstand more than 100 cycles without degradation.
Provides Major Energy Cost Savings [26], [38].	Moderate	Simulations and experiments indicate that HVAC demand can be reduced by 22% annually.
Risk of fire/mechanical weakness limits some applications [39].	Moderate	Organic polymers have an increased potential for fires, and if designed as composites, they may weaken the support structure of the host material.
Sustainability Issues with Petroleum vs Biobased (i.e., concerns) PCM's [40].	Moderate	Lifecycle assessment (LCA) studies indicate that the carbon footprint of organic polymers are significantly highe r than those of either plant or animal sources.

ii. *Fatty Acids, Esters, and Other Bio-Based PCMs*

Bio-based phase change materials (PCMs) that include fatty acids, esters, vegetable oils, and biopolymers have emerged as viable replacement options for petroleum-based PCMs (such as paraffin wax) to store thermal energy in buildings, textiles, electronic devices and many other industries. High latent heat, tunable melting temperatures (usually between 15 °C and 70 °C), stability against chemical degradation, non-toxicity, and biodegradability are all characteristics of fatty acids and their esters that make them attractive candidates for use as sustainable materials in both PCMs and biodegradable plastics [41], [42], [43]. Similarly, vegetable oils and their derivatives are used extensively as renewable resources for producing both PCMs and biodegradable plastics. Some recent improvements in this area include eutectic mixtures with tailored melting ranges; nano-composites with enhanced thermal conductivity; and methods of encapsulating PCMs to minimize leakage of PCM from structure. The recurrence of PCM structural integrity is largely due to the fragmentation of PCM after its solid-to-liquid transition. When the PCM becomes liquid and leaks from the host structure (or containment vessel) through a failure of the encapsulation/micro confinement/form-stabilization process or through insufficient encapsulation [25], [27], [28], [29]. While there have been some improvements made in these materials since their original development, there are still a number of issues that have to be addressed including cost, oxidation resistance, flammability, and scale-up issues [44], [45], [46]. This article summarizes the most recent research related to the properties, performance improvements, potential uses, and sustainability of bio-based PCMs (specifically those using either fatty acids or fatty acid esters) and other bio-based PCMs.

a. Thermophysical Properties and Chemistry

- ***Fatty Acids:*** The range of melting points is typically 23 to 78 °C with latent heats ranging between 100 and 300 J/g. They are also non-toxic, non-corrosive, biocompatible, and have low vapour pressure/supercooling [42], [47].
- ***Esters:*** Fatty acid methyl/pentyl/decyl esters exhibit high enthalpy of fusion (up to 225 J/g), have low levels of supercooling (less than 2 ˚C), and chemical stability for more than 1000 cycles [41], [48].
- ***Triglycerides, Oils, Fats:*** Triglycerides from animal and vegetable sources exhibit favorable thermophysical characteristics; however, if they have not been properly formulated, they can tend to polymorphism/supercooling/ineffective encapsulation [49].
- ***Biopolymers:*** The primary purpose for using these materials is to act as matrices or frameworks for encapsulation to prevent leaking and improve the mechanical properties of the encapsulate [50], [51].

b. Enhancement Strategies

Researchers have developed three main approaches to improve the thermal capability and structural continuity of Phase Change Materials (PCMs), as shown in Fig.3. These include eutectic mixtures, nano-additives, and encapsulation/form-stabilization methods. Eutectic mixtures consist of combining different types of fatty acids or esters so that their melting points can be sufficiently tailored to meet the application range (e.g., the eutectic of capric and myristic acid at approximately 20–25°C) while having a high latent heat storage capacity [44], [47]. Another way to enhance the low thermal conductivity of organic PCMs is to mix in nano-additives (primarily carbon-based materials) such as graphene nanoplatelets, carbon nanotubes (CNTs), or exfoliated graphite to potentially increase heat transfer rates up to 400% through the PCM; nano-additives work by creating a layer of contact between the PCM and the conductive nano-additive, thereby allowing for more heat transfer through the material. The third alternative used to combat PCM leakage during the liquid phase and to establish long-term cycling stability is through encapsulation and form-stabilization techniques. These techniques are employed by enclosing the PCM in a biopolymer shell (e.g., alginate), inorganic support such as fly ash, or porous carbon structure to allow for the PCM to move between phases while maintaining the structural integrity of the surrounding system [52], [53], [54], [55].

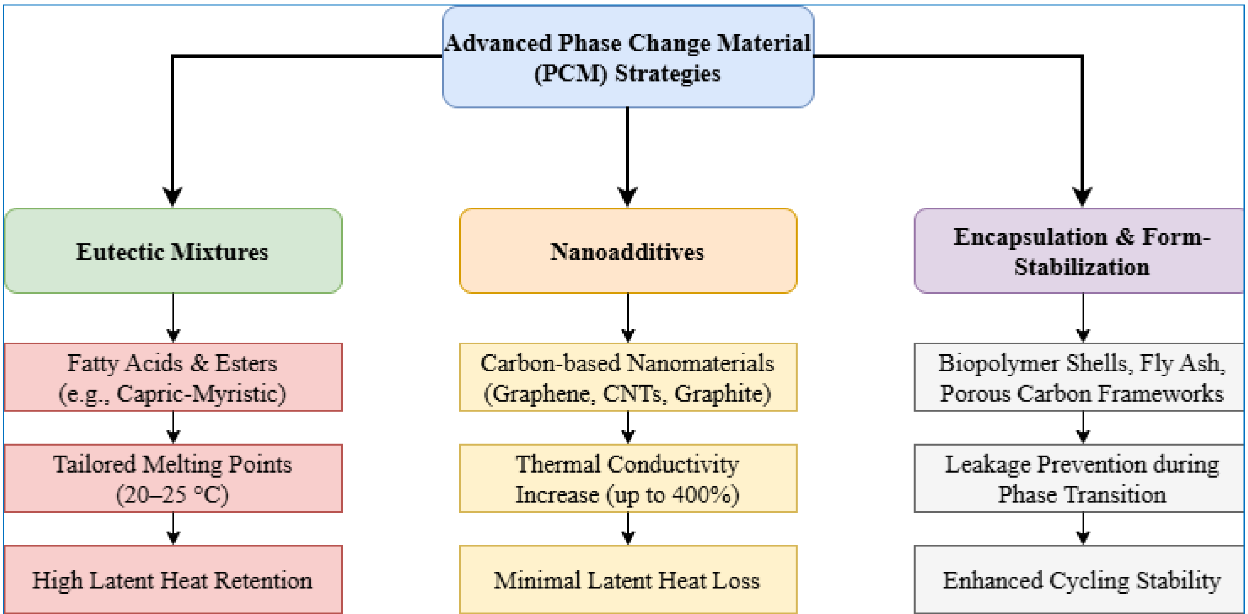

Fig. 3. The enhancement methods for phase change materials based on bio-materials: a: using eutectic mixtures for modification of the melting point, b: using carbon nano-additive materials to improve thermal conductivity, and c: encapsulation and other form stabilisation processes to prevent leakage. Adapted from reviewed literature [44], [47], [52], [53], [54], [55].

c. Applications

The enhanced properties of PCMs make them suitable for use as passive thermal regulators across various industries. See Table 4.

Table 4. The applications of Fatty Acids, Esters, and Other Bio-Based PCMs

Applications	Idea
Buildings	Integrating PCMs into roofs/walls can decrease yearly heating/cooling demands approximately 25%, while reducing the variation in temperature indoors by approximately 2-4 degrees Celsius [52].
Electronics and Batteries	Battery/electronic cooling systems utilizing bio-PCMs that possess high heat transfer competence can achieve peak temperature reduction of 10-15 °C [56].

Food Packaging and Textiles	Used in the cold chain logistics sector or smart textile production due to the biocompatibility of PCMs, as well as the ability to attain a stable phase change around 28-33 °C [56].
Polymers and Bio-Lubricants	Fatty acid esters can be used either as plasticizers or base oils for biodegradable polymers/lubricants, exhibiting superior viscosity indices at low temperatures [57].

In general, experimental evidence supports bio-based fatty acid esters as viable and environmentally superior PCMs over a fairly wide range of low to moderate temperatures; they have been shown to work in buildings, textiles, de-icing applications, for cooling beverages and for cooling batteries. The remaining work to be done is related to improving these materials for use in long-term applications, increasing the materials' conductivity, and scaling up production. Table 5, shows the major claims about organic PCM performance and limits.

Table 5. The Claims and Evidence: Organic Phase Change Materials (O-PCMs)

The claims	The evidence	Reasoning
There are many organic PCMs which have a high latent heat for wide and variable temperature ranges. They demonstrate effective performance as thermal energy storage media.	Strong	It has been reported that latent heat typically has a 5 to 10 times' higher density than thermal energy supplied by sensible storage. It has also been indicated that paraffins, fatty acids, polyols, Polyethylene glycol (PEG) and similar categories of materials have a useful melting temperature between approximately −5 °C to 190 °C, which make them suitable for both low and medium-temperature thermal energy storage applications [58], [59], [60].
The two biggest challenges with organic PCMs are their low thermal conductivity and their leakage; however, these issues can often be avoided via composite or encasing the PCM.	Strong	Numerous reviews have cited low thermal conductivity and liquid loss from melting as the major problems associated with the use of these materials, as well as the potential solutions that utilize macro/micro-encapsulation, shaped stabilized, porous supporting materials and carbon found in fillers to enhance thermal conductivity (up to about 10 times), while reducing liquid loss after melting [61], [62], [63].
Using organic PCMs that are ecofriendly and those derived or from waste can greatly increase the sustainability of PCMs but are not always going to be carbon positive throughout their life cycle vs. petroleum-derived paraffins.	Moderate	Bio-based, or natural, PCMs derived from fatty acids (primarily), oils (plant/animal) and waxes (primarily) are renewable and frequently biodegradable. A review has stated that bio-based PCMs intended for use as the primary source of thermal energy have an embodied emission that is at least equal, or sometimes less than, traditional paraffins. However, it has also been noted that bio-based PCMs from secondary or waste sources will result in a significant reduction in carbon during their life cycle [61], [64].
Organic PCMs have already proven to be effective for building construction, textiles, and electronics,	Strong	Studies of buildings have shown reduced energy required to condition space as a result of the proper size and placement of PCMs within buildings. Studies involving

Table 5. The Claims and Evidence: Organic Phase Change Materials (O-PCMs)

The claims	The evidence	Reasoning
but the real world application will greatly depend on how well they are designed with the entire system.		textiles and electronic cooling have demonstrated increased thermal comfort for people, and electronic components that utilize PCMs; however, all have documented durability issues, mechanical degradation of the matrix and high manufacturing costs associated [9], [64].
One of the largest safety concerns with organic PCMs is their flammable nature; therefore, we must put an intense focus on developing flame retardants for these products.	Strong	Most organic PCMs (e.g., paraffins, fatty acids, polymers) are combustible. An in-depth review of PCMs examined the availability of a broad range of non-halogenated flame retardant additives, char-forming additives and hybrid flame retardant systems, developed to increase limiting oxygen indices (LOIs) and reducing heat and smoke generated when combusted [9], [65].

3.1.2 Inorganic PCMs

Inorganic phase change materials (PCMs) have emerged as a key focus in thermal energy storage because they have a high latent heat storage capacity, large phase change temperature range, non-flammable nature, and are much more economical than organic PCMs [66], [67], [68], [69] . Hydrated salts (e.g., salt hydrates), molten salts, and metals are examples of common inorganic PCMs; small specific applications exist for each PCM type based on temperature - e.g., hydrated salts suit low to medium temperatures (e.g., buildings or solar water heating) and molten salts or metals are applicable in high-temperature environments (e.g., concentrated solar power or recovery of industrial waste heat). While several advantages exist with inorganic PCMs (i.e., higher thermal conductivity, storage density), significant challenges remain with the wider use of inorganic PCMs (e.g., supercooling, phase separation, leakage, corrosion, and low cycling stability) that restrict their current application potential. Current efforts to broaden use of inorganic PCMs through novel use of composites, encapsulation technology, nano-enhancements, and development of eutectic mixtures [66], [67], [68], [70], [71], [72].

A grouped bar chart (Fig. 4) that uses data to compare the primary thermophysical characteristics of the four types of inorganic phase change materials (PCM) that were discussed; these categories are: salt hydrates, molten salts, metal alloys and inorganic eutectic materials. Each category is shown with three descriptors; melting point range (°C), latent heat (J/g) and thermal conductivity (W/m·K) [66], [67], [68], [70], [71], [72]. The error bars cover the entire range of reported properties. The only sub-category of salt hydrate to have a melting temperature between the lowest and highest temperature of HVAC is the range of 20 °C to 80 °C. The metallic alloys and molten salts are used exclusively for high temperature industrial applications (> 200 °C). The thermal conductivity of metals is very high, between 50 W/m·K to 400 W/m·K. There is a break in the scale due to the high thermal conductivity of these materials [66], [68], [70], [73], [74], [75], [76].

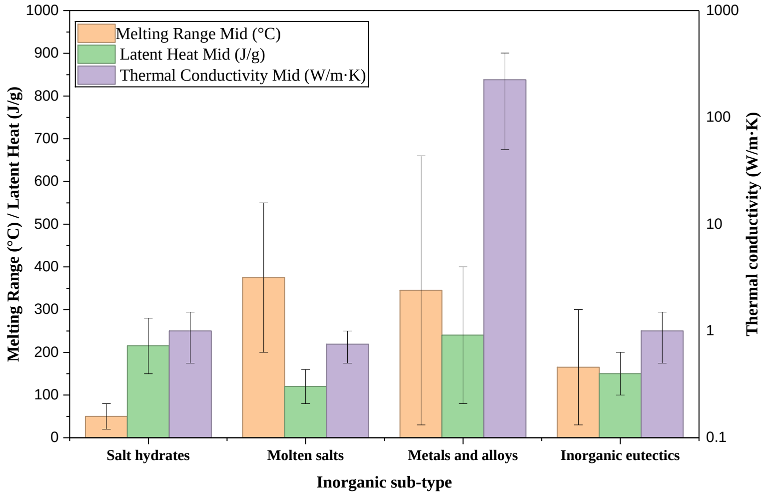

Fig. 4. Comparative thermophysical properties of inorganic PCM sub-types: melting temperature range midpoint, latent heat, and thermal conductivity.

i. Main Types of Inorganic PCMs

- ***Salt Hydrates:*** sodium sulfate decahydrate ($Na_2SO_4 \cdot 10H_2O$), calcium chloride hexahydrate ($CaCl_2 \cdot 6H_2O$), sodium acetate trihydrate ($NaC_2H_3O_3 \cdot 3H_2O$), magnesium nitrate hexahydrate ($Mg(NO_3)_2 \cdot 6H_2O$) all have the same physical properties [73], [77], [78]. Each of these has high latent heat (> 150 J/g), melting between 20 and 80 degrees Celsius, good thermal conductivity (approximately 0.5 to 1.5 W/mK), and are inexpensive to manufacture. However, drawbacks of these PCMs are all suffer from the same problems; they have supercooling, phase separation, and corrosion issues [77], [79].
- ***Molten Salts:*** The second type of PCM is mainly used as thermal storage for high temperature applications such as in hybrid concentration solar power (CSP) plants. They include materials such as nitrate salts ($NaNO_3$ and KNO_3) with melting points above 200 degrees Celsius. These PCMs provide a high volumetric energy density; however, they also exhibit high corrosion potential to the containment vessel [68], [74].
- ***Metals and Alloys:*** The third type of PCM is generally used in applications where extreme thermal conductivity and or extreme temperatures are required. These PCMs typically include metals like aluminum or tin-based alloys. These have very high thermal conductivity but are also relatively expensive and heavy [74].
- ***Eutectic Mixtures:*** The last PCM discussed here are eutectics. Of all the PCMs described above, eutectics consist of two or more salts that melt at a same lower temperature than the lowest melting point of any component constituting the eutectics. This melting behavior allows eutectics to have an adjustable melting temperature, which is desirable for many different applications, as well as a large amount of phase stability [74], [80], [81].

ii.Thermophysical Properties

Heat transfer is the way matter dissipates energy. These characteristics determine how well a material can tolerate temperature changes, both from an environmental and mechanical perspective. Inorganic PCM can be used in high-energy applications but are best suited for passive thermal energy storage systems such as cooling a high-power electrical vehicle battery or storing solar power for a city. Fig.5 shows the Thermophysical Properties of inorganic phase change materials [67], [68], [70], [71], [72], [73], [74].

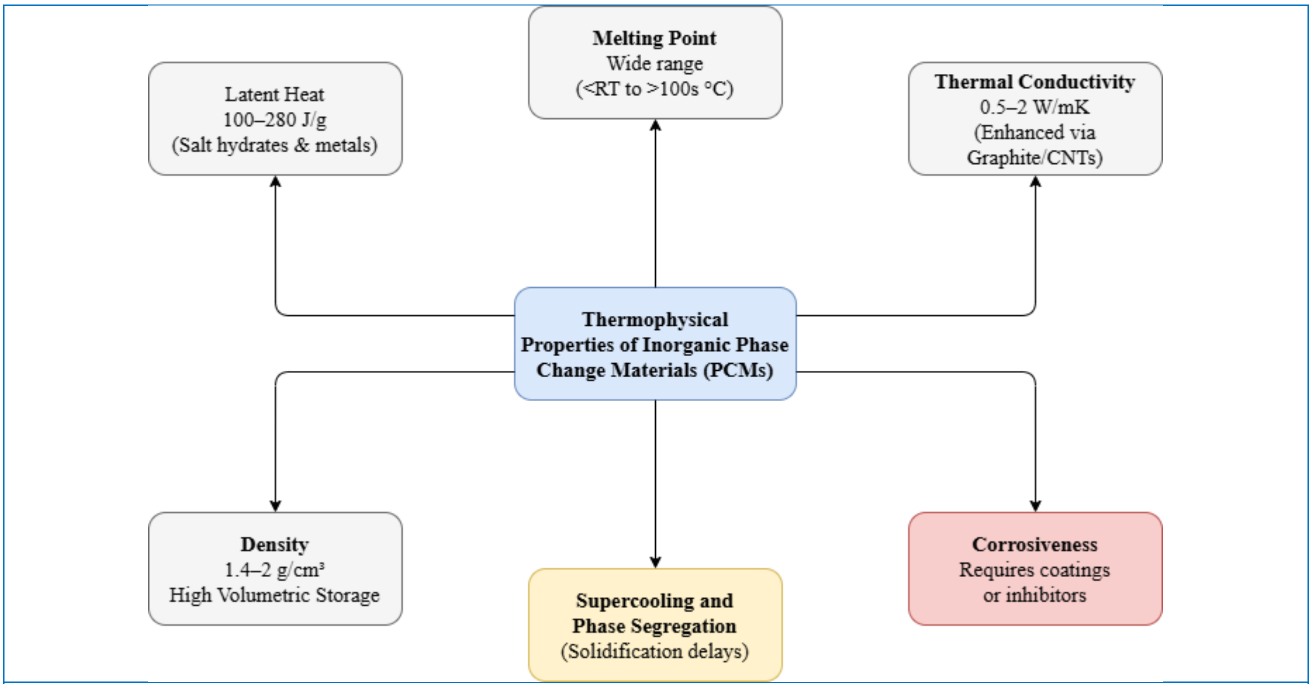

Fig. 5. Thermophysical Properties of inorganic phase change materials [67], [68], [70], [71], [72], [73], [74].

iii.Composite and Form-Stable Inorganic PCMs

To reduce the disadvantages inherent to inorganic phase change materials (PCMs), such as leakage, phase separation and supercooling, the advancement of composite and form-stable structures has emerged as a primary research focus. Encapsulation methods specifically, using a core-shell micro- or nano-confinement approach to hold the PCM in place with a polymer or inorganic shell serve as a strong barrier to improve containment via two mechanisms the barrier prevents moisture contained within a PCM salt hydrate from escaping; the barrier provides additional support and improves the reliability of the PCM during cycling [82]. Formed-stable composite materials (also referred to as shape-stabilized composites) use a porous matrix consisting of expanded graphite, diatomite or clay minerals to create capillary and surface tension forces which also physically anchor the PCM and prevent liquid from leaking during the melting phase; simultaneously, they reduce the degree of phase separation by maintaining close proximity between salt and water molecules during melting to allow for the most efficient latent heat transfer possible [83], [84]. Nano-enhanced composites also provide dual functionality to a system by both providing increased thermal conductivity due to the high-conductivity fillers (for example, graphene, carbon nanotubes (CNTs), or metal nanoparticles) incorporated into the composition, and by providing nucleation sites for heterogeneous nucleation. Therefore, both the enhancement of thermal conductivity and the presence of heterogeneous nucleation accelerate the thermal response time while maintaining the lowest degree of supercooling possible so that the latent heat contained within PCMs can be released at the desired transition temperature [85], [86].

iv. Applications

There are main applications of inorganic phase change that can be seen in Table 6.

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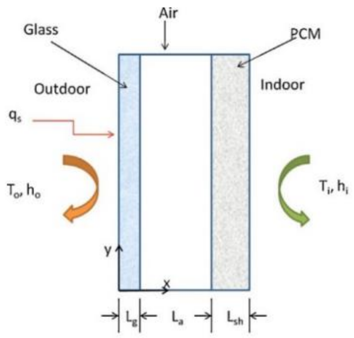
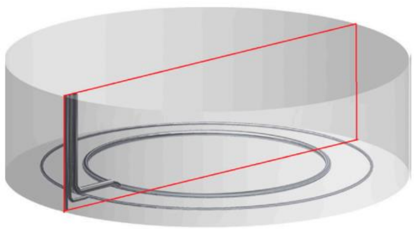
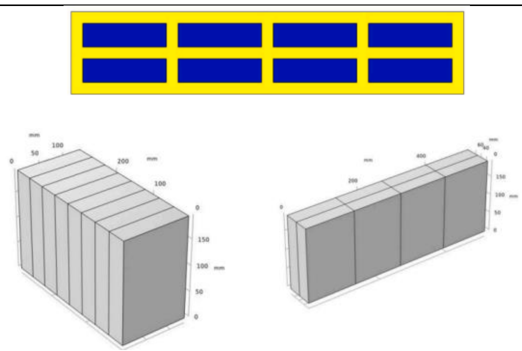
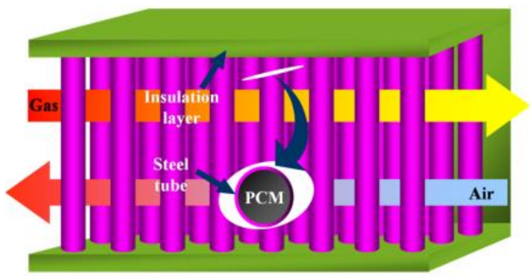
Table 6. The applications of inorganic PCM

Application	idea	Figure
Building	Wallboards, mortars, or plasters with salt hydrate PCMs for passive heating or cooling reducing indoor temperature swings and HVAC loads [87].	 PCM curtain used with glass layer for a window
Solar energy system s	Molten salts or eutectics in CSP plants or solar water heaters for load shifting or storage at various temperatures [88].	 The configuration geometry of the circulation rings in a molten salt tank (the plane of symmetry is presented in red
Battery Thermal Ma nagement	Salt hydrates or metals are used to maintain safe battery temperatures due to non-flammability or high heat absorption [89].	 Battery pack distribution with PCM layers
Industrial Waste Heat Recovery	High-temp molten salts or metals recover or process waste heat efficiently [90].	 Schematic diagram of the tube-type PCM thermal storage module for gas waste heat recovery

Compared to organics, the inorganic PCMs provide substantial benefits because of their considerably greater latent heat per mass/volume, superior thermal conductivity, being non-flammable, and less expensive. For these reasons, they can be used in both low/medium temperature building applications as well as high temperature industrial processes where organics cannot be used due to their volatility and degradation issues. There are many challenges associated with the practical application of PCMs, including supercooling and phase separation (particularly for salt hydrates), leakage during cyclic melting/freezing, corrosion of metal containers (e.g. molten salts), and inconsistent long-term reliability when not using additives or encapsulation methods [70], [72], [79]. Recently, advancements in encapsulation techniques (micro/nano polymer shells to porous matrixes) have contributed to a decrease in leakage and supercooling while improving the mechanical strength and cycling stability of the PCM; however these improvements may lead to increased cost/complexity in large scale applications. Nano-enhanced composites also enhance thermal conductivity; however they will require careful dispersibility and stability control through a larger number of cycles than traditional methods. According to economic studies, although the initial cost of PCM-based insulation or organic PCMs may be higher (particularly when employing 'advanced encapsulation techniques'), depending on the region of installation, there are significant operational savings resulting from superior operational efficiency which can justify investment in an environment in which cooling/heating needs are substantial. At present, there remain many voids in the use of PCMs: Large scale/deployment of PCM demonstration projects is limited; standard PCM testing protocols are non-existent; long-term cycling test data is limited; the possibilities of integrating PCM into 'smart-controls' is still in its infancy, yet it is promising [91], [92] .

3.1.3 Eutectic Phase Change Materials

Phase change materials (PCM) with eutectic characteristics can provide latent heat storage for air conditioning systems, therefore improving energy efficiency and thermal comfort. Eutectic mixtures consist of two or more materials that have a specific melting point that is lower than each of their individual melting points, solid to liquid, and will always melt and solidify in the same way, which is referred to as congruent melting, providing unique melting temperatures, high latent heat, and improved phase stability than an individual PCM component. There is growing interest in the use of both organic fatty acids or alcohols and inorganic salt hydrate eutectic phase change materials for applications including building envelopes, radiant cooling panels, commercial refrigeration systems, and passive/active thermal energy storage (TES) units [93], [94], [95]. PCMs can reduce cooling loads during peak cooling periods, stabilize temperature variations within buildings, and reduce the total amount of energy consumed for heating, ventilation, and air conditioning (HVAC) purposes. While there are issues related to using our PCMs, such as thermal conductivity, supercooling, phase segregation, and material compatibility, these continue to be studied by researchers in order to improve the understanding of their effects within an HVAC system. This paper reviews recent advances in developing, characterizing, integrating into HVAC systems, evaluating performance, and identifying problems with using eutectic PCMs in HVAC systems [96], [97], [98], [99]. Fig. 6 is a data-driven radar (spider) chart that compares the three categories of eutectic PCMs, which include organic-organic, inorganic-inorganic, and organic-inorganic eutectics. This comparison is made across five standardised criteria: (1) Capacity for latent heat (J/g, normalised), (2) Thermal conductivity (W/m·K, normalised), (3) Thermal cycling stability (number of stable cycles, normalised), (4) Supercooling tendency (inverted scale so that the higher the value, the better), and (5) HVAC system temperature suitability (Fraction of subtypes that have melting points between 15-35°C). The data point's respective axes are scaled from 0-5 using the normalised values derived from the ranges of values presented in the reviewed literature [73], [75], [76], [98], [100], [101], [102], [103]. The normalised values for all axes are documented in the accompanying Table 7 with the sources for the data provided.

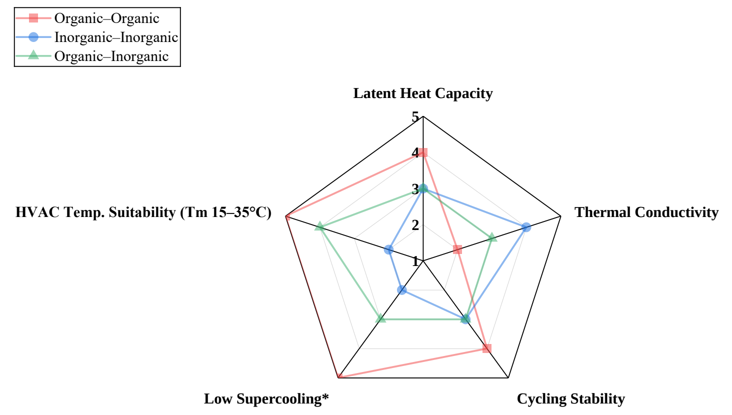


Fig. 6. Radar chart comparing the three eutectic PCM categories across five therm ophysical and practical performance criteria normalised to a 0–5 scale.

Table 7. Exact Scores for Each Radar Axis

Criterion (Radar Axis)	Organic–Organic	Inorganic–Inorganic	Organic–Inorganic	Cited References
1. Latent Heat Capacity	4	3	3	[73], [75], [76], [98], [100], [101], [102], [103]
2. Thermal Conductivity	2	4	3	[73], [75], [76], [98], [100], [101]
3. Cycling Stability	4	3	3	[73], [75], [76], [98], [100], [101], [102], [103]
4. Low Supercooling*	5	2	3	[75], [100], [102], [103]
5. HVAC Temp. Suitability (Tm 15–35°C)	5	2	4	[75], [98], [100], [102], [103]
TOTAL SCORE	**20 / 25**	**14 / 25**	**16 / 25**	**Organic–Organic ranks highest**

* Low Supercooling axis is inverted: score 5 = least supercooling (best); score 1 = severe supercooling (worst).

i. Classification of Eutectic PCMs

- ***Organic–Organic Eutectics:*** Fatty acids (e.g., lauric acid and myristic acid), paraffins, and alcohols are common examples of phase change materials and thermochemical storage candidates. Each has a melting temperature range of approximately between 13°C and 60°C, extremely high latent heats (120- 220 J/g), and provides an excellent degree of chemical stability [100], [101], [104].
- ***Inorganic–Inorganic Eutectics:*** Salt hydrates and/or molten salts (e.g., NaCl + KCl + $MgCl_2$, $Na_2SO_4.10H_2O$ + $Na_2CO_3.10H_2O$) are common examples of phase change material and thermochemical storage candidate materials and have a higher temperature range (>30°C to several hundred °C), a relatively high thermal conductivity, but are vulnerable to supercooling and/or corrosion [75], [76], [105].
- ***Organic–Inorganic Eutectics:*** By combining organic and inorganic salts or hydrated salts, it is possible to create hybrid materials that will yield intermediate properties—tunable melting points (approximately 20°C to 60°C), improved phase stability, although often at the expense of increased complexity of formulation [102], [103].

ii. Thermophysical Properties

The technical characteristics of Eutectic PCMs are shown in Fig.7.

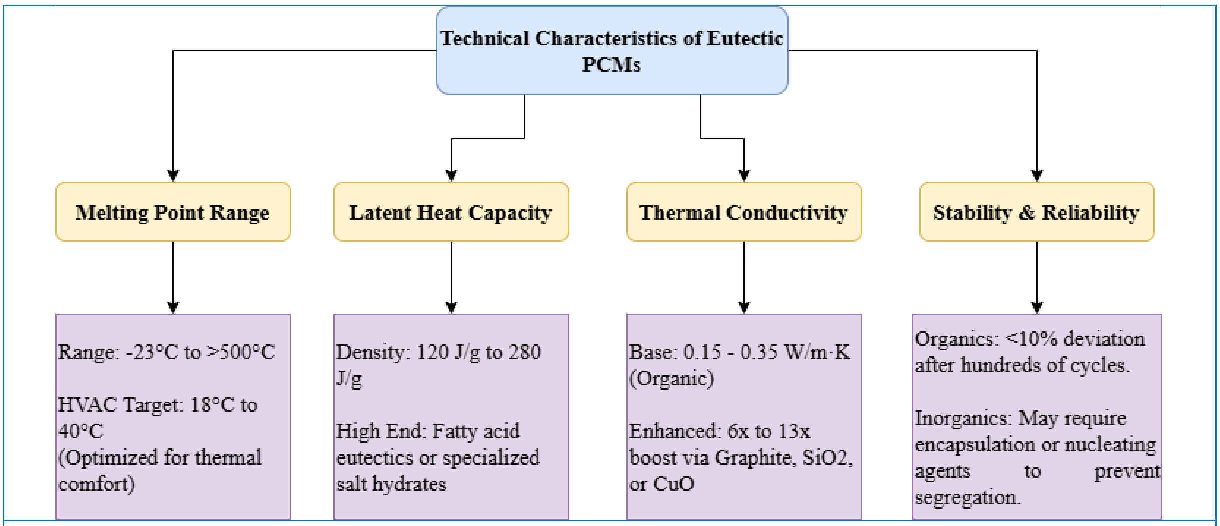


Fig. 7. The technical characteristics of Eutectic PCMs.

Based on the evidence in the literature, proper selection and integration of eutectic phase change materials (PCMs) can significantly enhance the energy efficiency of air conditioning systems. The unique properties of eutectic PCMs that allow for the storage and release of significant amounts of latent heat at desired temperatures make them suitable for both passive cooling and enhance active HVAC efficiency. Fatty acids, as a class of eutectic PCMs, are particularly appealing due to their stable chemistry and low environmental impact; conversely, the high latent heat storage capacities of hydrated salt/mixed salt-based eutectics require special treatment to address supercooling and leakage concerns [102], [106], [107]. Innovation in materials for the use of PCMs, including but not limited to nano-enhanced composites and encapsulated (expanded graphite) PCMs, are addressing traditional PCM limitations such as low thermal conductivity and leakage risk. There are still obstacles associated with practical applications of PCM technology: ensuring a PCM remains reliable in an ongoing manner across different operating conditions, optimizing PCM system designs for specific climates and buildings, monitoring cost-effectiveness, and selecting appropriate encapsulation and container materials to prevent corrosion (aluminum or aluminum alloys are preferred over copper or brass). The overall level of research quality among more recent studies utilizing experimental methods has been excellent, as almost all have used stringent methods of thermophysical characterization differential scanning calorimetry (DSC), thermogravimetric analysis (TGA), Fourier-transform infrared spectroscopy (FTIR), and X-ray diffraction (XRD) and have conducted accelerated cycling tests (more than 500-1000 cycles), as well as realistic simulations building energy simulation software (EnergyPlus), ANSYS-Fluent, and have been conducted in the field in a variety of climates [107], [108], [109].

In terms of the three PCM categories discussed in this document; organic materials remain a better choice for the thermal and mechanical performance of the heat transfer systems because they maintain their ability to cycle through changes in state and are chemically compatible with most mechanical components used in traditional HVAC systems, however, the thermal conductivity of these materials is relatively low (i.e., 0.15 – 0.20 W/mK), so in order to utilise these materials as part of an active system, they must be enhanced through various means including (but not limited to) the addition of nanoparticles, development of a porous support structure, and/or encapsulation. The high latent heat storage density and thermal conductivity of inorganic PCMs (i.e., salt hydrates) are offset by a tendency to experience supercooling and phase separation after repeated cycling; thus, inorganic PCMs (particularly salt hydrates) present a significant reliability issue for use in uncontrolled environments [70], [71], [72]. Eutectic mixtures offer a compromise between the characteristics of organic and inorganic PCMs, due to the fine-tuneable melting point, they are particularly well-suited for use in applications with narrow ranges in the temperature at which the PCM is utilized (e.g., radiant cooling panels near the setpoint established for occupant comfort); however, insufficient large-scale field test data and complexities associated with developing the

formulation of the PCM, impede widespread adoption in the near future [93], [94], [95].
The systematic review conducted on the performance data in this paper shows significantly greater COP improvements (up to 88%) and load-shifting performance (up to 89%) from studies of laboratory-based or short-term experimental conditions than was reported by field deployments within real buildings conducting operations typically experience more conservative results (7-30% annual energy savings). As such, it is essential that ideal laboratory performance be identified as separate from practical deployment for evaluating the technologies' readiness for use in PCM-assisted air condition systems [110], [111], [112]. See Table 8.

Table 8. The Claims and Evidence: Eutectic Phase Change Materials

The claims	The evidence	Reasoning
Eutectic phase change materials (PCMs) can help to cut down on cooling and heating loads in buildings.	Strong	Up to 47% less energy consumption has been indicated through both experimental and simulation methods [109], [113], [114].
There are many benefits of using fatty acid-based eutectics, as they have good thermal stability while being compatible with most materials.	Strong	Very high number of cycles (500-1000) exhibited little to no corrosion or other degradation [115], [116], [117].
Hydrated salt-based EQ's can produce more latent heat than fatty acid EQ's; however, they are subject to leakage or supercooling.	Moderate	The higher the enthalpy, the more additives and/or encapsulation materials will need to be used to extend the shelf-stability of the fuel [118], [119].
Nano-enhanced and composite EQs will increase thermal conductivity of the system.	Moderate	Expanded graphite and nanoparticle additives resulted in λ improvements of approximately 17x [120], [121] .
Corrosion will be an issue with certain metals.	Moderate	Copper and brass will lead to degradation of fuels; recommend using aluminum alloys instead [7], [120].
The amount of large-scale, real-world performance data is extremely limited.	Weak	Most studies have been focused on either lab-scale or short-term simulation experiments.

Table 9 compares and summarizes the key thermal physical properties and practical properties for each of the three major categories of PCM examined in this paper. This information can help users choose the best PCM material to use in specific HVAC applications.

Table 9. Comparative summary of thermophysical and practical properties of principal PCM categories for HVAC applications. Ranges represent values reported across multiple reviewed studies

Property	**Paraffins**	**Fatty Acids / Bio-PCMs**	**Salt Hydrates**	**Molten Salts**	**Organic–Organic Eutectics**	**Inorg.–Inorg. Eutectics**
Melting range (°C)	20–70	15–78	20–80	>200	13–60	30 to >300
Latent heat (J/g)	150–250	100–300	>150	80–160	120–220	100–200
Thermal conductivity (W/m·K)	0.15–0.20	0.15–0.17	0.5–1.5	0.5–1.0	0.15–0.20	0.5–1.5
Cycling stability	Up to 3000 cycles	500–1000 cycles	Moderate	High	500–1000 cycles	Moderate
Supercooling tendency	Low	Low (<2 °)	High	Low–Moderate	Low	Moderate–High

Corrosion risk	Low	Low	Moderate–High	High	Low	Moderate
Flammability	Moderate–High	Moderate	Non-flammable	Non-flammable	Moderate	Non-flammable
Relative cost	Low	Low–Moderate	Very low	Moderate	Low–Moderate	Low
HVAC suitability	High	High	High (with additives)	Industrial / CSP only	High	Moderate–High
Key refs.	[16], [17], [26]	[42], [47]	[66], [67], [70], [73]	[68], [74]	[93], [98], [100]	[75]

3.2 Integration methods of PCMs in air-conditioning systems

The use of Phase Change Materials (PCMs), such as paraffins and salts, is growing in popularity in the efficient functioning of air conditioning systems. Integrating PCMs into HVAC systems is typically performed in three ways: adding PCMs to heat exchangers, using PCMs for thermal energy storage, or embedding PCMs directly into the building materials [110], [122], [123], [124], [125]. Each of these methods can be employed to accomplish either passive or active cooling strategies and significantly reduce cooling loads, energy usage and peak demand [111], [126], [127]. To maximize the benefits of adding PCMs to an HVAC system, the PCMs must be properly selected, characterized and integrated. In addition, the HVAC system must be designed with consideration of the PCMs in the PCM (e.g., melting point, thermal conductivity) and the control strategies employed to charge and discharge the PCM. Although the potential use of PCMs in the HVAC industry is apparent, questions still exist regarding long-term performance, cost-effectiveness, scalability, and how they can be incorporated into the existing infrastructure Types of PCM Integration into HVAC Systems for Making Energy Efficiency Improvements with the Application of Phase Change Materials in Heating, Cooling and Ventilating Systems. This paper summarizes the current state of the art in PCM integration into HVAC systems, evaluates the impact of PCMs on various metrics related to performance (e.g., energy savings), discusses methods to enhance the performance of PCM, describes control strategies for managing the operation of PCM in HVAC systems, and highlights the results of experimental and numerical studies on the economic viability of PCMs in HVAC Systems [128], [129], [130]. Fig.8 shows three different integration methods (PCM-enhanced heat exchangers, PCM-based TES units, and PCM-embedded building materials) compared against three metric values (COP improvement, annual energy savings, and peak demand reduction/load shift) has been created based on data gathered through reporting. In creating the bar chart, the error bars shown above or below each bar reflect the range represented by the minimum and maximum of all reported values within this method. The height of the bar itself reflects the median value reported. The data that has been used to create the bar chart can be found in Table 10.

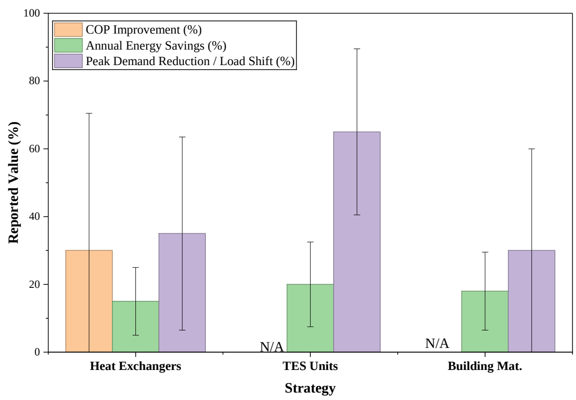


Fig. 8. Reported ranges of COP improvement, annual energy savings, and peak cooling demand reduction/load shift across the three PCM integration strategies, compiled from reviewed experimental and numerical studies.

Table 10. Median reported values and error ranges for three performance metrics across PCM integration strategies

PCM Integration Strategy	COP Improvement %		Annual Energy Savings %		Peak Demand Reduction / Load Shift %	
	Median	Error(±)	Median	Error(±)	Median	Error(±)
PCM-Enhanced Heat Exchangers (HX)	30	40.5	15	10	35	28.5
PCM-Based TES Units (TES)	N/A	—	20	12.5	65	24.5
PCM-Embedded Building Materials(BM)	N/A	—	18	11.5	30	30
Source references	[110], [111], [131]		[110], [111], [112], [114], [131], [132], [133], [134]		[110], [111], [112], [114], [131], [132], [133], [134]	

A direct comparison of the three PCM integration strategies assessed in this paper was made using eleven different criteria from a variety of fields (engineering/economic/evidence quality) in Table 11. This comparison will allow for a systematic way to evaluate the strengths and weaknesses of these three strategies.

Table 11. Side-by-side critical comparison of the three PCM integration strategies for air-conditioning systems. TRL = technology readiness level (1 = concept; 9 = commercially deployed). TOU = time-of-use electricity tariff. BEMS = building energy management system. All quantitative values are drawn from the reviewed literature as cited. The 'Conflicting evidence' row identifies the primary sources of inter-study performance variability for each strategy.

Criterion	PCM-Enhanced Heat Exchangers	PCM-Based TES Units	PCM-Embedded Building Materials
Primary benefit	COP improvements from 7%-88% and cooling capacity improvements of up to 54%.	Off peak load shedding improvements of up to 89%, with demand reductions of 10%-67%.	Passively reducing load by providing annual energy savings of 7%-30 %.
Operating mechanism	PCM serves as buffer to evaporator/condenser temperatures, thus reducing compressor cycling and condensing pressures.	Chillers are operated during the night when it is cooler/cheaper and the PCM is discharged during the daytime peak period.	The thermal mass will delay heat and will provide 'shaved' peak cooling loads.
Best PCM types	Organic materials including paraffin and fatty acids used to create an organic/eutectic material. Has melting temperatures (Tm) between 18-28 C.	Common use of NaCl hydrates in slightly different organic/inorganic eutectics. Has melting temperatures between 6-14 C.	PMC's are based on micro-encapsulated fatty acids, with melting temperatures between 22-28 C.
System complexity	Moderate: possible to retrofit an existing air-conditioning unit.	High: use of dedicated TES tanks, pumps, controls and piping are required.	Low: Completely passive, no mechanical/controls are required.
Capital cost premium	Moderate +15 to +25% above baseline AC.	High +20 to +35% greater than conventional c	Low-Medium $15-$40 per m² of treated area.

		hilled-water storage.	
Payback period	3–8 years (hot climates)	3 - 7 years (Commerci ally, time-of-use tariffs).	7 - 20+ years (High cli mate dependency).
Key advantage	Direct COP gain from use of existing AC unit and no separate storag e facility required.	Highest load-shift poten tial; very beneficial for time-of-use electric tarif f rate structures.	No moving parts; no m aintenance requirements; integrates passively wit h building envelope.
Key limitation	COP gain would be red uced significantly if PC M melting point is poo rly matched with refrig erant TD.	High initial capital expe nse; space required for TES tank; BEMs integr ation required for optim al control.	Requires complete solid ification of PCM overni ght; significantly reduce d effectiveness in clima tes that are not diurnal.
Conflicting evidence i n literature	COP gains of 7% vs 8 8% for similar configur ations — explained by PCM placement (evap. only vs dual evap.+con d.) and capsule geometr y [110], [111], [131]	Load shift of 40–89% depending on control st rategy — rule-based vs AI-predictive control [112], [114]	Energy savings 7–32% — range driven by cli mate, PCM melting poi nt accuracy, and wall c onfiguration [132], [133], [134]
Technology readiness (TRL)	TRL 5–7 (lab to pilot s cale)	TRL 7–9 (commercially deployed in some mar kets)	TRL 6–8 (field tested; l imited standardisation)
Key references	[110], [111], [124], [13 5], [136], [137]	[107], [111], [112], [11 4], [129]	[38], [122], [132], [13 3], [134], [138], [139]

3.1.1 PCM-Enhanced Heat Exchangers

The goal of including phase change materials (PCMs) in the heat exchanger is to improve the efficiency of the refrigeration cycle, as measured by the Coefficient of Performance (COP). Integrating PCMs into the evaporator side of the heat exchanger generally involves encapsulating PCM around the refrigerant tubes. As the air conditioner operates, heat is absorbed from both the indoor air and the PCM by the refrigerant, which causes the PCM to solidify (or charge) [110], [124], [135]. Once the indoor thermostat is satisfied and the compressor cycles off, this thermal mass will continue to transfer heat to the air circulated by the fan through passive cooling until the next air conditioning cycle begins. Therefore, the compressor will not have to start as often, which results in significant energy savings. PCMs on the condenser side serve as a heat sink. During the day, the refrigerant rejects heat, via the PCM, into the outdoor ambient air—thereby preventing the condensing temperature from exceeding desired levels in high temperature ambient conditions. Doing so minimizes the pressurization required for the compressor to operate, thus reducing power must be consumed by the compressor. The stored heat in the PCM on the condenser side can either be released to ambient air at night or repurposed for use in heating water [136], [140].

The literature reviewed reveals considerable diversity in the reported COP improvement of PCM-enhanced heat exchanger systems, with reported improvements ranging from 7% - 88% for seemingly similar system configurations [110], [111], [131]. However, the diversity in reported improvements was not due to random experimental variability; there are three systematic reasons that account for the differences. The first reason is that the placement of the PCM is the primary determinant of system performance. Studies that place the PCM at the evaporator only (to buffer return-air temperature during compressor off cycles) reported lower CPC improvements than studies with PCM placed at both the evaporator (to buffer indoor load) and the condenser (to reduce the condensing pressure of a heat exchanger when it is subjected to a high ambient temperature); that is, studies that utilized a dual placement configuration of PCM reported higher COP improvement values [110], [111]. The engineering implications of this conclusion are significant: single-sided installations are less costly and much easier compared to dual installations. However, the yield from single-sided systems is significantly lower than yields from dual-sided systems. Therefore, comparisons of data from single-sided studies versus dual-sided studies must take this inherent difference in design into account. The geometry of the capsule has been found to have a direct impact on COP: Ismail and Hassan [110], [111] have shown that concave versus convex capsule geometries exhibit better effective heat-transfer areas and lower thermal resistance between the refrigerant and PCM, leading to more significant COP increases than were achieved with earlier research utilizing flat-plate and cylindrical capsule configurations. In addition, research on the effect of climate severity has consistently shown that climate severity significantly amplifies the advantages: studies completed in some of the hottest areas in the world (e.g., Riyadh, Egypt, where the ambient temperature regularly exceeds 40 degrees Celsius) achieved greater absolute COP increases than studies completed in temperate climates where the elevation of the condensing temperature was less. PACM on the condenser-side of dual installation systems will significantly reduce the disadvantage associated with very high condensing pressures. Finally, when combined, these results show that the 7% - 88% range of COP reported in the literature is not due to inconsistencies in the underlying principals of physics, but is instead a reflection of design and operational changes as well as implementation differences. And dual placement installation configurations for cooling in the warmer climates represent the highest return design goal found in this study. See Fig.9.

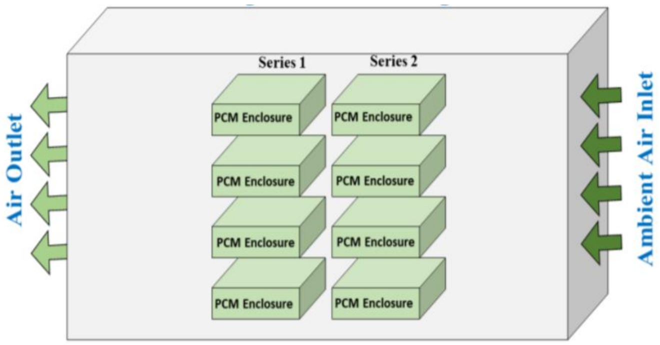


Fig.9. Employing a PCM into an AC duct [124]

3.1.2 PCM-Based Thermal Energy Storage (TES) Units

Thermal energy storage (TES) systems are designed to separate the production of cooling from the use of cooling. Generally, these systems are used in large commercial chilled water systems for the purpose of “load shifting.” A typical TES system will consist of a large tank filled with phase-change material (PCM) that might include macro-encapsulated materials like nodules, plates, and spheres. At night (when cooling is least expensive), when ambient air temperature is cooler and chiller operation is more efficient, water from the chiller is used to freeze the PCM in the TES tank [141], [142]. When cooling demand is high during the day, water from the building is circulated through the TES tank; as water passes through the TES tank, the PCM is melted, returning the cooled water to the building prior to entering any air handler. This allows the building owner to minimize or eliminate the use of their more costly chillers during peak electricity rates, or to downsize their equipment. There are advanced versions of this technology, such as the use of PCM slurry, which consists of micro-encapsulated PCM in a slurry form and acts as a pumpable storage medium with much higher energy density than traditional sensible water storage; therefore requiring much less space to provide the same amount of cooling capacity [111], [143]. See Fig.10.

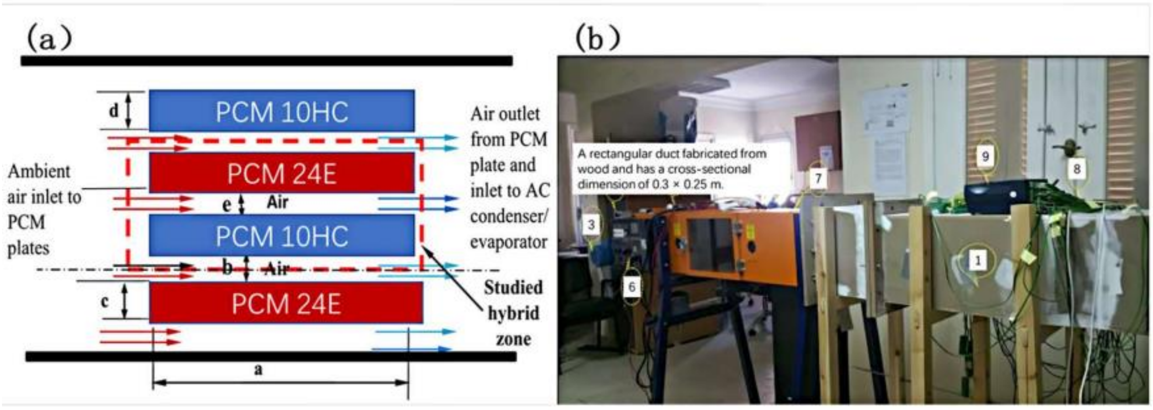


Fig.10. Physical model of PCM storage system [141]

3.2.3 PCM-Incorporated Building Materials

Passive (or "built-in") integration integrates the building’s thermal inertia with the goal of minimizing the total cooling load. This term refers to integrating PCMs (Phase Change Materials) within traditional construction materials e.g., gypsum wallboards, concrete, and floor tiles using micro-encapsulation and shape-stabilization techniques. The PCM absorbs a large amount of thermal energy when the temperature of the space (either indoors or outdoors) exceeds the PCM's melting point, but there is no corresponding increase in the temperature of the PCM itself during this time [138], [139].

The integration of PCMs into the building envelope effectively "shaves" the peak cooling demand from the air conditioning system by delaying the time it takes for heat to penetrate into the building's interior (thermal lag). By dampening the temperature variations inside the space, the air conditioning system can be sized to accommodate lower peaks and run more consistently, instead of being forced to respond to rapidly changing indoor temperatures. This approach is passive and does not utilize any mechanical energy; however, this type of integration is highly dependent upon the "regeneration" phase making sure that the PCM can completely solidify during the night due to natural ventilation or cool night air so the PCM is ready for the next day's heat [137], [141]. See Fig.11.

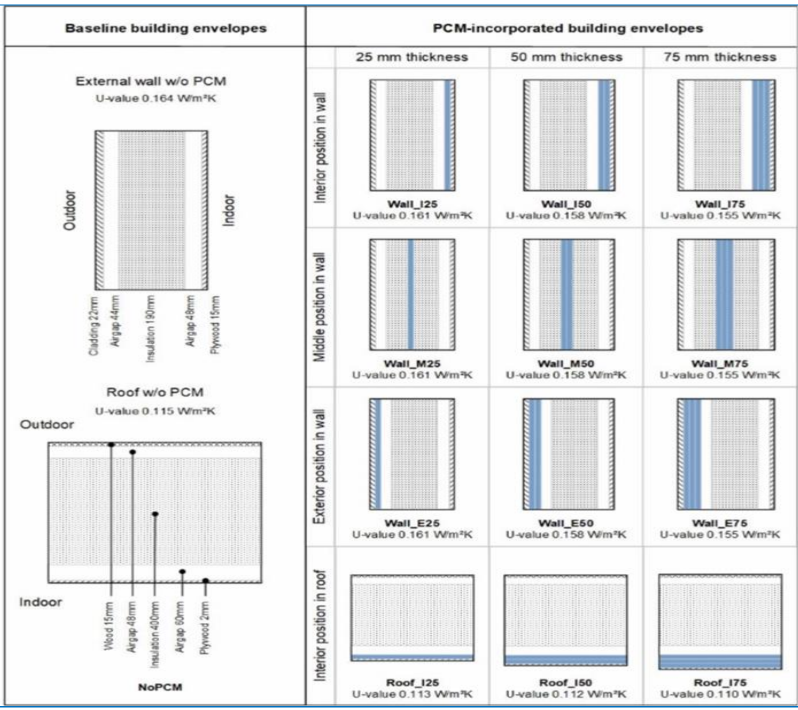


Fig. 11. Physical model of PCM storage system [138].

3.3 Thermal performance metrics

The performance of these methods to integrate has been evaluated using various metrics that determine effectiveness. One integration method to use phase-change materials (PCMs) for cooling purposes had an increase in the effective cooling capacity by 54% under optimum configurations. The ability to regulate temperatures in this manner has also been shown to reduce temperatures within PCB systems from 3° to greater than 13°, depending on the physical properties of the material and the climate conditions in which they are located[124], [125], [141].

From an energy-efficiency standpoint, PCMs were determined through both experimental and numerical studies to reduce electricity use in a daily cycle from 5% to greater than 20%. The coefficient of performance (COP), which is a measurement of the effectiveness of an air conditioning unit or other device used for cooling purposes, is reported to have been improved from 7% to 88% when PCMs were used within the system [110], [111], [131]. The improved performance of the cooling systems using PCMs resulted primarily from stable pressure levels in the refrigerant. In addition to improved energy efficiency, PCM thermal energy storage systems also have the ability to shift as much as 89% of the daily cooling load to off-peak periods via the use of TES technology. In urban areas, PCM thermal energy storage systems can provide demand-reduction improvements in peak-load conditions of between 10% and 67% and serve to relieve the strain on power grids and facilitate improved demand-side management (DSM) [137], [140]. See Fig.12.

The quantitative performance results from the major reviews of the experimental and numerical studies that were reviewed have been brought together in Table 12, to allow the COP improvements, annual energy savings and load-shifting efficiency to be compared directly between the three integration strategies.

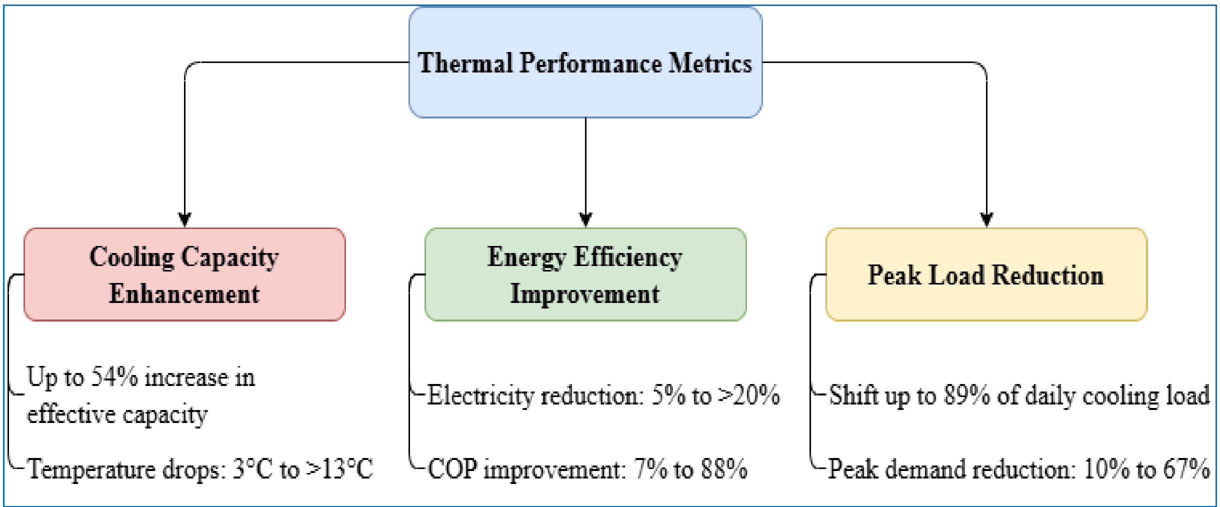


Fig. 12. The thermal performance metrics.

Table 12. Quantitative synthesis of reported thermal performance outcomes from key reviewed experimental and numerical studies.

Study (Author, Year)	PCM Type / Melting Point	Integration Strategy	COP Improvement (%)	Annual Energy Savings (%)	Peak Load Reduction / Load Shift (%)	Ref.
Ismail & Hassan, 2022	Paraffin, 24 °C	PCM-enhanced heat exchanger	Up to 88	Up to 20	Significant compressor off-time extension	[110]
Ismail & Hassan, 2024	Dual organic PCM, 18–26 °C	Dual PCM-enhanced heat	7–88	12–25	Peak demand reduced up to	[111]

		exchanger			67%	
Masood et al., 2024	Paraffin, air pre-cooling range	PCM air pre-cooling duct	~54 (cooling capacity increas)	5–20	Peak demand reduced 10–67%	[124]
Said & Hassan, 2021	Hybrid PCM-TES with AC unit	PCM-based TES (hybrid)	Reported	Up to 32	Up to 89% load shift to off-peak	[114]
Irshad et al., 2025	Cold-storage PCM, slurry	PCM-based TES unit	Not reported	Significant	Up to 89% off-peak shift	[112]
Al-Yasiri & Szabó, 2023	PCM wall panel, ~26 °C	PCM building envelope	Indirect	7–30	Indoor temp. 2 °C lower on peak days	[132]
Salihi et al., 2022	PCM wallboard, semi-arid climate	PCM building envelope	Not reported	Up to 30	Discomfort hours reduced 65%	[133]
Mohseni & Tang, 2021	PCM in lightweight wall	PCM building envelope	Not reported	Up to 32	Thermal lag extended several hours	[134]
Sharma et al., 2024	Retrofit PCM in AC system	PCM-enhanced heat exchanger	7–30	Significant	Peak demand reduced	[131]
Alasiri & Nasser, 2025	Various PCM configs., Riyadh	PCM-enhanced AC system	Varies by config.	Varies by config.	Significant in hot climate	[135]
OVERALL RANGE	—	All three strategies	7–88%	7–32%	10–89% load shift	—

4. Thermal Performance Enhancement Strategies

Improving the thermal characteristics of phase change materials (PCMs) requires strategies that alleviate the current limitations of these types of materials, primarily their low thermal conductivity, while simultaneously achieving the best possible integration of the PCMs into building systems. See Fig.13.

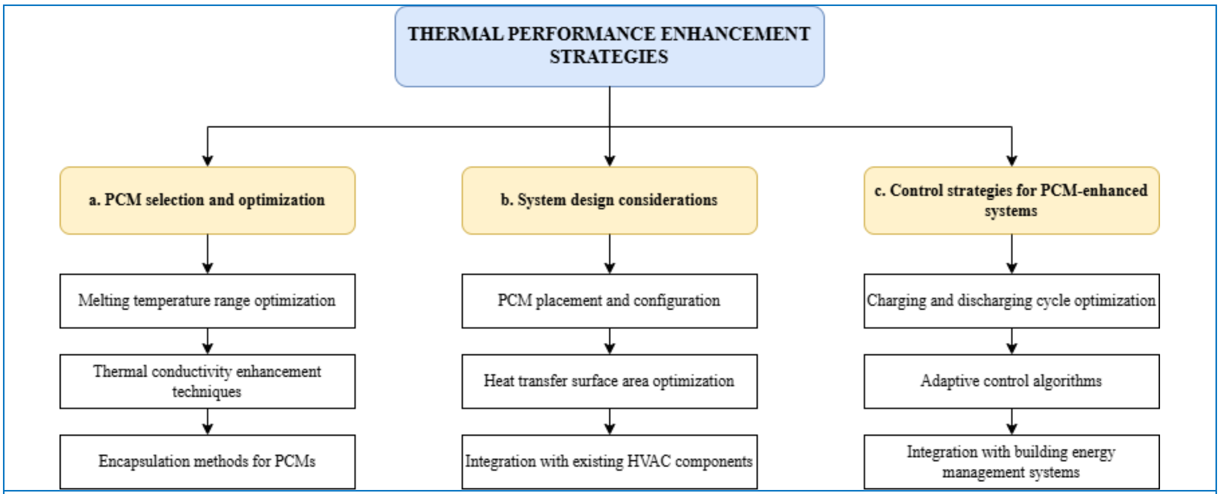


Fig. 13. The thermal performance enhancement strategies.

a. PCM Selection and Optimization

Selecting the right material for a Phase Change Material (PCM) is the first obstacle to overcome. If the PCM does not melt and solidify within the comfort zone established for any room, then it is thermally inert and provides no latent heat storage benefit [144], [145].

- **Melting Temperature Range:** The melting point for a PCM must be located directly adjacent or very close to the specified set point (typically between 20° C to 26° C) for human comfort. The PCM will not melt if the phase transition occurs at a temperature greater than the upper limit or won't freeze or release heat if the phase transition occurs at a temperature less than the lower limit [144], [145].
- **Thermal Conductivity Enhancement:** Generally speaking, most PCMs (paraffins and most organic PCMs) are naturally very poor thermal conductors. Therefore, to provide sufficient conduction in a PCM system, engineers incorporate high-conductivity additives into the PCM matrix, such as expanded graphite, metal fins, or copper foam [146].
- **Encapsulation of PCMs:** To prevent PCMs from leaking in the liquid state, PCMs are encapsulated in containers. Macroencapsulation: includes large pouches or tubes or panels. Microencapsulation: using microscopically sized polymeric shells to be blended with plaster or concrete directly into the desired structure [147] .

b. System Design Considerations

Even a well-specified PCM will not deliver its theoretical thermal benefit if the heat transf er path to it is inadequate. Therefore, the design of the storage unit focuses now on the shap e or configuration of the storage unit rather than the material that makes up the storage unit [144].

- **Placement and Configuration:** PCMs can be passive (embedded in walls, ceilings and/or floors) or active (in a stand-alone heat exchanger connected to HVAC systems) [148].
- **Optimizing Surface Area:** In order for PCMs to transfer heat, they have a low heat transfer rate; therefore, increasing the contact area of the PCM with the heat transfer medium (air or water) is key. This is typically done by using thin flat plates, or some type of corrugated surface[147] .
- **HVAC Integration:** PCM tanks can also provide operation as part of the air supply duct or be used as "thermal batteries" for chillers to move peak electrical loads to overnight [137].

c. Control Strategies

For a PCM system to work optimally, it must be "reset" (discharged) each day. If a wall is entirely melted due to insufficient airflow through the night, the wall cannot absorb heat from the sun the next day [143].

- **Charging/Discharging Cycle:** Cooling the PCM with "night purge" (used to circulate cooler night air around the PCM) will ensure the PCM is solidified for the absorption of heat the following morning [112], [149] .
- **Adaptive Control:** Artificial Intelligence or sensor-based intuitive systems can be used to gauge weather patterns. For instance, IF the system realizes that tomorrow will produce extreme heat, the system will cool the PCM below its normal required temperature to assure capacity [111].
- **Building energy management system (BEMS) Integration:** Connecting the PCM state-of-charge to the Building Energy Management System (BEMS) to determine whether mechanical cooling will take place or rely on the thermal battery [122].

5. Performance Analysis and Case Studies

5.1 Experimental Studies

a. Laboratory-Scale Experiments

At the lab scale, it has been confirmed that using PCM materials within building components or HVAC equipment has been shown to reduce temperature variations by up 'to' 46%, to delay the transfer of heat for several hours, and to reduce chill/heat loads 'by' up 'to' 31%. For example, the radiant heating and cooling systems that use PCM materials are providing significant improvements in terms of thermal comfort and energy efficiency when used within lightweight buildings. Skylights that use PCM materials provide a reduction in temperature peaks compared to non-PCM systems by 'up' to 6-7°C [132], [150], [151], [152]. See Fig.14.

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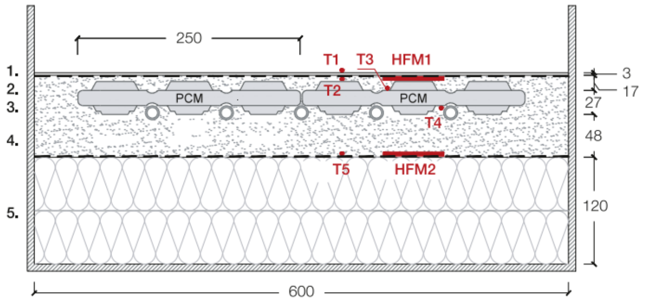
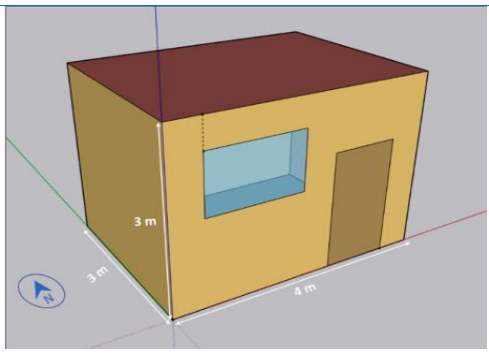


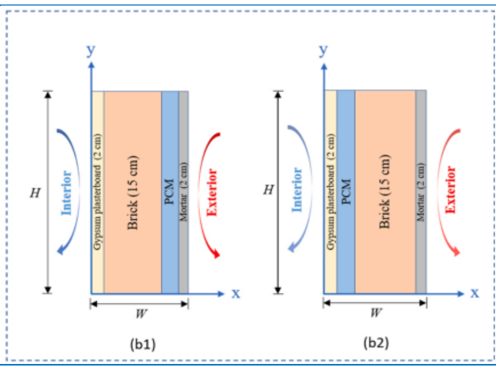
Fig. 14. Radiant floor configuration (layer thickness expressed in mm) [150].

b. Full-Scale Building Implementations

Cooling energy savings from field testing in actual structures have been reported at rates from as much as 30 to as little as 7% annually, and reduction of discomfort hours can be as much as 65% when using phase change materials (PCMs) in walls and ceilings. In climates where it is hot (such as Riyadh or Morocco), PCMs allowed for the average indoor air temperature to be 2 ˚C lower on the hottest days of the summer [122], [132], [133].



a. Building model.



b1. Wall with PCM: external configuration, b2. Wall with PCM

Fig. 15. Tested walls configurations [133].

5.2 Numerical and Simulation Studies

a. Computational Fluid Dynamics (CFD) Models

CFDs have proven to confirm the experimental results, as demonstrated by the ability of optimized PCM geometries (i.e., concave/convex capsules) to enhance the speed of charging/discharging cycles and overall responsiveness of the system. CFD simulations also indicate that airflow rates and proper location of the PCM are critical to achieving maximum benefit from these materials [153], [154].

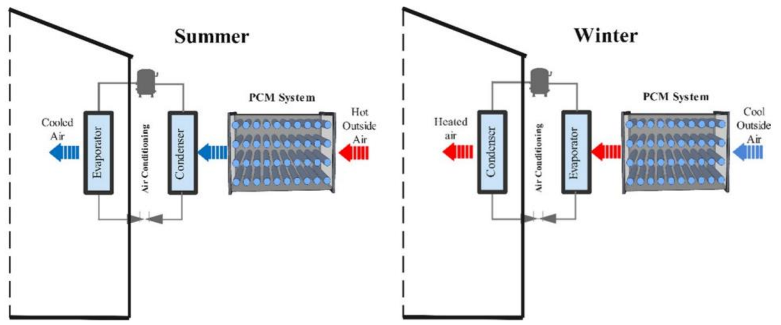
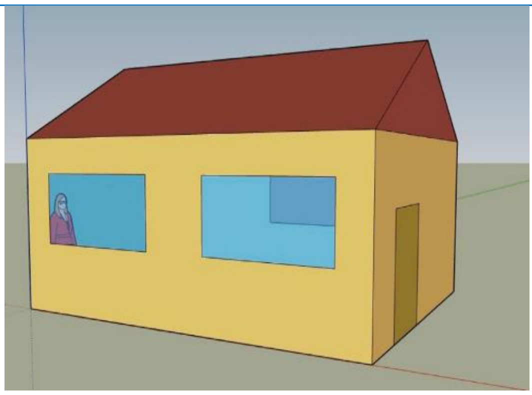


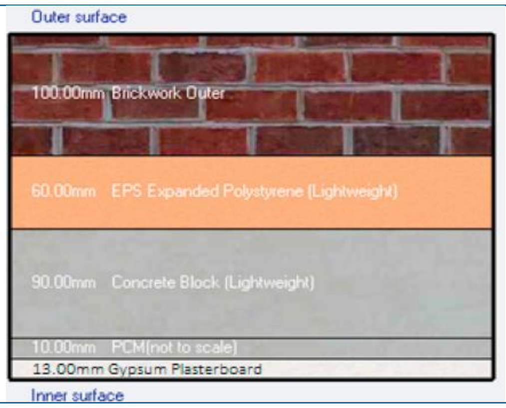
Fig. 16. The proposed air-PCM heat exchanger integrated with an air condition system during the summer and winter [153].

b. Building Energy Simulation Results

According to the EnergyPlusT-RNSYS modeling studies, as shown in Fig.17, the proper selection of PCM (melting point/thickness/location) can yield annual energy savings of up to 32%, depending on the building's climate zone. If you have a multi-layer / hybrid PCM configuration, your ability to shift loads will be even greater [134], [155], [156].



a. Model of residential house.



b. Details of wall composition.

Fig. 17. Building energy simulation model [134].

c. Life Cycle Assessment Studies

According to lifecycle analysis PCMs provide a significant reduction in operational carbon dioxide emissions (several tons per year) per building. Different areas of the country will have different payback periods for the installation of PCMs. Payback periods for installation of PCMs range from seven years in temperate climates to over 20 years in subarctic climates depending on the price of materials used and price of energy in that area [157], [158], [159].

5.3 Comparative Analysis

a. PCM-Enhanced vs Conventional Systems

Studies have revealed that cooling performance is better than conventional cooling systems, with PCM systems providing improvement in COP of 80% or more, power savings of 12-25%, and extended duration of cooling effects [110], [111].

b. Performance Across Different Climates

Payback from PCM systems will depend on the climate in which they are used; climates with large daily temperature swings or high demand for cooling yield the greatest benefit from PCM systems, as opposed to ultra-low energy buildings that are also highly insulated (in this case the PCM system benefits when used in conjunction with other forms of insulation) [142], [143].

c. Cost-Benefit Analysis and Payback Periods

Initial investment will typically be greater for PCM systems than for conventional cooling systems, but the long-term operational savings will typically offset the additional investment; particularly when PCM systems are integrated with demand-response projects and an intelligent insulation strategy [111], [123].

6. Challenges And Future Directions

Thermal comfort and energy efficiency can be greatly enhanced by using phase change materials (PCMs) in air conditioning systems. However, widespread utilization of PCMs has not occurred due to multiple technical and economic limitations. These include long-term stability, cycling behavior of materials, order-of-magnitude improvements to the scale of production, difficulties associated with their manufacture, compatibility with existing equipment, and cost-effectiveness of use. Research conducted over the last decade includes those associated with developing advanced PCM composites, optimizing various types of encapsulation techniques, and integrating PCMs into renewable energy systems. Therefore, the objective of this paper is to summarize previous published literature concerning the major technical and economic barriers to the more widespread use of PCMs as well as the emerging opportunities associated with their use and gaps in the research needed to develop next-generation PCMs [7], [9], [32], [53], [69].

6.1 Technical Challenges

a. Long-Term Stability and Cycling Performance

Many of the conventional phase change materials (PCMs) suffer from many of the same problems, including phase segregation, melting/solidifying during cycles, causing leakage, supercooled materials, and thermal stability degradation. Organic phase materials (like paraffins) are chemically stable, but their low thermal conductivity limits their use. Inorganic phase materials (such as salts) have higher thermal conductivity; however, they have issues with phase separation and cycling instability. Various encapsulation techniques, such as micro or macroencapsulation and shape stabilization, are under development to solve these problems and make the PCMs last longer and eliminate leakage [7], [9], [32], [53], [69].

b. Scalability and Manufacturing Issues

Many of the problems associated with large-scale production of advanced composites (such as carbon based and bio derived PCMs) come from difficulties in mass production and sourcing of very high-cost raw materials/additives used in advanced composite production like graphene or Metal-organic framework (MOFs) and the difficulty in achieving uniformly encapsulated advanced composite materials on a mass scale. In addition, spray dry process have been shown to create agglomeration issues. Also, standardization in mechanical testing continues to be on lacking [160], [161], [162].

c. Integration with Existing Infrastructure

The retrofitting of PCMs in existing HVAC/building systems require confirmation that the PCMs will not bother the current construction materials and that the building will not be disturbed during retrofitting. There is currently no resolution on how to maintain or replace the PCMs once they become degraded and are used in homes as there can be limited access to the areas containing the degraded PCMs once they are installed [163], [164], [165].

6.2 Economic Considerations

a. Initial Investment Costs

Advanced Phase Change Material (PCM) composites and Encapsulation Methods lead to higher upfront costs compared to standard Insulation or Storage products. The addition of high-performance additives (i.e. Carbon Nanotubes) will also drive up the cost of the material [118], [161], [163].

b. Operational and Maintenance Expenses

While there may be operating savings related to lower energy consumption, and peak load shifting; there may be increases in the maintenance cost if a PCM deteriorates, or if it must be replaced, especially if it integrates into an inaccessible portion of the building [165], [166].

c. Market Barriers and Incentives

Large scale demonstration projects have not been prevalent in order to instil market confidence in PCM. In addition the absence of standardised performance standards makes it difficult to compare to existing conventional technologies. Policy incentives for sustainable buildings could promote the adoption of PCM if they were to include clearly defined lifecycle benefits [9], [56] .

d. Lifecycle Cost Analysis and Payback Periods

When analysing the lifecycle costs analysis (LCCA) of PCM Integrated Cooling Systems, many studies have shown that although the initial capital investment is higher than that of traditional insulation or storage products, PCM Integrated Cooling Systems can provide acceptable financial returns over the long-term due to their operational energy savings and ability to shift peak load. Published studies suggest that the cost of installing PCM Integrated Cooling Systems can vary substantially based on the type of integration. For example, using PCM in the building envelope adds approximately USD 15 - 40 per m² of treated surface area, while producing PCM-based thermal energy storage for commercial chillers typically costs 20 - 35% more than conventional chilled-water storage systems. When accounting for demonstrated annual energy savings ranging from 7 - 32% and reductions in peak demand between 10 - 67%, simple payback periods of 3 - 7 years have been reported for hot-weather applications where there are many cooling degree-days and when electricity is charged based on time of use [111], [112], [158].
8-12 years is the typical payback period for PCMs in temperate areas with Mediterranean climates, while it can take longer than 20 years to pay back for PCMs in cooler climates/subarctic or with low cooling demand. PCM return on investment, therefore needs to be evaluated for context-specific conditions [155], [157], [158]. The cost of ongoing maintenance is an additional economic factor; as encapsulated materials are cycled (demanded) over long periods of time the integrity of the encapsulation will degrade, resulting in needing to replace part of the complete system once the encapsulation no longer functions properly; particularly for designs where the PCM has been installed in the wall or ceiling assembly and access has been restricted to performing maintenance or repairs [165]. The financial case for integrating PCM with grid demand reduction programs through building energy management systems (BEMS) will strengthen and will only work if the utility has an advanced metering infrastructure to track usage and tariffs that make it feasible for the utility to offer services back through the BEMs [111], [122].

6.3 Research Gaps and Future Opportunities

a. Critical Research Gaps

Section 6.3 identifies new opportunities and aspirational future directions. However, the critical reading of the publications reviewed in this research presents five identified, fully unresolved research gaps that represent true barriers to the reliable implementation of PCM-based cooling systems rather than promising directions of research. Each of these research gaps is represented in the following descriptions and evidence.

Gap 1: Lack of Test and Evaluation Protocols for the Performance Testing of PCM. In the 166 studies reviewed for this report, researchers utilised six distinct methods to quantify the latent heat of PCM (differential scanning calorimetry at a scan rate of anywhere from 0.5 to 20 deg C/min); made use of hot-wire, transient plane source and laser flash methods to measure thermal conductivity; varying length of time over which to evaluate cycling stability (50 to 3000+ cycles) at a rate which was on the order of magnitude from others. This lack of consistency in methodology used to quantify thermal properties of PCM represents the most significant structural explanation for the variation of COP improvement estimates (between 7% and 88%) reported by studies for nominally similar PCM-heat exchanger configurations [110], [111], [131]. Therefore, because there are no standard test protocols related to PCM testing and evaluation analogous to ASHRAE Standard 34 for refrigerants or ISO 10456 for building materials meaningful comparisons of data across studies are not possible, market confidence has not been established and evidence-based selection by system engineers have not been possible [82], [85]. This absence of a standard test protocol for PCM represents the most significant unresolved research gap defined in this research.

Gap 2: Long-term reliability of PCM systems under realistic HVAC operating conditions. Most of the data concerning cycling stability reported in the published literature comes from laboratory tests (generally 500–1000 cycles at a constant rate and in regulated conditions, using either DSC or bench-scale test methods) instead of actual HVAC systems with the variable charge/discharge rates, partial cycling, and actual thermal gradients typical of a building's normal operating conditions [7], [9]. Very few of the studies reviewed provide stability data beyond 1,000 cycles or longer than 1 year of continuous operation, and none consider the design life of most installed building systems to be 15–20 years. Without sufficient long-term field durability data, there is no way to accurately predict or estimate the temporary and/or long term performance degradation of installed PCM systems; thus it is impossible to include costs for possible replacements in the Lifecycle Cost analysis that can be used to estimate lifecycle costs.

Gap 3: The gap between laboratory and field performance of PCMs largely relates to the systematic procedure with which laboratory tests exhibit a consistent upper range of PCM performance (up to 88% COP improvement; up to 89% of total available off-peak load shifting) while field performance of PCM systems in real buildings using typical operational controls have substantially lower performance (7-20% annual energy savings) [110], [111], [112], [132], [133]. There are specific reasons for the systematic disparity of performance as described throughout this paper, including imperfect PCM nightly regeneration due to actual outside ventilation conditions, partial cycling due to changing occupancy, melting temperature mismatches due to varying outside temperatures throughout seasonal cycles, and control system constraints, but are not systematically and quantitatively broken out in the studies reviewed. Lack of such decomposition leaves both the expected and delivered performances uncertain, and therefore jeopardizes the potential accuracy of performance statements that have been derived from laboratory studies that are to be used in design.

Gap 4: Economic Performance Information for Small-Scale Residential and Commercial Applications. The majority of economic analyses (Life Cycle Cost Analysis), as well as payback period studies, identified in the current body of literature relate either to large commercial chilled-water thermal energy storage systems [112], [114] or to research buildings with a significant amount of instrumentation with the installation of PCM systems supported through grants [155], [157], [158]. Little to no independent and verified cost data are available through the peer-reviewed literature for residential PCM envelope retrofits, small split system air conditioning units significantly improved through the use of PCM heat exchangers, and for mixed-use buildings (i.e., multi-family dwellings) which constitute the preponderance of the global urban built environment being installed in hot climates. It is this lack of independent and verified cost data that limits the ability to provide evidence-based policy recommendations for the residential sector; the residential sector represents the largest percentage of global air conditioning energy consumption and the greatest potential market for PCM technology.

Gap 5: The compatibility of nano-enhancement additives with encapsulating materials during the long term is another area where we see an enormous gap. In sections 3.1.1–3.1.3, we reviewed data showing that nano-enhanced PCM composite materials made with graphene, carbon nanotubes, and the latest MXene materials demonstrated improved thermal conductivity (40–400%) [17], [21], [23], [24]. Unfortunately, very little research has been conducted on the long-term physical and chemical interactions between these nano-additives and the encapsulating shell materials (polymer, silica, or metallic) during extended cycling (e.g. agglomeration of the additives in the PCM matrix, long-term degradation of the shell material due to the volumetric stress imposed on it during the phase change, and the potential for release of the additives into the environment through the degradation of the shell material). All of the reviewed research has been performed under short-term laboratory conditions. Given that the materials and safety of materials used in buildings and the health of occupants must be ensured, long-term accelerated aging studies and field data must be completed before nano-enhanced PCMs can be recommended for widespread application in occupied residential and commercial buildings.

Numerous research gaps and future opportunities have been generated by the development of more efficient thermal energy storage, with particular emphasis on Emerging PCM Materials and Composites. Traditional solid-liquid PCMs are generally used widely, but solid-solid PCMs are a significant opportunity because they offer superior cyclic stability and no risk of leaking; however, the existing limitations are that they have a lower latent heat capacity and need to be addressed through molecular engineering. Along with this is the increasing demand for bio-polymer based materials and green composites to reduce environmental impacts within construction materials, but while these materials are sustainable, there is still work needed to improve the balance between high thermal performance and cost efficieny. In addition to this improvement, multifunctional composites, especially with hybrid nanoadditives, show promising potential to improve both thermal conduction and structural stability in one product, although their long-term behavior in actual use has not been thoroughly studied [132], [134], [163].

As material sciences move forward, researchers are pursuing the development of advanced control and optimization techniques to realize the full theoretical benefits of materials. Currently, machine learning algorithms are being used to help design a PCM system, with the aim of developing real-time optimization capabilities for fluctuating climatic conditions. If implemented, adaptive control techniques have the potential to greatly reduce energy consumption; however, these methods require substantial, large-scale validation across numerous building types. The absence of supporting empirical evidence will hinder commercial adoption due to the construction industry's need for reliable proof prior to using sophisticated logic in a standard building management protocol [111], [138], [141].

Last but not least, Integration with Renewable Energy Systems is an important way to reduce carbon emissions in our built environment. Due to this benefit, PCMs are becoming more frequently used in conjunction with solar and wind energy to act as a thermal buffer for load balancing to help smooth out the variability of renewable power sources. While encapsulated, nano-enhanced PCMs have the potential to significantly improve the overall efficiency of these storage systems, they also introduce an added level of mechanical complexity and an increased initial capital cost. Future research must concentrate on conducting comprehensive life cycle analysis (i.e., cost versus benefit analysis) to demonstrate that these costs are justified based upon the environmental and operational benefits achieved over the life of the system, relative to the original investment and any technical barriers [107], [121], [126]. Can summary in Fig.18.

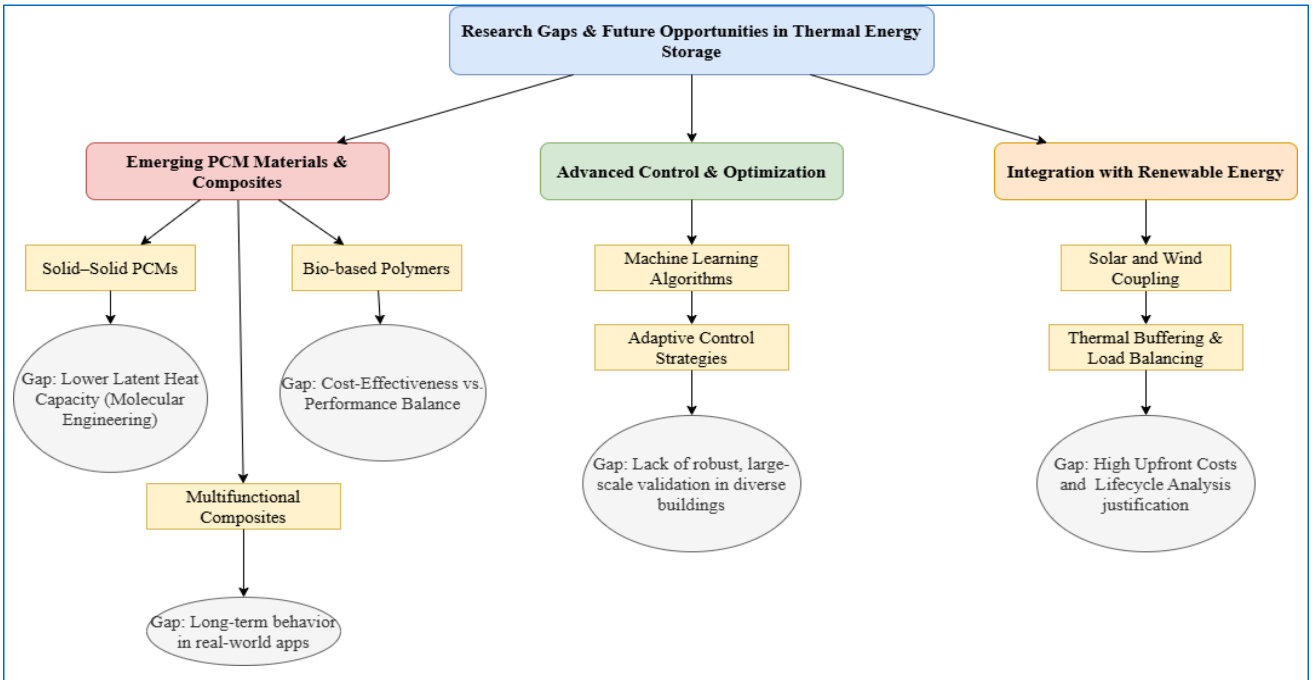


Fig. 18. The flowchart of research gaps and future opportunities in thermal energy storage.

7. Conclusions

This review has examined the role of phase change materials (PCMs) in enhancing the thermal and energy performance of air-conditioning systems, drawing on 166 peer-reviewed experimental, numerical, and field studies published between 2013 and 2025. The evidence demonstrates that PCM integration, when appropriately selected and implemented, provides quantifiable improvements across all three primary integration strategies reviewed. The key findings are summarised as follows:

- Organic PCMs are typically paraffin waxes or fatty acids. Organic PCMs show good cycle stability (up to approximately 3,000 cycles for paraffin wax), tunable melting points (20-70 °C for paraffin wax and 15-78 °C for fatty acids), and low corrosion potential; however, organic PCMs display inherently low thermal conductivity (0.15 to 0.20 W/m·K). Inorganic PCMs such as salt hydrates and molten salts typically show higher latent heat density and thermal conductivity; however, they suffer from the detrimental effects of super cooled and phase-separation. Eutectic phase change materials (PCMs) and composite PCMs utilize the benefits of individual materials to allow for very precise customization of their melting points making them ideal candidates for narrow temperature window HVAC applications.
- The addition of nanoparticles (graphene nanoplatelets, carbon nanotubes (CNTs), metallic oxide nanoparticles) to PCMs has been shown to improve their thermal conductivity by 40-50% or greater. The use of porous support structures (e.g., copper foam or expanded graphite) has been shown to reduce the amount of time required to melt and solidify the PCM by approximately 40%. Micro and nanoencapsulation of PCMs are capable of providing greater than 90% containment efficiency of the PCM, resulting in a reduction of PCM leakage and a significantly improved cycling lifetime of the PCM. These strategies are critical in achieving practical heat transfer rates when utilizing active HVAC systems.
- The studies examined provide information on the following COP improvements: from 7% to as much as 88%, annual energy savings associated with air conditioning are from 7%-32%, reductions in indoor temp fluctuations are up to 46%, reductions in the number of cooling loads are as much as 31% while shifting peak cooling loads from on-peak to off-peak periods by more than 89%. Laboratory studies generally show the highest end of variation but actual field evaluations of products used on building sites and under normal building operation show lower but still statistically valid percentages of 7%-30% energy savings.
- Many (more than one-half) of the PCM formulations tested have not been characterized (i.e., tested for long-term cycling stability) under actual building conditions during the expected duration of use. In addition to long-term cycling stability, there are many manufacturing scalability & costs of advanced additives, and other technical and economic barriers that must be overcome before commercial manufacturing of PCM becomes a cost-competitive high-volume (large scale) production process. In hot climate environments and high air conditioning demands, lifecycle costing (LCC) indicates that the average payback period for the application of PCM is between three to seven years with time-of-use electricity tariffs while in lower demand cold climates or very cold climate regions the payback periods for LCC exceed over 20 years. It is important to understand that deployment of PCM is entirely context depend.

Looking forward, there are several research paths to explore; including developing next-generation PCMs (solid-solid & bio-based) that offer high latent heat, cycling stability, are safe, and environmentally sound; as well as developing scalable and low-cost manufacturing processes for them. In addition, methods of integrating PCMs with advanced controls and optimization techniques for peak load shifting as well as energy efficiency (e.g., predictive and AI-based) based on building energy management systems must be researched and developed to effectively utilize the load-shifting capabilities and efficiency of PCMs.

Abbreviation	Full term
AC	Air conditioning
AI	Artificial intelligence
ANSYS	Analysis System (commercial simulation software)

BEMS	Building energy management system
CFD	Computational fluid dynamics
CNT	Carbon nanotube
COP	Coefficient of performance
CSP	Concentrated solar power
DSC	Differential scanning calorimetry
DSM	Demand-side management
EnergyPlus	Building energy simulation software (US Department of Energy)
FTIR	Fourier-transform infrared spectroscopy
HVAC	Heating, ventilation, and air conditioning
LCCA	Lifecycle cost analysis
LCA	Lifecycle assessment
MOF	Metal-organic framework
PCM	Phase change material
PEG	Polyethylene glycol
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
TES	Thermal energy storage
TGA	Thermogravimetric analysis
TRNSYS	Transient System Simulation Tool
XRD	X-ray diffraction

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