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Review

# Comprehensive examination of thermal energy storage through advanced phase change material integration for optimized building energy management and thermal comfort

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ABSTRACT

Several countries all over the world are interested in the energy business. The scientific community is creating new energy-saving experiments in response to the present fossil fuel problems. Buildings are one of the components that use more energy, so it is highly desirable that knowledge is being generated and technology is developing to provide answers to this energy demand. When used in building elements for heating and cooling like coatings, blocks, panels or wall panels, phase change materials (PCMs) have been demonstrated to enhance the capacity for heat storage by absorbing heat as latent heat. Thus, during the past 20 years, research has been done on the application of phase change materials (PCMs) in latent heat storage systems. The most practical way to incorporate PCMs into construction parts is through the macro encapsulation approach, which is examined in this review together with the microencapsulation method. Furthermore, given that additional research is required to process biobased PCMs, we must pay greater attention to them, as evidenced by our examination of the literature on the encapsulation process of PCMs. Due to the lack of information provided in other reviews, there is a section dedicated to the superior PCM with lightweight material to ascertain its macro and microscale thermophysical and mechanical characteristics as well as to determine whether it would be feasible to switch from PCM that are made from petroleum to more ecologically friendly bio-based ones. Above all, this study also focuses on reviewing recent PCM research and evaluating the thermal performance of prototypes used in experimental PCM investigations, i.e., how the layout of design affects several variables and potential applications of PCM.

## 1. Introduction

Building energy consumption accounts for a significant portion of global energy usage, particularly in heating and cooling systems. As global demand for energy-efficient solutions grows, phase change materials (PCM) have emerged as an innovative approach to enhance thermal performance and reduce energy consumption in buildings. PCMs can store and release large amounts of latent heat during phase transitions, which helps maintain indoor thermal comfort while reducing the reliance on conventional heating, ventilation, and air conditioning (HVAC) systems. Numerous studies have been conducted on the integration of PCMs in building materials [1–7], emphasizing the role of latent heat thermal energy storage (LHTES) systems. Early research primarily focused on petroleum-derived PCMs, which have been widely used due to their thermal efficiency and availability. However, environmental concerns have prompted a shift towards bio-based PCMs, which offer similar thermal properties with a lower carbon footprint. In addition, recent advancements in encapsulation techniques, such as microencapsulation and macro encapsulation, have improved the thermal performance and long-term stability of PCMs in various building applications.

Despite the clear potential of PCMs, there is still a need to explore their full range of applications, particularly in building retrofits and new construction. This review aims to provide a comprehensive examination of thermal energy storage through advanced PCM integration, addressing the latest advancements, challenges, and practical implementations. By focusing on bio-based and petroleum-derived PCMs, encapsulation techniques, and economic viability, this review seeks to provide key insights that can drive the widespread adoption of PCMs in built environments.

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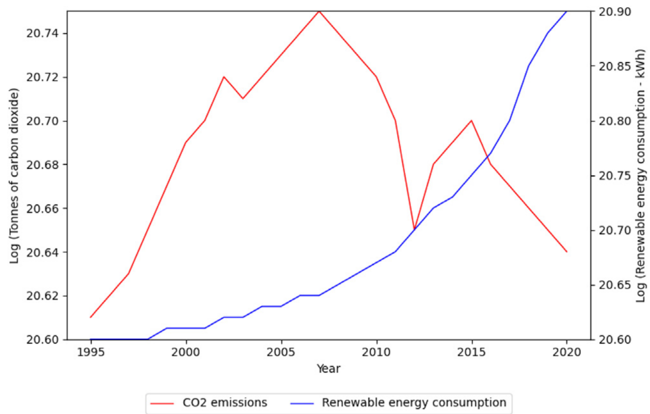


**Fig. 1.** Relation between $CO_2$ emissions and renewable energy consumption.

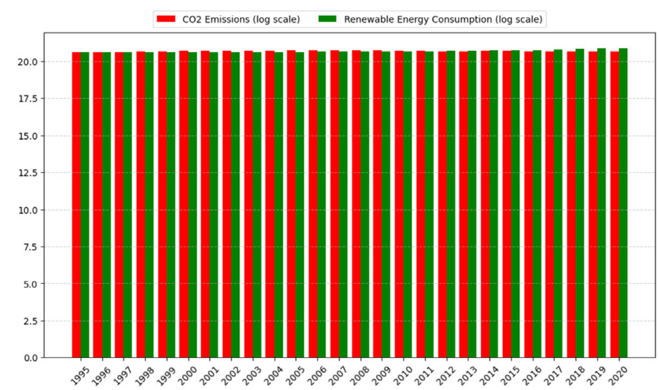


**Fig. 2.** Relation between $CO_2$ emissions and renewable energy consumption (1995-2020).

## 2. Literature Review

Global energy demand has resulted in an unprecedented increase in global energy-related $CO_2$ emissions, which rose by 1.7% in 2018 to 33.1 $GtCO_2$, according to the International Energy Agency's (IEA) 2019 global energy and $CO_2$ status report. In addition to being the principal cause of global warming, $CO_2$ emissions from the combustion of fossil fuels, notably coal, have been found to account for 0.3 of the 1-degree Celsius rise in average annual global surface temperature above pre-industrial levels [8]. This illustrates the reality that burning fossil fuel provides more than 75% of the world's energy [9]. The present focus of the study is on increasing the percentage of renewable and sustainable energy in response to the world's grave environmental issue caused by increased energy consumption, as shown in Figs. 1 and 2, because of fast population expansion and rapid economic development [10–17]. Fig. 1 illustrates the correlation between $CO_2$ emissions and renewables consumption over time. At first $CO_2$ emissions rose, while renewable energy use was still low. But around 2010, things changed. Then, when renewable energy consumption started to increase, $CO_2$ emissions began to decrease. This negative link indicates that the growing integration of renewable energy sources has played a role in lowering $CO_2$ emissions, a positive indicator of more sustainable energy practices.

Fig. 2 illustrates that over these long years, $CO_2$ emissions are stable and are hardly noticeably dropping. Renewable Energy Consumption, however, displays a slow but steady rise, indicating a growing trend in its uptake. Despite the growing consumption of renewable energy, however, there seems to be little evidence that it has led to a meaningful reduction in $CO_2$ emissions, indicating that transition to renewable energy has not been significant enough to significantly lower emissions during this period.

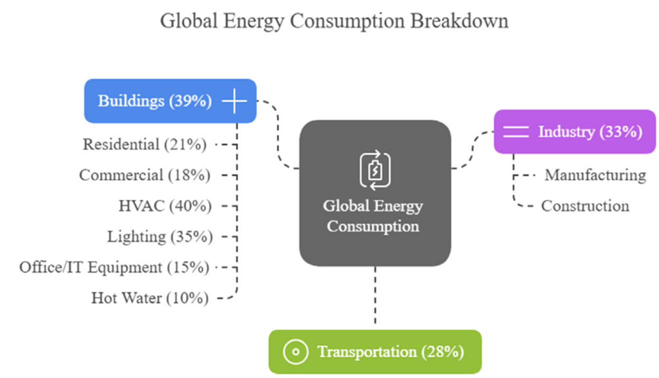


**Fig. 3.** Key contributions towards global energy consumption.

The growing worldwide population is one element influencing the rise in electrical energy usage. It is estimated that in most developed nations, residential and commercial buildings account for 20% to 40% of total electrical energy use, while interior space thermal cooling accounts for approximately 50% [18]. There are several dimensions to the solutions used to lower these high electrical energy consumption rates [19,20]. Most of this tackles the issue by making thermal conditioning equipment more efficient [21]. Alternative approaches aim to create materials that enhance the hermeticity of the areas that need to be conditioned [22]. Several engineering specialties have recently formulated studies into phase change materials. These have to do with actual concepts of embedded heat or the energy that is taken in and expelled when a material undergoes a phase change. This study provides excellent illustrations of the solid-liquid and liquid-solid state transformation mechanism associated with the material's fusion and crystallization [23–25]. As shown in Fig. 3, most of the energy used globally is used by buildings, with residential and commercial spaces accounting for the majority of this amount. Since HVAC accounts for the majority of building energy consumption, it consumes the largest percentage of energy. Hot water systems and office and IT equipment make up the remaining proportions, with lighting coming in second. To reduce energy consumption, these sectors highlight the necessity of energy efficiency in buildings, particularly in lighting and climate management.

Heating, ventilation, and air conditioning (HVAC) systems account for half of the energy consumed by the building sector, owing to the need for thermal comfort enhancement and the substitution of high thermal mass materials for lightweight, low thermal capacity buildings in contemporary homes, resulting in high heating and cooling loads [26,27].

The fabrication of building materials and the provision of electrical energy for sustaining people's thermal comfort in current constructions are the key drivers of these high percentages [28]. However, if energy solutions are not developed and executed, scientists anticipate that global energy consumption will grow by 50% by 2050 [29]. According to statistics collected from various areas, buildings account for 28% of total energy consumption in Tunisia [30], 24% in the United States [31], 20% in China [32], and 40% in the European Union [33,34]. Buildings account for about 30% of $CO_2$ emissions and almost 40% of total energy use worldwide, indicating their involvement in global warming [35].

A significant melting enthalpy and an appropriate phase change temperature are the two fundamental needs of a phase change material to obtain high storage density relative to sensible heat storage. As shown in Fig. 4, Solid, liquid, gas, and plasma phases of matter are depicted together with their transitions, including melting, solidification, vaporization, condensation, sublimation, deposition, ionization, and recombination. Enthalpy, or energy content, varies during these phase transitions, with higher-energy phases requiring more energy. Phase change materials (PCMs) are made to take advantage of these transitions, especially those between the solid and liquid states, to store and release heat in the context of thermal energy storage. In any building applica-

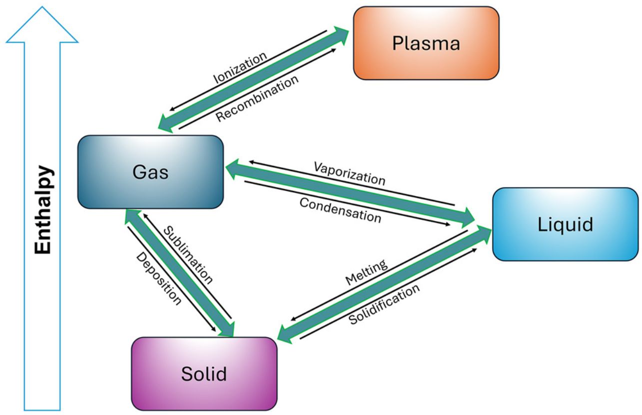


**Fig. 4.** Phase transition for property enhancement of phase change materials.

tion, phase change materials are a valuable addition since they collect and release heat when going through a phase change. By holding excess heat during hot weather and releasing it during cool weather, PCMs reduce the demand for HVAC systems. The buildings become more sustainable and energy efficient because of the improved thermal comfort and energy savings. PCMs can be used to help regulate temperature variations in walls, floors, and even ceilings [36]. Nonetheless, for building conditioning to perform as well as it should, certain physical, technological, and financial requirements may need to be met, depending on the application. To prevent "phase separation" because of cycle instability, the primary criteria are reproducible phase change (cycling stability). Reliability of solidification and melting within a minimum temperature range is ensured by minimal subcooling (temperatures much below the melting temperature); enough thermal conductivity permits latent heat to be either emitted or retained with adequate power for heating and cooling. PCMs must be stored in matrices because they frequently transition from a solid to a liquid state [37–39]. The design of PCMs needs to consider various technical specifications, including chemical, mechanical, safety, and economic ones. These include minimal volume change, stability in chemicals, lower vapour pressure, connectivity or compatibility with other materials, non-flammable and non-toxic materials, long lifespan, abundance, and cost-effectiveness [40,41].

Renewable energy technologies bring energy conservation management solutions, for example, including latent heat storage (LHS) systems into buildings, conscious that a 20% drop in the use of buildings might result in a 50% reduction in $CO_2$ emissions from the existing state [26,27,42–45]. The three basic subcategories of thermochemical energy storage (TES) are sensible heat storage (SHS), latent heat storage (LHS), and thermal chemical energy storage, or combinations of all these energy systems [35,46]. For example, LHTES has 5-14 times the storage capacity per unit volume of SHS [47]. Two investigations found that latent heat storage of paraffin wax required less than seven times the storage mass of SHS material to store the same amount of energy, whereas $Na_2SO_4{\cdot}10H_2O$ requires eight times less storage mass [48,49]. LHS materials are mostly composed of PCMs. These materials are further divided into three basic types based on the regions or states of their transition phases:

(1) liquid-gaseous;
(2) solid-liquid;
(3) solid-solid, with being used in constructions [50].

The thermal storage application determines how the PCMs are stored. The degree of purity provided by each phase change material's manufacturer must also be considered in a reliable thermal storage system design for any application; otherwise, materials that contain PCMs may exhibit differences in thermophysical properties [51,52]. For the LHTS system to work properly, it needs two or more additional parts in addition to the PCM:

(1) a vessel (which encapsulates phase change material);
(2) an exchanger heat surface (which is necessary to transport heat from the heat source to the PCM and from the PCM to the heat sink;

To obtain an adequate process of phase change process such as solid–solid, solid–liquid, solid–gas, or liquid–gas, the storage ability of the material depends on both of its SH and LH (which are sensible heat and latent heat values). TES systems are sensitive to either LH storage, heat storage, or a combination of both. The following methods or processes of integrating PCMs into construction materials and structures to stop PCMs from escaping in a melted condition have been documented in several research studies and papers:

(1) (PCMs can be encapsulated in a small capsule (micro-encapsulation);
(2) Sealed tightly (Hermetically) inside a container (macro encapsulation);
(3) Shape-stabilized; and
(4) Impregnated into porous building supplies or materials.

Because some organic chemicals in phase change materials may dissipate or leak out, maintaining the stability of a PCM in a liquid matrix is challenging [53]. This is the primary disadvantage of introducing PCMs through immersion in porous materials (such as concrete). This discovery is supported by a review of the findings from earlier publications. The thermal storage driving force is divided into two subcategories:

(1) passive systems, in which the temperature differential between the environment and the PCM causes the charging/discharging of PCM, relying on daily variations in solar radiation.
(2) active systems, where forced convection of a fluid by heat contact affects PCM charging and releasing, and

Furthermore, the climate of the test site influences the type of thermal stress. Hybrid systems employ either heating or cooling, or both. Include prospective research methods for PCM applications, such as numerical and/or simulation studies. Finally, the kind and size of the facility have a significant impact on how PCM research results are affected. This literature-based classification includes four basic categories:

(1) full prototypes,
(2) compact prototypes,
(3) transforming multiple compartments, and
(4) partitioning chambers under lab control.

For PCM building applications, the categorization criteria are described in a hierarchical structure as demonstrated in Fig. 5.

Furthermore, because of their high-water content, salt hydrates are especially inappropriate for this kind of containment. The addition of PCM might inhibit the process of hydration of cement in some situations involving combinations including Portland cement and alkali-activated components, which could have a negative impact on the mechanical characteristics [54–57]. Regarding the macro-encapsulation procedure, the PCM is not combined with the raw material (such as plaster or concrete), and many articles discuss an appropriate way to incorporate PCMs into building components, particularly prefabricated roofs, and walls. Moreover, macro-encapsulated PCM members could be created by making use of shape-stabilized PCMs or micro capsules [58–60]. One term used to describe PCM development in aggregates that are lightweight is "macro-encapsulation." Nonetheless, this procedure might be linked to an additional encapsulation method [61–63]. The ability to combine the PCM-filled capsules with other materials (things like wood-plastic, composite form, geopolymer mixture plaster, and concrete) is an advantage of this confinement method. A physical barrier separating the product's core substance from other constituents can be constituted by the micro-capsule layer. When PCMs are utilized with building materials, they must be enclosed in a tougher, more flexible shell [64–68].

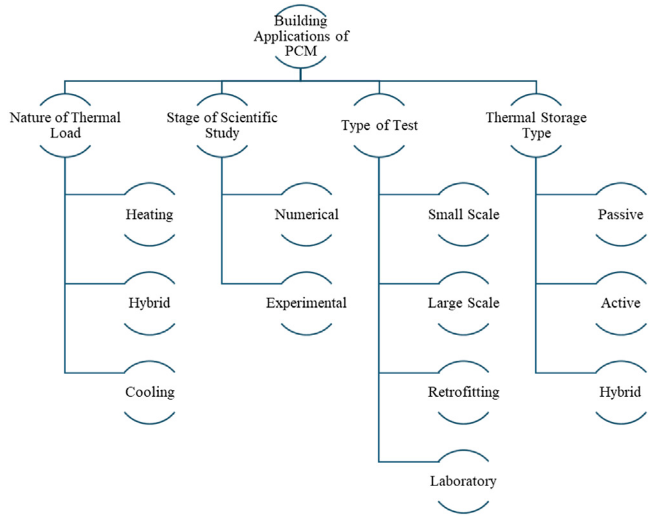


**Fig. 5.** Categorization criteria for PCM building applications.

However, based on an examination of the data from the studied publications, it appears that most of the materials used to create microcapsules have low thermal conductivity, and this, along with PCM's very small mass fraction, results in a small total heat storage capacity. Certain mechanical property criteria must be met by the concrete, mortar, and plaster; adding a lot of microcapsules can lower these requirements [69].

In terms of the shape of stabilized PCMs, a porous supporting material with a high heat conductivity is used to stabilize the material [70–72]. The following substances have been recommended in various studies: kaolin, bentonite, diatomite, graphite powder, and silica fume [73–78]. Furthermore, they describe three approaches (direct absorption, vacuum impregnation, and sol-gel procedures) for obtaining shape-stabilized PCMs. One feature of these manufacturing processes is that the structure with pores absorbs the molten PCM of the host material [79–83]. The sol-gel procedure is a way of creating shape-stabilized PCMs in both organic and inorganic forms, and vacuum impregnation is a great substitute to have the largest amount of molten PCM absorbed in the porous structure [84–90]. Because of their superior application and increased absorption capacity, silica fume and graphite powder have been utilized frequently in cementitious composites. In the past, silica fumes were used in mortar and concrete or cementitious composites as a pozzolanic micro-filler. However, according to several studies, it is possible to add shape-stabilized PCMs to cement, mortar, concrete, and paving materials to lower their elastic modulus and compressive strength.

To control interior temperature changes, several researchers have also employed various shape-stabilized PCM composites in both lab and real-scale samples for non-structural construction components such as walls and building envelopes [91–94]. Creating ecologically friendly materials is now crucial in all fields of research and engineering. Numerous studies have examined the viability of employing biomass feedstocks in PCMs, which have the potential to yield high-value products for PCM materials. This study has examined the viability of employing a novel carrier for phase-change material produced by the pyrolysis breakdown of waste biomass. Here, char made from biomass is added as a carrier of PCM [95]. The biomass was derived from the products of the inedible chestnut (Aesculus hippocastanum), while any waste biomass could serve as the basic source of the char [96,97]. The procedure in order to acquire the char and the initial laboratory thermal analysis is reported in this article. The work involved obtaining the thermodynamic properties of the PCM, which was composed of pure PCM (Char and Rubitherm RT22) and comparing those properties to those of a micro-encapsulated PCM (Micronal 5040X). It's noteworthy to note from the results that using char as a PCM carrier could have thermodynamic benefits and be a viable substitute for manufactured goods. To confirm the mechanical and thermal capabilities, tests integrating this biobased PCM with building materials have not yet been conducted. This research has compared the thermal behaviour of three PCMs based on paraffin (RT24, RT25, and RT26) as well as one bio-based PCM (PureTemp25). Other works examine the thermo-physical properties of several organic biobased PCMs [98].

PCM composites were made by [99] using fat wastes from abattoir residues without additional chemical processing. Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) were employed in this study to assess the materials' thermophysical properties and calculate their thermal energy storage capabilities. The findings of these studies show the viability of replacing Petroleum-derived PCMs with more ecologically friendly bio-based ones [100]. It is important to note, nonetheless, that the mechanical qualities of building materials including bio-based PCMs should be assessed regarding the thermal characteristics before they can be used in real-world applications [101–104]. Additionally, the knowledge gained from these studies can be used to create standards for the characterization and analysis of organic PCMs [105–108]. Since 1970, research has been done on the employment of PCMs in buildings for thermal energy storage. In addition, as opposed to our review, several review papers that have been published ever since have concentrated on analyzing and discussing the thermal performance of different kinds of systems, including PCM building blocks, PCM wallboards (including gypsum), PCM shutters, ceiling boards, floor heating, and air-based heating systems. They report using PCM materials that are available for purchase and discuss current initiatives to create novel phase change materials [109–113]. The characterization of thermal characteristics, long-term stability, encapsulation, and heat transmission using numerical simulation and experimental methodologies have all been the subject of several studies [114–117].

The subsequent structural components have been published about some recent experimental investigations that use environmental chambers or real-world climatic settings to evaluate the effectiveness of PCM incorporated into building components: The items include test huts, a concrete wallboard sample, masonry brick walls, concrete sandwich panel walls, a concrete core slab in test cubicles, a tiny house and room model, and pavement. The PCMs were incorporated into these building elements in a variety of methods, including porous inclusion, PCM microcapsules, hollow steel ball macrocapsules, PCM underfloor heating system, and macro-encapsulation. The goals differed and included evaluating thermal performance, validating numerical simulations, controlling thermal stress in concrete, and melting ice and snow [118]. Nevertheless, based on the above-mentioned papers, it can be deduced that there aren't many studies conducted on real-scale models, and the ones that do exist mostly concentrate on research on thermal behaviour, which is unquestionably the most important property of PCM materials and the reason why using them in building components makes sense. To guarantee that they may be used safely to provide parameters and construction rules with such systems, investigations on the structural behaviour of buildings with PCMs subjected to both dynamic and quasi-static monotonic loads must be conducted, even when the PCM-equipped systems meet the necessary heat requirements. However, more research on cementitious materials has shown that adding PCMs to lab specimens can lessen the tendency of concrete to crack at high temperatures. The heat flow and temperature change in concrete elements during the hydration process of Portland cement have been studied in research studies. Similarly, research has been done on the harm caused by freeze cycles in concrete pavements that contain PCM [119–121]. Created by mixing PCM with cementitious materials, envelope elements (panels, walls, or clay partitions made of lightweight composite materials) are among the most often studied in research. By directly comparing the thermal behaviour of complete models both with and without PCM components, research has shown the advantages of including PCM materials. In certain instances, it has been possible to lower the highest temperature reached by at least 2 °C [122–126].

To effectively meet real-world conditions, PCM research in buildings should include as many studies as possible and a wider range of parameters. Regarding the driving force for thermal storage, a lot of PCM studies focus on a specific PCM application, such as an integrated active radiant heating system [127,128]. Most applications aim to heat or cool objects. To save money, researchers undertake numerical investigations. When trials are done to validate models, they are often limited to the partitioning of structural elements like the partitions, rooftop, or floor. Test settings presented in the literature can be used to assess the impact of including PCM with limited variables. Studies concentrating on the kind of PCM utilized are robbed of the ability to analyze the location of PCM, for example, and studies exploring PCM placement in walls deprive them of an opportunity to compare active systems to the examined passive situation.

In conclusion, this research is a unique type of review article that tries to summarize PCM experimental testing of various sizes and configurations before concluding with major results, suggestions, and conclusions in the PCM sector, as well as the vast majority of melting and solidifying PCMs across a broad temperature range, have been discussed thus far in this article. The aggregate techniques for building materials are examined, with a focus on macro and micro-encapsulation, being the most practical approach to incorporating particulate matter minerals (PCMs) into building components. The techniques and procedures employed to accomplish this confinement are explained. Furthermore, this article highlights the need to study both the micro and macro levels, thermophysical and mechanical behavior, as well as the bio-based PCMs processes, to show that it is feasible to replace petroleum-based PCMs with more environmentally friendly bio-based ones. This is based on the papers that have been critically revised. To better understand the nonlinear behaviour of materials containing PCMs and build systems that maximize performance, Multiphysics models of their behaviour are also essential. The PCM with lightweight aggregate portion is finally provided. To bolster the distinctions with other reviews found in the literature, it is important to note that some reviews focus on thermal transfer and energy storage [51,107,114,129–131]. Other reviews, such as [110] and [132], discuss micro or macro-encapsulation in brief along with long-term stability and thermophysical properties, and reviews by [133] and [111] only address microencapsulation techniques. Potential ways to incorporate PCMs into building materials (micro and macro-encapsulation) are examined by [112], with a focus on concrete stabilization materials and methods. On the other hand, the macro-encapsulation technique is covered in this review [113], along with thermal energy storage methods used in buildings. In the meantime, the review [134] explains the concrete integration, immersion, and impregnation processes.

Following the introduction, this research is broken down into seven sections. The remainder of the paper is structured as follows: Section 3 provides a general classification of PCM materials. Encapsulation processes and their types have been covered in Section 4. Section 5 deals with the mechanical properties of PCM-integrated building materials. A piece of detailed information on PCM encapsulation processes and a Summary of the Reviews on PCM Building Recent Applications and studies on test facility specifications that fall into one of the following four categories: full large-scale prototype-based experimental studies, compact scale prototype experimental studies, transformed multiple compartments-based experimental studies and under lab control partition chamber-based experimental studies is presented in Section 6. Section 7 puts forward PCM with lightweight aggregate an additional intriguing approach for incorporating PCMs as well. Section 8 presents the future perspective followed by suggestions and discussions and Finally, Section 9 draws conclusions.

## 3. General Classification of PCM Materials

High thermal conductivity and significant latent heat are necessary for materials used in phase change thermal energy storage. They should be inexpensive, chemically stable, non-toxic, non-corrosive, and have a melting point that falls within the realistic range of operation. They should also melt with the least amount of subcooling. The PCMs are classified into three categories as shown in Fig. 6: (a) eutectic, (b) inorganic, and (c) organic, combinations of chemicals with varying phase transition temperatures. This classification is the result of research conducted over a 40-to-50-year period, during which time other researchers have demonstrated the benefits and drawbacks of PCMs. Various experimental methods [135–137] have been documented and applied to ascertain the melting and solidification behaviour of various materials. Therefore, it can be concluded from the examined studies [138–142] that no substance possesses all the ideal qualities needed to a PCM and that choosing a PCM for a particular utilization necessitates carefully weighing the qualities of different compounds. Differential scanning calorimetry techniques (DSC) are extensively employed in the identification and classification of PCMs based on those characteristics that are thermophysical, comprising their specific heat, heat of fusion, and melting point. It may be argued, though, that additional techniques have also been employed [143–148], including the T-history method and traditional calorimetry techniques. Thermograms are used to analyze these characteristics, allowing us to determine the phase transition temperatures at which melting and freezing occur. However, because the values of these attributes are determined by using small samples, large samples may yield different results [149–154].

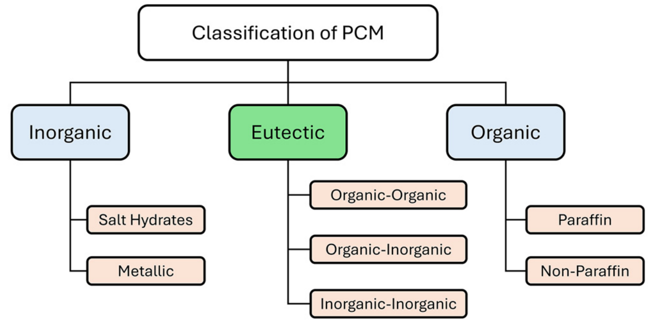


**Fig. 6.** Classification of PCM.

### 3.1. Inorganic

Fewer inorganic compounds can be utilized in the building business as opposed to organic PCMs. Hydrated salts and metallic salts are the two most used varieties; in all PCM-related study disciplines, hydrated salts have been the most extensively explored.

### 3.2. Organic

Among the phase-changing organic compounds, paraffin, fatty acids, and (PEG) polyethylene glycol are three subtypes that stand out. These substances often have excellent chemical stability and good thermal characteristics [52]. Consequently, a large amount of current study is focused on the various types of paraffin and how they can be used as building materials because of their stability in terms of chemicals, which makes the combo of materials and products easier. The two main types of organic PCMs are paraffinic materials and those that are not. The majority of paraffins have not been employed in PCMs due to their significant flammability. But because paraffin has a large latent heat and strong thermal features (little supercooling, varying phase transition temperature, low vapor pressure in the melt, good thermal and chemical stability, and self-nucleating behavior) in the right container, it has been employed extensively [98,155,156].

On the other hand, research demonstrates that non-paraffin, biological PCMs are significantly less toxic than paraffin. Bio-based PCMs, or

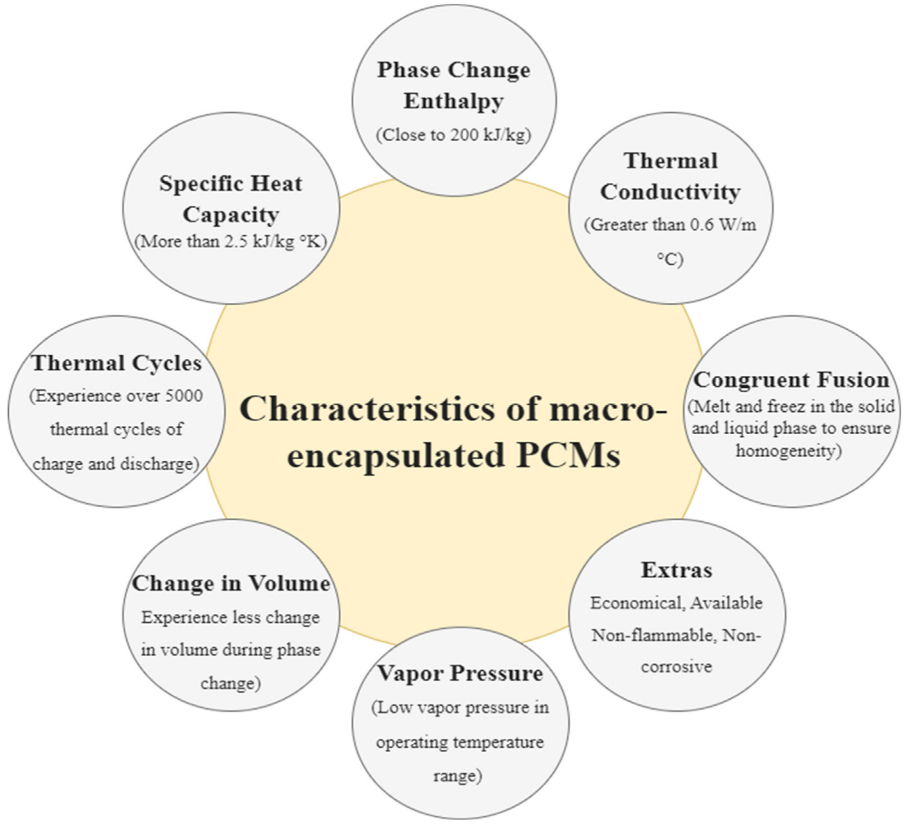


**Fig. 7.** Properties of PCMs with macro-encapsulation for buildings.

PCMs containing organic fatty acids, are primarily made up of incredibly sustainable bio-sources and are produced from underutilized and renewable feedstock, such as vegetable or animal fats, animal fats, and industrial or agricultural wastes. These bio-based (non-paraffin) PCMs have drawn the attention of several researchers [157], who have tested their appropriateness in terms of thermophysical characteristics as well as heat storage capability measured in melting temperature, specific heat capacity, and phase-change enthalpy. Unfortunately, literature currently only has a small amount of thermal data. Moreover, bio-based PCMs are not characterized by any rules or standards.

### 3.3. Eutectics

To reach a certain melting point, a eutectic PCM is a blend of two or more PCMs. Eutectic materials almost always melt and freeze without segregation. These PCMs gained significant prominence because they contain a variety of eutectic chemicals, each with unique features that can help thermal energy storage systems. The literature [158–162] generally indicates that non-organic PCMs have superior thermal storage properties; on the other hand, their cost is typically higher than that of paraffin. A few of the chemical components utilized in building materials are displayed in Fig. 7. Even though these are the primary characteristics, it is practical to consider additional secondary characteristics as well since these may be crucial based on the usage, region, and quantity of cycles [51,152], and [163] all describe the thermodynamic characteristics of PCM that are appropriate for buildings. Meanwhile, also lists the benefits and drawbacks of different PCMs.

## 4. Types of Encapsulation Processes for PCMs

A surface for heat exchange that transmits heat to the PCM from the heat source and the PCM from the heat sink is vital to the functioning of a PCM thermal storage system . The encapsulation must be strong, flexible, resistant to corrosion, thermally stable, structurally stable, and easy to handle for it to function well. The most common forms of confinements that are investigated for PCMs are macro-encapsulation, and microencapsulation [164,165].

### 4.1. Macro-Encapsulation

Macro-encapsulation, in which a sizable amount of PCM is contained in a distinct unit, is the most prevalent type of PCM confinement. The enclosed shell can take on any shape, including cubes, tubes, cylinders, and pouches. Tin-plated metal cans, mild steel cans, and plastic bottles (polypropylene and high-density and low-density polyethylene bottles) are the most economical packaging options. PCM can weigh anywhere from a few grams to a kilogram per unit. The examination of the updated articles demonstrates how simple it is to create macro-encapsulated PCM in any size or form to fit a variety of uses. PCM's macro-encapsulation does not call on a pre-established procedure, in contrast to micro-encapsulation, which encapsulates the PCM using a variety of approaches and strategies. There are numerous applications for macro-encapsulation in terms of energy storage demand, and it is simple to integrate into any kind of building envelope, size, or dimension by carefully choosing the capsule geometry and material. Nonetheless, more research is still needed to determine whether the shell material is compatible with PCM and building materials [166–173]. The benefit of macro-encapsulation is that it is easier to handle and transport, and air or liquid can be utilized as heat transfer fluids with it.

Since the facades of buildings are exposed to the elements and solar radiation, macro-capsules are typically included in outside walls and precast slabs. Its function depends on many factors: (a) the microcapsules location (interior or exterior surface); (b) the region's local weather conditions (sun radiation, ambient temperature); (c) The geometric characteristics of construction; (d) conductive properties of the construction material and PCM type. A few reliable producers of macro-encapsulated PCM have produced and marketed it under different brands, including HDPE (High-Density Polyethylene) panels, breather membranes, plastic blocks, aluminum tubes, pouches, breather membranes, and aluminum panels [174–180]. The features of macro-encapsulated PCMs for buildings are compiled in Fig. 7, manufacturers of goods suitable for building applications are listed in [181,182].

### 4.2. Microencapsulation

The techniques known as "microencapsulation" involve the continuous, sealed encapsulation of microscopic PCM droplets or particles, which can have a spherical or rod-shaped form. By using this method, PCM reactivity with the external environment can be reduced and melted PCM leakage from latent heat thermal energy storage devices can be prevented. The microencapsulation approach is more expensive than other thermal storage methods. A thorough review of the literature [182–184] shows how phase separation is confined to minuscule distances using micro-encapsulation, which improves cycling stability and enhances the transport of heat to the surroundings because of its high surface to volume ratio. After that, it is possible to combine the coated particles into a powder or distribute throughout a carrier fluid in any matrix that works with the encapsulating film. As a result, the film needs to work with the matrix and PCM. Numerous morphologies, or shapes, are available for microcapsules, depending on how the shell is deposited and how the core material is arranged. Distributions can be classified as matrix encapsulation, polynuclear, multi-film, and mononuclear (core/shell) [185–187]. With a melting point that is close to human comfort—roughly 20°C organic PCM core offers several benefits over other PCM material types. Several kinds of organic PCM are included, such as polyethylene glycol, fatty acids, alcohols, esters, and paraffin (n-alkane) (PEG).

The most common selection for core materials in organic PCM is the paraffin class of compounds. However, encapsulating polyethylene glycol (PEG) is a challenging task. Likewise, because inorganic salts dissolve in water, they are also infrequently enclosed. Shell materials, which can be either inorganic or organic, or hybrid shell materials composed of an organic and inorganic mixture, are what make up the capsules that hold the PCM. Most of the shells are made of organic materials and are produced chemically using processes like polymerization. A shell material should have strong chemical and thermal stability and should not react chemically with the PCM core. Its surface shape needs to be smooth, with the least amount of porosity possible, to stop PCM from leaking at temperatures higher than its melting point. In addition to providing shape stability and mechanical strength (thick layers exhibiting superior mechanical behaviour), a high heat conductivity shell material is preferred.

Regarding the encapsulation process, it can be observed from the literature that there are three distinct approaches to microencapsulated PCM, and the best method relies on the materials' chemical and physical characteristics [188,189]: Physical methods include spray drying, solvent evaporation, air-suspension coating, pan coating, centrifugal extrusion, vibrational nozzle, and Ionic gelation. Physic-chemical methods include coacervation, sol-gel, and ionic gelation. Chemical methods include interfacial polymerization, suspension polymerization, and emulsion polymerization. According to research findings, the quality of the microencapsulation process PCMs is correlated with the mean diameter, the thickness of the shell, and the mass percentage of PCM relative to the overall mass of the capsule. The PCM approach still requires refinement since, in active systems, the microcapsules may shatter upon collision with one another. In other places, Improvements in heat transfer rate and efficiency have been observed when employing integrated carbon additives in construction materials made of composite materials including PCM microcapsules [190,191].

In conclusion, we can see from the literature that has been edited so far that numerous researchers have examined microencapsulation, but the study is dispersed [192]. Two companies, BASF and Microteklab, have developed PCM micro-encapsulated products for use in homes and offices. Additionally, commercial PCMs are already available from Rubitherm GmbH (Germany), Cristopia (France), TEAPEnergy (Australia), PCMProducts (UK), Climator (Sweden), and Mitsubishi Chemical (Japan). Enhancing the sustainability and durability of mortars and concretes is one of the goals of including PCMs, irrespective of the technology used [193,194]. This study used micro-capsules made by Microteklab and Micronal-BASF to assess the durability of mortars based on Portland cement. Their findings revealed that the phase change enthalpy has decreased by about 25%. The chemical reaction with the sulphate ions during the mixing process were blamed for this decrease rather than the mechanical impact of the microcapsules. Furthermore, this study demonstrates that the reaction between PCM and ions does not affect the mortar's endurance [195].

Although microencapsulation offers better stability and heat transfer performance, its higher production costs may prevent it from being used in projects where money is tight. However, macro-encapsulation may not reach the same degree of thermal efficiency but provides a more cost-effective alternative with easier production procedures. The application requirements, such as the required thermal reaction time, financial limitations, and implementation size, frequently influence which of these approaches is best. For instance, macro-encapsulation works better for large-scale building envelopes or retrofitting, while microencapsulated PCMs are best suited for high-precision applications like thin wall panels or sophisticated HVAC systems. In summary, the requirements of the project, such as the trade-off between cost, thermal efficiency, and scalability, will determine whether to use microencapsulation or macro-encapsulation. While macro-encapsulated PCMs provide a more practical and cost-effective alternative for large-scale deployments where cost-effectiveness and convenience of manufacturing are more important than thermal precision, microencapsulated PCMs are well-suited for high-performance applications where precision is crucial. Furthermore, hybrid strategies that combine the two approaches are being investigated to maximize cost and performance, increasing PCMs' adaptability for a greater variety of building applications.

## 5. Mechanical Properties of PCM Integrated Building Material

The mechanical characteristics of construction materials including plaster, concrete, and wallboards may be affected by the incorporation of Phase Change Materials (PCMs). To guarantee that PCM-enhanced systems retain the required structural integrity for long-term use, it is imperative to comprehend these consequences.

**Strength:** Particularly when microencapsulated or macroencapsulated PCMs are introduced, the compressive strength of materials like concrete or gypsum may be marginally decreased. While PCM integration can reduce compressive strength by up to 10%, studies like those by [196] have demonstrated that the loss is frequently within acceptable bounds for non-load-bearing constructions. The impact on strength must be carefully evaluated for load-bearing applications, though, and mixture modifications (such as the use of stronger binders) might be required to make up for the loss in mechanical performance.

**Elasticity:** Additionally, materials with embedded PCMs may lose some of their elasticity, especially in systems that employ macro-encapsulation. Large PCM capsules may cause the material to develop weak spots, which would decrease its flexibility and increase the likelihood that it will shatter when subjected to mechanical stress. However, because the smaller particle size permits more uniform distribution and reduces weak points, microencapsulation often has less of an effect on the material's elasticity. According to research by [197] the PCM content and encapsulation technique can be optimised to reduce the effect on elasticity.

**Durability and Longevity:** PCMs can improve a material's overall durability by preventing thermal fatigue, especially when they are enclosed in metals or polymers. By buffering temperature variations, PCMs' thermal cycling qualities lower the chance of thermal cracking in materials like concrete or plaster. However, if the PCM is not sufficiently encapsulated, frequent phase transitions may cause problems

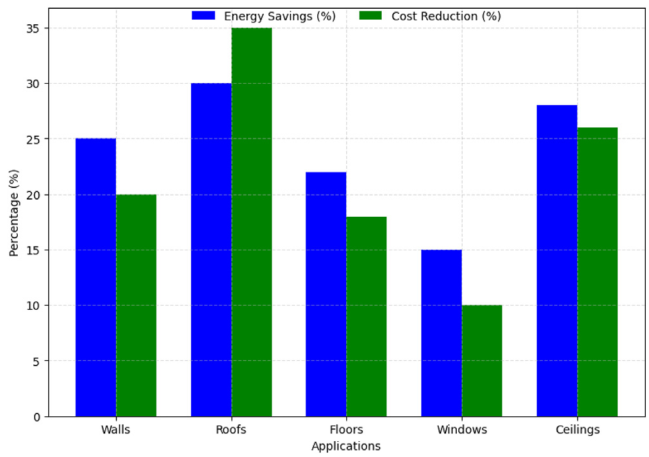


**Fig. 8.** Properties of PCMs with macro-encapsulation for buildings.

like delamination or microcracking, particularly in applications that are prone to mechanical stress.

**Adhesion and Compatibility:** The PCM's adherence to the surrounding material is another crucial mechanical characteristic. Delamination or separation may result from poor adhesion, especially in systems containing PCMs that are macro-encapsulated. For the PCM and matrix to remain cohesive and prevent mechanical failure over time, appropriate materials must be used.

## 6. Summary of the Reviews on PCM Building Recent Applications

Over the last two decades, much effort has been made to make better use of the available technology, paying attention to applications of PCMs as shown in Fig. 8.

A number of review studies have been conducted to composite multiple PCM research into one to suggest further calls for forthcoming findings. Research has moved on from just cooling applications [198] to PCM encapsulation methods [184,199], active and passive PCM applications classification [114,200], LCA of PCMs in buildings life cycle assessments (LCA) improvement of PCMs in buildings [201,202]. This work contributes more to defining the technical structure, outlining key working principles, and proposing technological standards within the PCM frameworks.

Du et al. [10] have provided a comprehensive review of PCM applications in power generation, heating, and cooling. Navarro et al. [203,204] have published a two-part review paper on active and passive thermal energy storage systems in buildings. 1$^{st}$ part was centered on seven buildings applying PCM-TES within two distinct systems e.g. suspended ceiling, solar facade, ventilation system, solar collector, PV array, and heat storage water tank. However, the 2$^{nd}$ part reviewed passive applications of PCM in building envelopes — impregnation in materials, as an added layer to components, and two options for windows and sunscreens. Song et al. [205] reviewed the use of PCM in building energy performance based on different applications such as those related to the building envelope (side walls, roof, floor) and those that modulate energy needs due to some built-in equipment (air conditioning; heating; ventilation). PCM temperatures of building equipment were on the level 15.4°C–77.0°C and the envelope levels was 10.0°C–39.1°C. Lizana et al. [206] investigated the combined cooling heating and power with thermal energy storage systems and focused on carbon free energy solution for cooling and heating purpose. Romdhane et al. [207] investigated that passive PCM application could enhance the thermal comfort in buildings, reduce energy demands and save money as well. Li et al. [208] examined the frontiers in PCM-based applications on building heating, highlighting those related to heat pumps and solar heaters. The solar chimney and PCM in roofs, walls and windows both passive and active applications were reviewed. The authors advised that additional long-term experimental studies, include economic, energy and ecological evaluations. Javadi et al. [209] investigated use of PCM in residential buildings energized by solar energy with reduced thermal radiation while solar thermal systems implemented increased the performance. Magrini et al. [210] talked about the conversion of landscapes to active energy contributors with particular reference to the use of PCMs and advanced materials in European projects aimed at conversion of NZEB into PEB, using a case study.

### 6.1. Practical Viability of PCMs Across Various Applications

The scope of this review has been refined to focus on the practical applications of PCMs in heating, cooling, and Hybrid systems within the building. PCMs integrated into heating systems, such as underfloor heating, demonstrate enhanced thermal storage and consistent heat release, which improve energy efficiency during winter. For instance [170], reported a 15% reduction in energy consumption in residential buildings equipped with PCM-based underfloor heating systems. In addition, a study [181] demonstrated that incorporating PCMs into the interior walls of residential homes in colder European climates resulted in a 20% reduction in heating demands during winter, significantly improving thermal comfort. In cooling applications, passive systems like PCM-enhanced walls and ceilings are effective in reducing peak indoor temperatures, as evidenced in [181], which achieved a 35% reduction in cooling loads in tropical climates by integrating PCMs into external walls. Another successful case was observed in the same study [181] where PCM-infused ceiling panels in a Portuguese office building reduced peak cooling loads by 40%, extending thermal comfort to occupants without the need for additional HVAC systems. In southern Spain, a similar system was found to reduce indoor temperature by up to 5°C during peak summer months. Hybrid applications combine both heating and cooling functionalities, utilizing active control mechanisms to optimize performance year-round. A notable example includes [180], which demonstrated that PCM-integrated facades reduced annual HVAC energy consumption by up to 30% in temperate climates. Furthermore, a study in Japan [187] tested hybrid PCM systems in office buildings, utilizing both solar heat gain and night cooling strategies. The results indicated that PCM-enhanced walls provided a 25% reduction in heating demands during winter and a 30% reduction in cooling loads during summer, achieving substantial energy savings across seasons. Another key area of application is retrofitting existing buildings with PCM technologies to improve energy efficiency. For instance, a large-scale retrofit project in a historical building in the UK utilized PCM-based plaster to regulate indoor temperatures, reducing energy consumption for heating by 15% without altering the structure's aesthetic or historical integrity. Similarly, a retrofit of residential buildings in Australia with PCM-insulated roofs resulted in a 25% reduction in both heating and cooling energy consumption over the course of a year [195].

These case studies highlight the adaptability and energy-saving potential of PCMs in diverse building scenarios, making them a promising solution for sustainable energy management, while also being retrofitted into existing structures, makes them a promising option for future energy efficient building design. The investigation on PCM applications as per the experimental key studies, design requirements, etc. are explained below focusing on prototypes in laboratory testing for retrofitting to optimize the overall performance. Before proceeding it is very necessary to know about active and passive systems, in order to improve heat transmission, active systems use mechanical components (such as fans, pumps, or heat exchangers) to move fluid or air over the PCMs. These systems are more effective in controlling the building's temperature in response to heating or cooling requirements because the stored thermal energy is actively handled and controlled. Active systems, which actively absorb or release heat in a controlled manner, are frequently linked with HVAC systems to optimise their performance. An example would be an air handling device with PCM enhancements that heats or cools the air before it enters the living area. On the other side, passive systems do not require mechanical devices and instead rely on natural heat exchange processes including convection, conduction, and radiation. In passive systems, the PCMs help to regulate indoor temperatures by absorbing heat during the day and releasing it at night. Building materials like walls, floors, and ceilings frequently have these systems built into them. A PCM-enhanced wall that collects surplus heat during the day and releases it at night when temperatures drop is an example of a passive PCM system, which improves thermal comfort without the need for external energy.

### *6.2. Large-Scale Prototype PCM Experimental Studies*

The experimental study of thermal performance using PCM integration in buildings can help to promote the commercial use of PCMs and better understanding for builders and architects. Modern dwellings are developed with full-scale test cells designed to be like real-world trials that show potential results. We perform a literature review that span works over passive and active large-scale applications to generate insights into practical implementation.

#### *6.2.1. Active Large-Scale Applications*

Two full-scale cubicles developed by Mourid et al. [211] were tested in cold winter weather. The product with the walls that consist of two 72 mm brick layers separated by a 116 mm gap of air, which had a PCM wallboard was tested for thermal performance with or without PCM in the ceiling or internal walls. It was found that the experiment with the PCM and no PCM in the ceiling resulted in a 30% and 50% reduction of heat losses, respectively. A more extensive amount of research was done on the PCM in the floor combined with the solar water heating by Lu et al. [212], in which the model was validated in the TRNSYS with a 95.1% coincidence of experimental and numerical results. It was also found that 5.87% more energy is saved at 20°C compared with the reference model. The authors report test results of active PCM storage systems in two huts where air conditioning, solar air heater, and electric heating were included, and one of the huts was equipped with PCM heat storage. Thus, results have shown that the coupling of an air-based solar collector and an active PCM storage system was capable of providing 30% and 40% energy savings in both test campaigns (March-April and May) [213]. In another study [214], the performance of passive and active PCM systems was compared in two large-scale prototypes in winter and summer in Auckland. The first hut used PCM wallboards and the second employed a PCM storage unit with a fan. It has been found that the active system is more effective for load shifting; with a reduction in the energy used by 32%, whilst the passive type is better in terms of cooling. In Auckland, using an active system allows saving about 22% of energy in winter increasing electricity usage by 8%.

Gracia et al. [215] conducted an experimental investigation of a ventilated double-skin solar façade with PCM in Puigverd de Lleida, Spain, and used two large-scale prototypes. In agreement with the CFD results, PCM integration enhanced the thermal performance, which can be further improved by thermal control. Zhou et al. [216] studied four system configurations regarding sensible/latent heat storage and pipe types using polyethylene coils and capillary mats. They found that capillary mats improved indoor temperature uniformity and halved the charging time. Meanwhile, PCM's latent heat storage was half as effective as sand, while the application of PCM improved sand energy discharge twice. Kong et al. [217] explored the feasibility of using a radiant heating system with PCM in the walls of test rooms. The radiant heating systems are supplied by solar thermal energy. The energy use in daily terms was 44.16% than the radiant heating of the room using traditional radiators.

The work by Sinka et al. [218] is another study analyzing the effect of PCM in the walls and ceilings of a building. The research was performed in Riga, Latvia, in four test rooms. The two PCMs were tested: Bio-PCM Q25 M51 in a massive building, and DuPont Energain® plates in a light building, compared to the reference buildings. Although different materials were used, both objects had similar heat transfer U-values. The results proved that ventilation plays a key role. To ensure that PCM is not heating up, it is recommended to use mechanical ventilation. The maximal efficiency is achieved if PCM is combined with radiant cooling ceilings. It is also recommended to use complicated control systems to make an output as best as possible.

#### *6.2.2. Passive Large-Scale Applications*

Lee et al. [219] studied the thermal performance of cellulose insulation reinforced with PCM cell under small-scale prototype wall cavities. The outdoor experiment using two large-scale identical prototypes showed that the daily and hourly average heat flow decreased by 25.4% and 20.1% for heat flow and also decreased by 13.8% and 10.3% for indoor tracking. Wang et al. [220] investigated a brick wall in PCM in a large-scale prototype in Shanghai. The large-scale prototype technology helped to reduce cooling loads by 24.32%, and indoor temperature is higher than outdoor temperature, reducing heating burdens by approximately 10 to 15%. Luo et al. [221] have investigated a modified Trombe wall system that provides both passive cooling and solar heating in the wall. It was determined that the summer overheating is reduced, and the winter heating is an effective solar wall with a higher temperature water jacket to improve the convective heat transfer between the air and wall. Sun and Wang [222] have studied the winter heating efficiency by transferring heat inside the system by a solar wall with PCM in Jilin, China. Cooling is another problem related to increased efforts to increase cooling efficiency, but most buildings still use air conditioning systems. A lot of energy can be wasted, but energy to run the system is necessary. One of the least expensive and exciting ways to store PCM is by using a solar wall with PCM. The findings showed improved air circulation due to a combination of chemical and sensible heating and reduced interior temperature fluctuations.

Guarino et al. [223] studied a PCM wall outside a glass window in Montreal, Canada, in the winter. It was shown that the PCM stored good solar energy and discharged it at 6-7 hours, which reduced heat annual consumption by 17% and reduced stratification. Lee et al. [44] optimized the placement of PCM in the layers of the wall using a PCM thermal shield. It was found that the south and west walls' peak power was reduced from 51.3% and 29.7% at 6.5 and 2.3 hours, respectively. Souayfane et al. [224] investigated the glass brick wall with PCM with aerogel insulation and glazing. It was shown that the wall worked well in winter, and the shutdown of the PCM on the overheating of the wall in the summer was due to inadequate hardening. However, the numerical model regime was shown to prevent the wall's overheating. Hu and Heiselberg [225] used a vented window of a full-scale prototype with a heat-exchange PCM. The temperature of the vented air was reduced by 6.5°C, which occurred at 3.9 hours, and the best thickness of the PCM heat exchanger was 10 mm. Thus, the benefits of this vented window have been confirmed for night dilution and pumping-out. Li et al. [226] developed a multi-layered roof with a ventilation gap and added PCM to the lower layer. Two types of roofs were constructed in a comparative description of the roof's work: standard and common with PCM layers. The indoors's maximum temperature was reduced by 16.9-18.8%, and the phase's transition temperatures were 31-32°C in the top layer, and the sides 24°C.

### *6.3. Small-Scale Prototype PCM Experimental Studies*

Small-scale prototypes are introduced to solve the problem of the high cost of preparation for a large-scale prototype as well as to facilitate installation and testing preparation. Small-scale prototypes are known for being low-cost and easy to install.

#### *6.3.1. Active Small-Scale Applications*

He et al. [227] tested using a new radiant cooling PCM wall. The wall has combined the use of PCM as an LHTES material beneficial for its high energy density, micro-channel heat pipes used for not permitting the PCM to become solidified at night and releasing the stored heat in the room because of their high thermal conductivity, and a plate used for radiative cooling with high emissivity. There were tested three prototypes: A and B had brick walls for controlling the cooling load for the ordinary walls while capillary tube synthetic copper sheets with conductive walls charged with 40% salt hydrate and 60% water were used for room B's prototype. Room C had 47.9 and 23.8 percent lower cooling loads on the south wall than room A and room B, respectively. Garg et al. made a small-scale prototype for an experiment with three roof systems: a thermally activated ceiling, a radiant panel in the chamber, and an encapsulated PCM heat exchanger cooling system. Encapsulating the piece of PCM in the heat exchanger cooling system allowed reducing the room heat load by 50 percent leading to a 6 °C decrease in the average air temperature. Small-scale prototypes are usually introduced in the research of a specific application experiment and supported with a numerical model. The combination of experiment and numerical analysis is to verify the numerical model to be used in further full-scale prototype construction research. Other reasons are the necessity to support the experiment for a long period, which is as difficult and as high-costing as experiments do. In the experiments, authors [228,229] researched and performed tests on the capability of a capillary tube-embedded PCM device when placed in the wall and ceiling of a testing chamber made previously in this research. The results of the author's work saw the development of a numerical model that was validated by experiments. The system consisted of three major components: CT-PCM charges and discharges PCM through a 140 m long capillary tube, a dynamic thermal chamber, and a water bath system. The results showed that with capillary flow rates higher than 800 ml/min, the experimental data and numerical simulations are in validation, while a lower flow rate requires a different correction factor varying between 1.2 and 1.6.

However, in a certain setting, an electric radiant heating system equipped with PCM may be potentially considered as an energy-saving underfloor heating. For instance, Fang et al. [230] proposed a new eutectic PCM composite comprising of sodium acetate trihydrate-formamide and expanded graphite as a carrier. The tested PCM reportedly had desirable heat of phase change 187.6 kJ/kg, a high thermal conductivity of 3.11 W/m ·K, reasonably good solidification temperature of 38.54 °C, and was reportedly more resistant to deformation, and more stable thermo-rally. During the experiment, the prepared PCMs were exposed to heating by an electric radiant heater. The experimental analysis revealed that their use reduced the room air temperature, and the PCM usage raised total heat comfort duration to 12.65 hours in the case of the PCM room and 1.836 hours for the non-PCM room. Additionally, the use of PCM was shown to significantly reduce up–down air temperature variation. Guo et al. [231] utilized mortar blocks with PCM micro-encapsulation and topping them on the floor. The way it worked was that hot air was then blown into copper tubes lining the floor area of the room. Supposedly, the most important factor was the dispersion area of the PCM on the floor.

#### 6.3.2. Passive Small-Scale Applications

Abbas et al. [232] investigated the thermal performance of a hollow-brick wall with PCM capsules in a small-scale test room. Encapsulating PCM reduced indoor and wall surface temperatures by 4.7°C compared to conventional bricks. PCM decreased temperature fluctuations by 23.84%. Rathore and Shukla [233] used two identical test cubicles in Mathura, India: one with tubular macro-capsules of PCM along the walls and ceiling. The presence of PCM tubes reduced the fluctuation of the temperature by 40.67%-59.79%. The peak temperature was delayed by 60-120 minutes compared to the cubicle with no PCM, while the cooling load was reduced by 38.76%, saving around 0.4 USD/day. Khan et al. [234] studied the effect of paraffin wax PCM on heat transmission of the wall in two composite wall models. The use of the PCM in the inner layer of the wall increased counter times reaching certain temperatures and specific materials. Zhu et al. [235] tested double-layer

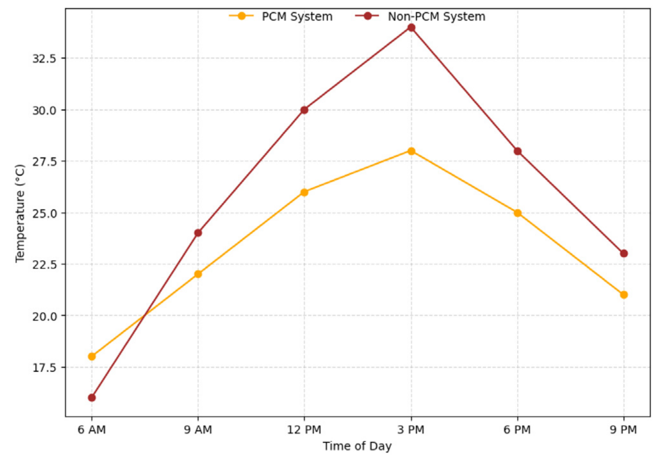


**Fig. 9.** Temperature change with and without PCM incorporation.

stabilized PCM wallboards in two identical test rooms in China. PCM decreased overheating in the summer and undercooling in the winter. Berardi and Soudian [236] studied passive PCM composites in walls and ceilings to reduce heat gains in high window-to-wall ratio buildings. The systems use composite PCM layers Energain ® and the BioPCMTM and can reduce interior temperature to 6°C in both summer and winter conditions in Toronto, Canada, and surface temperatures up to 6°C. Since the thickness of composites is 2 cm, they can be used in retrofitting Sun et al. [237] have experimented with PCMs for building walls and tested them in the lab over summer. Heat flux reductions were 36.5% and 22.5% for 1.27 cm and close to the wallboard, respectively, however, the PCM did not freeze completely from the first day. Following the ratio of the surface area to the volume of PCM, the smaller pipe is the most effective. Mehdaoui et al. [30] have also tested PCM wall typos in a 14-day-long experiment and found that the thermal swing has been minimized. In addition, a numerical simulation suggested that the upper sides of the PCMs melt faster. Zhang et al. [238] designed and experimented with the Dynamic Wall Simulator to test the effects of insulated structural panels (PCMSIPs) on thermal comfort. They found that: 1. The urethane structural insulated panel (SIP) looks better than the expanded polystyrene (EPS) cored SIP; 2. The heat flux reduction of PCMSIP compared to the non-composite PCMSIP is about 10-20%. 3. Vertical SIP of PCM is more efficient than horizontal. Meng et al. [239] also had a similar experiment with PCM composite envelopes. The temperature fluctuation was significantly reduced by 28.8%-67.8% in the summer and 17.7%-25.4% in the winter with the use of PCM. The temperature change throughout the day can be seen in Fig. 9.

### 6.4. Retrofitting PCM Experimental Studies

The bulk of compartments are already full of occupants. It is necessary to improve the thermal climate within their homes without modifying architectural components (walls, roof, floor, or ceilings). Engineers were interested in the method of retrofitting existing envelopes with additional layers. Several researchers conducted experiments to investigate retrofitting PCM uses.

#### 6.4.1. Active Retrofits Applications

Cheng et al. [240] studied underfloor heating thermal performance using shape-stabilized PCM plates of paraffin, high-density polyethylene, and expanded graphite. Plates were installed over electrical mats and the room heating system was examined under different heating systems in Anhui province, China. The phase change energy storage system had the lowest energy expenditure and showed the best cost-effectiveness. Lu et al. [241] tested a twin-pipe PCM floor heating system in Zhangjiakou, China. Encased PCM allowed thermal comfort to improve reducing temperature fluctuations by an average of 3°C.

Stritih et al. [242] investigated the impact of PCM-LHTES integration at the terminal of a solar air heater in a solar façade located in Ljubljana, Slovenia. PCM-LHTES reduced operational costs by 24% as compared to a solar air heater without LHTES. Lamnatou et al. [243] evaluated BIST installed in Ajaccio, France, based on myristic acid as PCM. The life cycle assessment showed that PCM was the system component with the largest environmental impact. Nada et al. [244] studied the impact of adding a PCM module with SP-24E PCM plates to a typical HVAC system. Increasing the ambient temperature and airflow increased the number of PCM plates, but the PCM discharge time decreased.

#### *6.4.2. Passive Retrofits Applications*

Wang et al. [245] carried out experimental research on the thermal response of disaster alleviation prefabricated temporary abodes with PCM plates installed on the interior region of the temporary abode. The aim of the research work was to ameliorate the thermal atmosphere of the residing abode without having an electrical thermal environmental controlling system. The results of the research work were conclusive in the sense that it was ascertained that using fixed PCM plates, the internal surface temperature, and the internal temperature reduced. Furthermore, it was concluded by the scholars that it is appropriate in the sense that employing the moveable PCM energy storage system can be done in order to guarantee that the PCM can go outdoor, so that it can avail the cool temperature of outdoors and ascertain that the PCM will completely solidify. However, in taking the PCM to establish that it benefits from the cool temperature at nighttime and solidify, it is a very hefty task requiring a permanent hard work to fix as well as remove many plastics net-shaped containers. Therefore, a new, expedient design is proposed, which was terminated in a safe way in case of PCM plates on a traditional wall divided into many pieces fixed to the wall turning in outdoors and finally inside.

Lee et al. [246] introduced the concept of plug-and-play walls in which building materials intended for residential and commercial construction can be easily and perfectly tested in all weather. The addition of a PCM layer led to a heat transmission decrease of 27.4% and 10.5% on average on the south and west walls. In addition, it was observed that the PCM impeded for 2 to 3 hours on average. Vik et al. [247] evaluated the use of PCM plates as suspended ceilings and side walls. After analyzing five different cases, the authors concluded that the most effective way of using PCM plates was as suspended ceilings not covered by aluminum ceiling panels and that PCM on the partition side reduced the energy consumption required for mechanical cooling in the building. Li et al. [248] developed a novel PCM blind system and combined it in a double skin façade to avoid summertime overheating, which did not occur due to a paucity of prior knowledge. The blind prepared with a layer of aluminum plate was epoxy coated and the viscos metric PCM mixture. The PCM blind's ideal inclination angle and location were also optimized in the study. The best inclination angle was found to be 30 degrees. Throughout the day, the system provided a 1 to 2.9 °C difference between the temperature of the interior and the outside glass skins.

Experimental results from the developed system have provided significant enhancements in solar energy capture and energy management [249]. Gracia [250] proposed a novel design of a dynamic PCM layer for building envelopes. The The purpose of the developed method is to overcome the two main limitations of the passive PCM applications in the building envelopes: 1) the PCM starts to solidify partially at night; and 2) the absorbed internal gains of the building become released inside the building. The system consists of two layers of the plastic polymers that are separated by an insulating wool layer, and the PCM is on one side. The system uses the actuated rollers that are capable of shifting the PCM's location from close to the inside to close to the outside, which allows the discharge to the outside and the PCM to completely solidify.

### *6.5. Laboratory-Based PCM Experimental Studies*

Performing experiments using smaller-size prototypes or specifically planned module/partition experimental investigations is one of the most practicable ways to conduct deep research of system performance. It provides not only more control over factors but also a lower cost and the opportunity to operate in a laboratory-controlled surrounding. Laboratory-based PCM building partition experiments can include not only building partition but also the use of heating/cooling systems and a reduced-size prototype. At the same time, it is preferable to distinguish between active and passive laboratory-based applications

#### *6.5.1. Active Laboratory-Based PCM Applications*

Guo et al. [251] evaluated the space heating and energy use of ventilated blocks for six different distributions of the micro-encapsulated PCM. By concentrating PCM in the blocks upper half with simultaneous heating and ventilating, the heating rate increased by 41.5%. Another PCM wall was introduced by Yan et al. [252], the process of nighttime radiative cooling was used to completely solidify PCMs and run the system without electricity. The PCM wall with gravity heat pipes hence, had 74.5% lower heat transfer compared to a conventional wall after one-week service in a hot climate.

Qiao et al. [253] developed a personal cooling system with a heat exchanger made of PCM, which improved cooling uniformity, and charge rate. Xu et al. [254] tested the PCM Macro-Capsule in vertical and horizontal latent heat thermal energy storage tanks to balance the performance of a heat pump and found that the vertical tank could enhance the charging and discharging time by 20%. However, it also reduced the thermal capacitance by 8.2%. Plate-type heat exchangers were explored by Saeed et al [255] for the purpose of load shifting, and with 83.1% efficiency, the system was properly used despite the weak conductivity of the PCM. Sun et al. [256] discovered the efficient utilization of PCM in a flat-heat-pipe system and a thermoelectric unit. Such a system handled intermittent heating efficiently, while the required coefficient of performance exceeded 1.7. Sun et al. [257] tested vented slabs with paraffin-based PCM in a wind tunnel. They concluded that increasing air temperature from 35°C to 55°C could result in the increase rate of charging as 201.7%. A slight increase in airspeed, in the turn, enhanced the charging speed by 8.7%.

Wadhawan et al. [258] have installed a Lauric acid PCM in a TESD solar air heater with a result of 86.47% increase in output air temperature. Abuska et al. [259] have examined the PCM plate structure honeycomb fins in the solar air heater. The result is that the PCM charge-discharge time is reduced, and the daily thermal efficiency was slightly reduced by using the honeycomb fins. Chen et al. [260] installed a closed-loop solar air heater with PCM. The result is that the PCM was raised to a temperature of 68.52°C and 132 minutes via the multichannel flat-tube thermal storage unit.

#### *6.5.2. Passive Laboratory-Based PCM Applications*

Fateh et al. [26] developed a dynamic computational model to investigate the performance of PCM in wall insulation. The simulation results match experiments, showing that PCM inserted between insulation layers can reduce overall heat energy consumption by 15% and delay peak heat flow for 2 hours. Further experiments utilize the dynamic wall simulator to incorporate PCM with cellulose-based insulation from Evers et al. [261]. The activity of PCM in the dynamic model showed that the paraffin wax based PCM exhibited peak heat flow reduction by 9.2%. For the salt-hydrate PCM, its majority's influence was ineffective as the material was hygroscopic.

Ryms and Klugmann-Radziemska [262] experimented with various PCM-containing construction bricks: microencapsulated PCM powder, liquid RT22, and RT22 impregnated into a porous aggregate. The last case was most promising, solving cost issues of microencapsulated PCMs. Li et al. [263] tested PCM wallboard melting at 12, 18 and 29°C and concluded that the Mode 2 PCM performed the best for an all-year perimeter comfort. Drissi et al. [264] developed solar energy storage concrete panels with PCM aggregates, the maximum improvement being the peak temperature decrease by 1°C. Saxena et al. [265] proved that PCM bricks reduce the body temperature by 4-9.5°C, providing passive cooling. Wang et al. [266] tested a PCM honeycomb wallboard, finding improvements for the next day's heat mitigation. Li et al. [267] used PCM with nanoparticles in the window system to improve the performance of solar thermal inertia and the optical system. It also beat the performance of the pure PCM window. The CuO nanoparticles' performance was the best, mostly when the level was below 1% and the diameter was below 15 nm.

The efficiency of PCMs in enhancing building thermal comfort and energy efficiency is demonstrated by several successful real-world applications [268]. The use of passive PCM walls in homes and businesses in a variety of European climes is one noteworthy example.

(1) Residential structures in Italy: A study conducted by [269] investigated the application of PCM-enhanced external walls in Mediterranean-climate residential structures in Italy. To absorb extra heat during the day and release it during cooler evenings, PCMs were placed in the walls. This led to more consistent indoor temperatures and a 25% decrease in energy use for heating and cooling. The study emphasised how PCM walls can lessen the need for conventional HVAC systems, particularly in areas with significant daily temperature fluctuations.
(2) Commercial Buildings in Germany: In an attempt to lessen the cooling burden on office buildings, PCM panels were erected in the walls of these structures. Peak indoor temperatures were lowered by up to 4°C during the summer months thanks to the PCM panels' absorption of heat during the day. As a result, the building's cooling energy consumption was reduced by 30% while preserving cosy interior conditions. According to [270] the integration's success proved that PCM walls are appropriate for temperate areas where heating and cooling are needed at different times of the year.
(3) Spain-Refitting initiatives: PCM-based retrofitting initiatives in Spain have also shown significant energy savings. PCM-enhanced gypsum boards were used in a large-scale refurbishment of an office building in Barcelona to control interior temperatures without the use of mechanical cooling. During the trial, occupants' thermal comfort improved, and energy savings of up to 20% were noted [271].
(4) Passive PCM walls were utilized in low-energy house complexes in France to lessen the requirement for cooling in the summer and heating in the winter. The incorporation of PCMs into the walls led to a smoother indoor temperature profile and a 15% decrease in heating and cooling energy use. According to the study by [272] the PCMs were essential for preserving thermal comfort, especially in the event of severe weather.
(5) PCMs have been incorporated into roofing systems to regulate inside temperatures in Australia, where heating and cooling are required based on the season. According to a 2019 study by [273] PCM-enhanced roofing can effectively lower peak indoor temperatures by up to 5°C during the sweltering summer months. As a result, more than 20% less energy was needed for air conditioning. The PCM reduced the demand for heating in the winter by absorbing solar heat during the day and releasing it at night. The versatility of PCMs in areas with significant climatic fluctuations is demonstrated by this application.
(6) PCMs were used in the façades of a sizable commercial building in Beijing, China, to maximize energy efficiency in both the summer and the winter. According to [274] this integration resulted in a 30% reduction in the building's energy usage for cooling and a 20% reduction in winter heating demands. This was accomplished by employing PCMs, which could release stored heat on chilly winter nights and absorb surplus solar heat in the summer. The efficiency of PCM façades in controlling heating and cooling loads in harsh climates is demonstrated by this example.
(7) PCM-infused concrete flooring has shown promise in enhancing interior thermal comfort and lowering heating needs in cold climates like Canada. In residential structures, adding PCMs to concrete flooring decreased heating energy usage by 15–25%, according to a study by [275]. Even in the chilly winter months, the PCM floors helped keep the interior temperature steady by absorbing solar heat during the day and releasing it at night.
(8) PCMs have been used in air conditioning systems to maximize cooling efficiency in the hot and dry UAE climate. PCM-based thermal storage was evaluated by [276] in a big office complex's centralized HVAC system. The PCM reduced energy consumption by 25% by storing excess cooling capacity during off-peak hours and releasing it during moments of peak demand. The potential of PCMs to increase energy efficiency in areas with high cooling demands was shown by this application.
(9) [277] investigated the use of PCMs in passive solar buildings in Switzerland, where they were incorporated into the walls and ceilings to store solar heat during the day and release it at night. This prevented overheating in the summer and decreased heating loads in the winter by 30%. The study also demonstrated that PCMs could reduce the building's overall energy consumption by 25%, making them an essential part of low-energy building designs.

These European examples demonstrate the usefulness of PCMs in both new construction and retrofit applications. PCM-enhanced walls and panels lessen dependency on conventional HVAC systems by absorbing and releasing heat over daily temperature cycles, which results in significant energy savings and improved thermal comfort. These case studies show that PCMs provide a flexible way to increase building energy efficiency, especially in regions with large temperature swings.

Furthermore, an effective use of PCMs in residential and commercial buildings has been established in a few numbers of studies, demonstrating their potential for energy savings and realistic payback periods. By retrofitting the walls and ceilings with microencapsulated paraffin-based PCMs, [240] investigated the effectiveness of PCMs in a commercial building. According to the findings, overall energy consumption was reduced by about 20%, mostly as a result of fewer cooling loads in the summer. Additionally, the peak load on the HVAC system was decreased, which led to lower operating expenses. Depending on the building's consumption and local energy costs, the project's payback period was projected to be between six and eight years. This study showed that PCM integration could have a major positive impact on commercial buildings located in regions with notable temperature swings. The performance of PCM-enhanced walls in a residential building situated in Spain's Mediterranean climate—which features hot summers and moderate winters—was examined by [271]. By stabilising indoor temperatures during periods of high heat, the PCM utilised in this study contributed to a 25% reduction in HVAC energy use. According to the study, PCM retrofits in residential buildings are a practical way to save energy because they have a payback period of about seven years. The study also showed how passive temperature control could reduce the need for active heating and cooling systems for residents. In Germany, which has a moderate climate with a balanced need for both heating and cooling, [270] studied the incorporation of PCMs into office buildings. The office buildings' PCM-enhanced ceilings and walls resulted in an average 18% yearly energy savings. The installation's entire payback period was anticipated to be five years, and it greatly decreased the building's need on air conditioning during warmer months. The building's high energy requirements for temperature control and the comparatively cheap cost of PCM materials were blamed for this very short payback period. In another study [271] used PCM-enhanced gypsum boards to retrofit a university building in Spain. Significant energy savings were achieved in the university building, especially in the cooling demand. Energy sav-

**Table 1**
Summary of payback periods and energy savings.

| Location | Building Type | Energy Savings | Payback Period |
|---|---|---|---|
| U.S. | Commercial | 20% | 6-8 years |
| Spain | Residential | 25% | 7 years |
| Germany | Office | 18% | 5 years |
| Spain | University | 15-20% | 6 years |
| Switzerland | Residential | 10-15% | 8-10 years |
| China | High-Rise Residential | 30% | 6 years |
| India | Residential (Roof System) | 20-25% | 5-6 years |

ings of 15% to 20% were achieved by the PCMs' ability to collect surplus heat during the day and release it during colder times. This upgrade was expected to pay for itself in six years. The significance of choosing PCMs that are especially appropriate for the thermal loads and environment of the building was also emphasized by this study. The effects of PCM-integrated wallboards in a residential structure were examined. According to the study, PCM integration resulted in a 10%–15% decrease in the yearly energy consumption for heating and cooling. Switzerland's colder climate made heating more important, and the PCMs helped reduce temperature swings, especially in the spring and autumn transition months. Because of the lower energy costs and more moderate energy savings compared to areas with more extreme temperatures, the payback period for the PCM retrofits in this study was somewhat longer, estimated at 8 to 10 years. The usage of PCMs in high-rise residential structures in China, where regional climatic variations are substantial, was investigated by [274]. To improve thermal insulation and lower cooling loads, this study concentrated on integrating PCM into external wall and window glazing systems. In areas with hot summers and chilly winters, the researchers found that energy savings might reach 30%. According to the study, PCM retrofits were very successful in lowering peak cooling loads, enhancing indoor comfort, and postponing the entry of heat into the building. These retrofits showed promise for large-scale residential applications, with an expected payback period of about six years. In an experimental investigation, [265] examined the performance of PCM-based roof systems in a tropical environment in India. During the hottest summer months, the PCM roof was able to lower internal temperatures by 5 to 7°C, which significantly decreased cooling loads. According to the study, energy savings ranged from 20% to 25% annually, with a payback period of roughly five to six years. This study showed how PCM systems have a lot of promise in areas with long cooling seasons and high sun radiation. Table 1 summarizes payback periods and energy savings across different locations and building types.

Although PCM's technical benefits in lowering energy use and improving thermal efficiency are widely known, PCM-equipped buildings' comfort and user experience are just as crucial to their widespread use [278]. How well PCMs control indoor temperatures, preserve constant thermal conditions, and reduce temperature swings affects occupant comfort. By absorbing and releasing heat during moments of peak heating or cooling, PCMs, when appropriately integrated, can improve indoor thermal comfort and create more stable and comfortable living or working spaces. Nevertheless, there are obstacles in the way of attaining the highest level of user satisfaction with PCM systems. For example, poor heat regulation due to incorrect installation or insufficient PCM material might cause discomfort for the user, especially in severe weather. Furthermore, although PCMs' passive design helps lower HVAC energy consumption, it might not offer the instant temperature adjustment that some consumers anticipate from active systems like air conditioners. To learn more about how PCMs affect occupant comfort, future studies should concentrate on evaluating user feedback in buildings that have these materials installed. Comparative studies of indoor temperature differences between buildings with and without PCMs and surveys of building inhabitants to determine subjective comfort levels could be included in future research. Concerns regarding possible overheating or undercooling in PCM-based passive systems must also be addressed because they could impact user acceptance, especially in areas with extremely high or low temperatures. User satisfaction results from real-world case studies have been encouraging. For instance, residents of a Spanish residential structure with PCM walls reported better thermal comfort in the summer and winter because the PCMs helped to lessen temperature swings inside. Similarly, workers in a German office block with PCM had a more stable interior environment, which raised their level of satisfaction and productivity. These illustrations highlight how PCMs can improve thermal comfort; however, to guarantee that PCM systems satisfy the requirements of a wide variety of building occupants, more thorough user acceptability studies are required. In conclusion, the building industry's adoption of PCMs is greatly influenced by user comfort and acceptance. For PCM systems to be widely used in residential, commercial, and industrial buildings, it will be crucial to make sure that their implementation and design take occupant demands into consideration.

## 7. New Perspective PCM with Lightweight Aggregate

There are ways of integrating PCM directly into lightweight aggregates, as found in the literature. The concrete PCM can be built in different ways, which can be direct, rather than through a shape-stabilized PCM, immersed, or encapsulation. The light aggregate used is pumice, perlite, expanded shale/clay, vermiculite, or slate. The support in the LWA method is medium in the PCM. While the process using shape-stabilized PCMs requires fine powders, such as silica fume or graphite, the coarse group works with whatever fine material is available. The PCM-LWA composites are generally manufactured through vacuum or direct infiltration. However, because of the inventors removed the air present in the LWA using pores, it led to the successful filling of 74% by absorption during the vacuum. Direct immersion has less than 18% absorption. However, the process is very complex and takes a long time. Thus, it is not commonly used [279–283]. Several facts should be considered for the usage of PCM lightweight aggregate in mortar or concrete: the type of aggregate, PCM absorption capacity, impregnation method, PCM type and viscosity, the type and size of aggregates (porosity, pore size, aggregate size, surface area, temperature, pressure, and time of impregnation), coating materials, performance testing. It was established that PCM absorption capacity in the case of LWA is influenced by aggregate size and porosity and it is recommended to remove particles smaller than 150 µm to avoid PCM adhering to the surface instead of entering the pores. In order to prevent PCM leakage and improve mechanical and thermal properties, the use of coatings can be suggested: cement paste, silicone, bituminous emulsion, epoxy resin, graphite powder, and silica fume [284–292]. The conducted experiments revealed that low thermal conductivities of the coating may slightly reduce the efficiency of latent heat storage within the encapsulation produced using porous material particles impregnated with PCM. Two strategies have been presented to achieve maximal thermal storage capacity; they include. Overall, the best outcomes were achieved when the cover particles were significantly smaller and up to ten times better at accumulating energy than the larger covers packed or empty in bulk.

The studies by [293,294] revealed that adding graphite to PCM reduced the loading or unloading time of thermal energy, without compromising the energy storage capacity. However, these outcomes were not fully replicable for mortar combination weighting particles in the range 5–10mm. Additional studies of thermodynamics and thermal transfer processes of materials with PCMs were conducted by [295–297]. Similarly, [298,299] researchers concluded that mortars and concretes with paraffin-based PCMs had the risk of catching fire in the case of exposure to flame despite their thermal properties being superior to those of PCMs with hydrated salt. For one of the reviews, a differential calorimeter was applied, and organic PCM based on soy wax and butyl stearate was prepared before being vacuum impregnated in previously crushed pumice particles. It included graphite powder as well for ameliorating the thermal conductivity. In the study, the PCM-LWA comprised of different

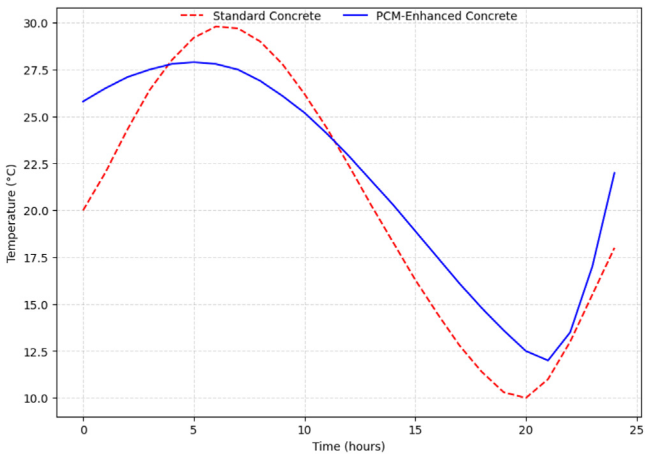


**Fig. 10.** Thermal cycle performance of lightweight aggregate (LWA) PCM concrete.

minute amounts of graphite were to be examined to estimate their thermal properties and Latent heat storage over 100 temperature changes at a given time as a result of Peltier cells. The results demonstrated an overall effectiveness for the heat energy storage of organic LWA PCM.

Further studies have conducted microstructural analyses of PCM-LWA (SEM, DSC, TGA, and FTIR), and mortars and concrete with PCM effects in thermal and thermo-mechanical properties [300–303]. Most research shows that including PCM in concrete yields a lower compressive strength regardless of the technique. Several studies [157,304–317] demonstrated that two considerations explain why the compressive strength of microcapsule-enriched concrete was substantially lower than that of conventional concrete. The first is the sensitivity of the microcapsules during the mixing, which results to PCM leakage, and the second is the substantial difference in strength between the microcapsules and the concrete. As a result, the highest method for maintaining the strength while also preventing leakage is the macro encapsulation with a strong shell. There is a need for further research so that PCM-LWA optimal mechanical, thermal, and heat-storage properties for structural concrete are developed. Additionally, research should be conducted to determine the effects of the coating and supporting materials on the mechanical and thermal behaviour of PCM-LWA. The thermal cycle performance of lightweight aggregate PCM is shown in Fig. 10.

Practical applications may be discouraged by the difficulties of incorporating PCMs into existing building designs, particularly in retrofitting efforts. PCMs can be readily incorporated into the design of new buildings from the beginning, while retrofitting existing structures with PCMs frequently calls for more involved interventions. The compatibility of PCMs with current structural materials, such as brick, concrete, or insulating layers, is one of the primary obstacles. For instance, removing walls, ceilings, or floors to install PCM panels or layers may result in higher labour costs and potential structural damage. The integration efficiency also depends on the building's thermal performance and existing insulation. For instance, the efficiency of PCMs may be put at risk in an older structure with inadequate insulation or high thermal leakage, as energy losses from thermal leaks may offset the benefits of PCMs. For this reason, before choosing the optimum PCM integration technique, the thermal performance of the building must be assessed. Putting PCMs in places that will optimise their effect on temperature regulation—such direct contact with heat sources like those that the sun initiates or enhances through south-facing walls or roofs—is another difficulty. This is frequently not feasible in existing constructed environments. Additionally, PCMs' ease of integration into an existing building may be significantly impacted by their encapsulation technique. Microencapsulated PCMs that can be distributed in plaster or concrete offer comparable levels of thermal efficiency to macro-encapsulation, despite the latter's potential ease of installation in walls, ceilings, or floors. However, it must carefully consider curing timeframes and material compatibility, since these factors may have an impact on the retrofitting procedures. The disruption of building occupants is another factor. There will be a lot of construction work involved in the installation of PCM materials, which will result in noise, dust, and the temporary eviction of residents. This can be a major obstacle, particularly in commercial or residential buildings where continuous occupancy is necessary. Nevertheless, there may be ways to overcome these obstacles and make it easier to incorporate PCMs into already-existing structures. Prefabricated PCM panels, for example, can be made to match the size of existing walls or ceilings, negating the need for significant structural changes. Additionally, integrating PCM retrofits with other energy-saving strategies, such replacing windows or improving insulation, can increase the building's total energy efficiency and justify the PCM technology investment. Ultimately, the integration of PCMs with existing building designs presents issues mostly related to labour, cost, and other compatibility factors. However, these can be lessened with careful planning and appropriate integration with more comprehensive energy retrofitting techniques. For PCMs to reach their full potential in terms of existing buildings' energy efficiency, these obstacles must be removed.

Comprehension of the results of the review studies is displayed in Table 2.

## 8. Suggestions and Discussion

After reviewing the papers listed in this study, we can state that a thorough debate regarding the development of model that unites mechanical and thermal behavior for PCM-based building units is still lacking. The contact phenomenon's boundary condition, which simulates how bodies interact across boundaries, is necessary for both actions. Contact is a non-linear process that depends on surface roughness, contact surface, adhesion (chemical, frictional, mechanical anchoring), and other local factors that influence the behaviour of the bodies when they are in contact (level macro). Similarly, through the phenomenon of contact, PCM construction systems and PCM encapsulates (micro and macro-encapsulation) within a structure interact across their boundaries. Specifically, the articles cover effects like material compatibility and presume knowledge of the subject without going into detail. Determine the ability of a PCM encapsulation to store and release thermal energy based on its constituent parts and the processes of heat transfer by conduction, convection, and radiation. These methods of transfer are all dynamic processes that depend on the surface of contact between the bodies.

The proportionality coefficients like conduction (k), convection (h), and radiation (s) that correspond to each heat transfer mechanism also have an impact on the transfer of energy through heat flow. These constants are obtained through experimentation, and their values vary depending on the material type, surface roughness, and radiant energy emissivity of each material. The transfer of stresses, deformations, and loads through the borders of the elements of the materials with PCMs is more uniform and effective the greater the contact area. In other words, the contact phenomenon determines the thermal and mechanical behavior of materials with PCM. Furthermore, as the contact phenomena affect the mechanical such as state of stresses and deformations as well as the thermal behavior of constructive systems with PCM, it is crucial to create and thoroughly examine a Multiphysics model that couples these two behaviors. However, the continuity of the contact area also affects how effective the transfer is; near discontinuities (holes, sudden changes in shape, material change), and stress concentrators are created, causing stress gradients to shift, and causing maximum stresses that lead to non-linear failures. Regrettably, discontinuities of this kind exist in both macro and microencapsulated materials, influencing their mechanical properties.

There may be variations in the contact phenomenon between macro- and micro-encapsulation. For example, the container conditions that

**Table 2**
Summary of the list of studies on PCM building applications.

| Author | Methodology | Findings | Challenges |
|---|---|---|---|
| [233] | Exp | Peak temperature reduction: 7.19-9.18%. Thermal amplitude reduction: 40.67-59.79%. Cooling load reduction: 38.76% | Simulation validation is needed. PCM type and climate zone affect performance; further study needed |
| [318] | Sim | PCM wallboards transfer peak load to off-peak. Thermo-physical properties impact heat transfer | Simulation validation with other software. Experimental validation required |
| [319] | Sim | Office temps rise by 4°C in winter, lower by 7°C in summer | An experimental study is needed. PCM optimization for climate required |
| [320] | Exp, Sim | PCM maintains indoor temp at 27°C. Cost-effective and energy-efficient | LCCA needed. Study expansion to various climates required |
| [321] | Sim | Proposed PCM variant useful for evaluating building applications | No experimental or modeling validation |
| [322] | Exp | PV-PCM systems are less cost-effective in Ireland, and better performance in Pakistan | Design and optimization of heat exchangers needed |
| [323] | Exp | Microencapsulation outperforms macroencapsulation. Heat capacity improved by 40%, indoor temperature lowered by 1.1°C | Full-scale testing is required. Simulation validation suggested |
| [324] | Exp | CuO nanoparticles improve thermal storage. PCM structure stores and releases significant heat | No climatic consideration. Simulation validation needed |
| [325] | Sim | PCM is effective in cold climates, but the high initial cost is not recovered in summer | Alternative PCM types for cost efficiency. LCCA suggested |
| [326] | Sim | Evaporative layer more cost-effective than thermal insulation | Experimentation needed. Expansion to other climates required |
| [327] | Exp | Free-form PCM is better for temperature regulation. Microencapsulated PCM is better for reducing melting time | Mediterranean climate focus; other climates needed. Simulation needed for further evaluation |
| [328] | Exp, Sim | PCM reduces heat flux by 38.45%. Annual cost savings: $456.75 vs. $831.60 for non-PCM | Experimental study for PCM thickness optimization needed |
| [329] | Exp | Fins improve heat distribution, reducing peak temperatures. Honeycomb fins outperform machined fins | Mathematical model needed for validation |
| [330] | Exp, Sim | 2°C indoor temp reduction, 17-25% energy savings. PCM layer optimization improves energy efficiency | Study expansion to hot climates. Optimization strategies needed |
| [331] | Exp | PCM with ventilation improves indoor temperature fluctuations | A mathematical model is needed. Techniques for full PCM melting/solidification needed |
| [332] | Exp, Sim | PCM reduces energy use and carbon emissions | More research on winter heating and solar integration required |
| [333] | Exp, Sim | Increased PCM reduces air temperature fluctuations. Performance improves with increased melting temp | Study confined to one climate zone. An extended testing period needed |
| [334] | Exp | PCM reduces daily temp swings by 4°C. Summer energy savings up to 34.5%, winter up to 21% | Study expansion to various climates. Economic analysis needed |
| [335] | Sim, Opt | PCM reduces overheating by 7.23%, efficiency at 35.49% | Experimental validation is required. Studying across multiple climates needed |
| [336] | Exp | PCM reduces indoor temp by 2.18°C. 20.9% peak hour cooling reduction, cost savings of $1.35/day | Simulation validation and a longer test period needed |
| [337] | Sim, Opt | Thermal load reduction from 6.7% to 33.1%. Reduced electric resistance use by up to 26.7% | Experimental validation needed for insulation thickness |
| [123] | Sim | PCM's latent heat function and lower thermal conductivity in liquid form are highlighted by the considerable reduction in annual energy consumption to 564.17 MJ/m2 with a 20.9% $\eta$. | Specific climate and PCM cost should be considered while choosing PCM parameters. The designer should also take the project's PCM installation orientation into account. |
| [338] | Sim | Using TRNSYS 16, the study models ASHRAE Standard 140-2001 case 600 in Toronto, changing the h-value from 0.5 to 10 W/m2K. The findings indicate that PCM thickness reduces surface temperature sensitivity, with phase transformation occurring more frequently during the winter. | For best results, simulations can be run for different outside convective heat transfer coefficients, PCM placements in building envelopes, and thickness ranges of 1 mm to 10 mm. |
| [62] | Exp | In addition to determining the quantity of cold stored in a thermal storage system, the study investigates the "free-cooling principle" and examines how various velocities affect air cooling. | It is possible to create and conduct experimental research on cold storage base products, calculate buffer emptying and air-cooling periods, and study the real-time integration of cold storage systems into building envelopes. |
| [339] | Exp | With a three-hour discharge and one-hour charging delay, PCM is being investigated as an indoor temperature regulator. It attenuates temperature peaks by 2.5°C and reduces thermal amplitude by 50%. | The PCM's melting temperature and layer thickness can be optimised through research. Studies in technical economics can be conducted using passive solutions. |
| [340] | Exp | The PCM blind has a cooling effect that varies according to the angle between the blind and the user's position, with surface temperatures never rising above 28°C. In closed slats, the cooling effect is more effective. For PCM regeneration, airflow and angled windows work better together. | The study investigates the mechanism of heat discharge in PCM-filled slats at night, analysing the effectiveness of slanted windows and ventilation systems, and investigating possible methods for validation. |
| [341] | Opt | By enhancing insulation capacity, PCM passive LHTES systems can lower peak loads for heating and cooling, make use of renewable energy sources, and enhance building envelope performance. | Numerical forecasts are evaluated, simulation hysteresis is evaluated, results from various PCM modules are compared, and thorough lifecycle evaluations are carried out utilising Life Cycle Assessment approaches for economic and environmental issues. |
| [342] | Exp | The study looked on measuring the heat transfer coefficient in PCM modules using external fins. The use of vertical fins shortened the cooling time from 60°C to 45°C and enhanced the rate of heat transmission, according to the results. In comparison to the situation without fins, the heat transfer coefficient for natural convection was also calculated, demonstrating a reduction in temperature difference for 20 mm fins and a fourfold increase for 40 mm fins. | Although simulation results can corroborate experimental data, the study could not find any connections to precisely forecast the heat transfer coefficient for the analyzed geometries. |
| [343] | Opt | Numerical solutions to verify and improve scaling analysis predictions for the Elemental Composite Heat Sink's (ECHS) critical dimensions are presented in this study. It establishes a significant upper-bound dimension for the CHS and tackles the problem of incomplete melting leading to underutilisation of PCM latent heat. All CHS with high conductivity BM and high latent heat storage PCM can use the thermal design process. | The thermal design process works for finned-CHS setups, but to guarantee accuracy and generalisability, it must be validated for different PCM and BM combinations. Numerical and simulation data can be used to validate experimental findings. |
| [344] | Exp | To reduce energy consumption, a new double-layer radiant floor system with phase change material is suggested. This system can store heat or cold energy during off-peak hours and use it during peak hours. | The study's main objectives are to optimise a double-layer radiant floor system using phase change material, compare materials, assess durability and practicality in real-world settings, and evaluate performance in summer cooling mode. |

hold the base PCM in place during macro-encapsulation result in a more equal contact surface. This feature may guarantee a larger surface area of contact between the inside surface of the container and the base PCM; as a result, there is a higher chance of achieving increased energy transfer efficiency from the base PCM to the container and vice versa. In terms of the interface between the exterior surface of the macro-encapsulate and the building component, a larger contact area could not be guaranteed; hence, the heat transfer might be less efficient. As was previously indicated, if the building element material and the conduction, convection, and radiation coefficients that correspond to the PCM base material's container are ideal for the application, there will be more efficient energy transfer in addition to the contact area. Lastly, a rough surface reduces the contact area and influences convection and thermal emissivity, which lowers transfer efficiency. As a result, the roughness both inside and outside of the materials in PCM systems may have an impact on the heat transfer mechanisms.

In contrast, the effective contact surface in micro-encapsulation might depend on several factors, including the microcapsule's geometry and the quantity of it present in the building materials. If there are spaces or another substance between the microcapsules that have differing thermal characteristics, the phenomena may not be as effective. Theoretically, if there are numerous microcapsules in the material, their surface area is greater and thus, the energy transfer needs to be more efficient. Surface roughness and stickiness can similarly influence energy transfer phenomena as macro-encapsulates, however, the behaviour of these physical phenomena can be more erratic. Given that microencapsulates are typically combined with other substances while still fresh and then allowed to set or harden. To guarantee compatibility in the system, chemical adhesion in the cover of such encapsulates is particularly desirable.

Furthermore, the uneven surface form of the microcapsules may lead to the development of mechanical anchoring. Lastly, according to the references included in this article, adding microcapsules to Portland cement-based materials disrupts the hardening or hydration processes, which has an impact on the materials' resistance. Therefore, it makes sense to create microencapsulates that are compatible with these materials' hydration processes. This suggests that changing the contact area, roughness, and adherence in the building system using PCM materials is a way to improve the efficiency of the transfer processes in PCMs. This is related to selecting the proper PCM foundation, cover, container, and encapsulation procedure based on the building's application. A critical analysis of the literature demonstrates how micro-encapsulation increases cycling stability and enhances heat transfer to the surrounding area due to its large surface-to-volume ratio and phase separation limitation to microscopic distances. The cost of the microencapsulation system may be higher than that of other thermal storage techniques. Conversely, the examination of the updated publications demonstrates that macro-encapsulated PCM is simply manufactured in any size or form to accommodate various uses. The microencapsulation of PCM does not call on a pre-established procedure, in contrast to micro-encapsulation, which encapsulates the PCM using a variety of approaches and strategies.

Now let's talk about the thermophysical characteristics of PCMs, which may be found using differential scanning calorimetry (DSC) techniques. These characteristics, which include heat of fusion, specific heat, and melting point, are important for PCM classification. It may be argued, although, that additional techniques like the T-history method and traditional calorimetry techniques, have also been employed. Thermograms are used to analyze these qualities, allowing us to determine the phase transition temperatures at which melting and freezing occur. However, because the values of these attributes are determined using small samples, large samples may yield different results. Unlike previous reviews, this one makes clear how sophisticated PCM systems are. This article outlines a few of the micro and macro-specific characteristics that affect the behaviour of PCM materials. Even though much research works mention compatibility and assume a thorough understanding of the idea, there is currently no consensus to establish a model that represents all the multiphysics phenomena that are coupled in each material component of the system and the entire system of materials for construction with PCMs. Furthermore, there are no guidelines for building procedures or for the mechanical, thermal, and microstructural characterization that would allow us to determine the index parameters needed for PCMs to perform properly.

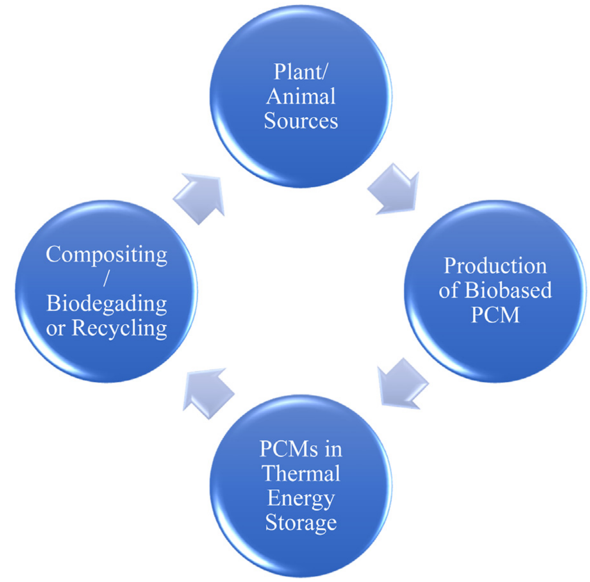


**Fig. 11.** Biobased PCM in thermal energy storage for a sustainable future.

Every newly developed material must have its constitutive equations or behavior rules under various load states to forecast service conditions and failure theories, which can then be applied in real-world scenarios. PCM-containing composites are not an exception. This is on top of the previously mentioned complexity. We want to highlight the numerous research studies that have examined the applicability of employing biomass feedstocks that have the potential to be converted into PCM materials, high-value goods. Testing integrating this biobased PCM with building materials has not yet been carried out to confirm the mechanical and thermal qualities. Similarly, several studies examine the thermophysical characteristics of various organic bio-based PCMs; the outcomes of these studies' thermophysical performance indicate that replacing petroleum-derived PCMs with more ecologically friendly biological or bio-based ones is feasible. However, it is important to assess the mechanical qualities of building materials that contain biobased PCMs before putting them to use in real-world situations.

Natural, renewable materials like fatty acids, plant oils, or other organic substances are used to make biobased PCMs as shown in Fig. 11. Although the topic of PCMs made from biobased raw materials is still in its infancy. The primary kinds of biobased materials along with their respective melting temperatures and enthalpies of fusion has been explored in [345].

The sustainability and environmental advantages of these materials have drawn attention. The biodegradability of biobased PCMs makes them more environmentally friendly than petroleum-based substitutes, which is one of their main benefits. Furthermore, biobased PCMs usually produce fewer environmental contaminants during production and disposal at the end of their useful lives, and they are generally less hazardous.

Fatty acid-based PCMs, for instance, have been effectively applied to building materials to improve thermal performance and lower carbon emissions. The application of a biobased PCM in a passive cooling system for a residential building in a Mediterranean climate was illustrated in a study by [130]. When incorporated into external walls, the

**Table 3**
Comparison of Biobased and Petroleum-Derived PCMs.

| Property | Bio-Based PCM | Petroleum Derived PCM |
|---|---|---|
| Initial Cost (per kg) | \$10-\$15 | \$5-\$8 |
| Thermal Efficiency | High | High |
| Environmental Impact | Low (Biodegradable, Renewable) | High (Non-Renewable, Pollutive) |
| Stability | Moderate (Susceptible to degradation) | High (Chemically Stable) |
| Availability | Limited | High (Widely Available) |
| Payback Period | 3-5 years (Depends on Climate) | 5-7 years |

biobased PCM reduced cooling energy use by 20% throughout the summer while preserving internal comfort. Furthermore, the carbon footprint of the biobased PCM was 30% less than that of a petroleum-derived PCM utilised in a comparable project, according to their environmental impact study. Another illustration is the EnergieSprong refit project in Germany, which uses biobased PCM panels. To improve thermal comfort in shared housing without the need for active heating or cooling systems, biobased PCMs were included into prefabricated panels. According to the project, residents experienced more consistent indoor temperatures all year round, and annual heating and cooling expenses were reduced by 25% [346].

Petroleum-derived PCMs, which are mostly made of paraffins, have been utilised extensively because of their accessibility, affordability, and consistent thermal performance. The high latent heat capacity of paraffin-based PCMs enables them to store and release thermal energy effectively. However, because they come from fossil fuels, these materials are non-renewable and have greater environmental effects than biobased alternatives. Petroleum-derived PCMs have many real-world applications as already been covered in above portion, especially in large-scale projects where cost is a key consideration [347] study, for instance, examined the application of paraffin-based PCMs in a US commercial office building. During the summer, the PCM-enhanced ceiling panels greatly increased energy efficiency by reducing cooling demands by 35%. Due to lower HVAC energy use, the installation's high upfront costs were offset by a five-year return on investment. Another example is the integration of a petroleum-derived PCM into the façade of a Singaporean high-rise building to lower the need for inside cooling. In the tropical region, the PCM façade decreased peak inside temperatures by 4°C, resulting in a 20% reduction in cooling energy usage [348]. The project's life cycle study identified the environmental impact as a drawback, even though the petroleum-derived PCM was economical and offered notable energy savings.

Based on studies, a table has been created Table 3 that contrasts PCMs made from petroleum versus biobased sources according to attributes including stability, cost, thermal efficiency, and environmental impact.

In addition, this paper presents a synopsis of current studies that examine experimental studies of thermal performance for PCM-LHTES building applications in heating, cooling, and hybrid modes. A facility that most closely mimics PCM's real-world performance is needed for experimental research. Following the introduction of the idea of LHTES in buildings, the study examined current literature and categorized it into four primary groups: (1) large-scale prototypes; (2) small-scale prototypes; (3) retrofitting; and (4) laboratory-based partitions/modules. Presented literature in each category was then classified into two sets: active and passive systems and a summarization of all applications was briefed.

It is clear from a careful analysis of the body of research that more work is needed in several areas to improve our knowledge and application of Phase Change Materials (PCMs) in construction. The following are topics needing further research and testing that may yield tangible improvements:

- To improve their practical applicability, future studies on Phase Change Materials (PCMs) in buildings should concentrate on a few important areas. These include creating Multiphysics models to combine thermal and mechanical behaviour in PCM-based systems and conducting tests to describe how building materials and PCM encapsulation interact under different load conditions.
- It is crucial to optimize PCM encapsulation methods, investigate the performance variations between micro and macro-encapsulated PCMs, and conduct research on the effects of encapsulation material and shape on energy transfer efficiency. To verify practical application, compatibility tests between biobased PCMs and building materials such as concrete should be carried out to evaluate their effects on mechanical and thermal qualities. Furthermore, improving thermophysical characterization methods for large-scale PCM samples will yield more precise information for practical building uses. Creating uniform standards for mechanical, thermal, and microstructural characterization will guarantee uniformity in a range of building settings.
- Lastly, data on the energy efficiency, durability, and user comfort of biobased PCMs will be obtained through their integration in actual building situations, including pilot projects in various climates. By filling up current gaps, these research avenues hope to improve PCM performance and sustainability in the building industry.

## 9. Conclusion

Thermal comfort sustainability and a reduction in building energy consumption are made possible by a promising technology known as phase change material acting as a latent heat storage system. Based on the size of the facility used, four categories were created for the experimental studies:

i. Although there are several benefits to using small-scale prototypes, such as changeable control, there is a chance that they won't precisely reflect reality.
ii. Although large-scale prototypes are costly, they work quite well under real weather conditions.
iii. The possibilities for retrofitting applications are constrained.
iv. While research conducted in laboratories can be readily modified, they are fraught with uncertainty when contrasted to more practical studies that make use of prototypes.

In conclusion, it is important to note that PCMs represent a promising emerging technology that can aid in the decrease of energy use in the direction of sustainable living. Such an area has an infinite horizon of untapped potential, hence further well-organized and guided study is needed.

It is recommended that more attention be paid to biobased PCMs in light of the long list of references concerning the encapsulation of both micro and macro techniques for building materials that are discussed and critically reviewed in this work; these are being the most practical way of including PCMs in building materials. However, further investigation is required to process these PCMs and ascertain their macro- and micro-level thermophysical and mechanical behaviour to assess the viability of replacing Petroleum-derived PCMs with more ecologically friendly bio-based ones. An additional practical option for adding PCMs to concrete is provided by the superb PCM with lightweight aggregate concrete.

Again, though, further investigation is required to produce and comprehend a structural PCM lightweight aggregate concrete with practical mechanical, thermal, and heat-storage qualities and to understand how these features affect PCM-LWA when coated and supported by various materials. Therefore, the current review could be a valuable tool for identifying areas for further research and development in the areas of PCM techniques and methods, as well as for helping to optimize processes and develop new encapsulation techniques to achieve the desired mechanical and thermal properties of the finished product for the most economical use of microencapsulated phase change materials possessing the largest capacity for thermal energy storage.

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## CRediT authorship contribution statement

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