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Review Article

Phase change materials (PCMs) used in buildings: A critical review

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ABSTRACT

The construction sector deserves special attention due to its energy efficiency potential, high energy consumption, and environmental impact. Indeed, reducing energy consumption in buildings means reducing the carbon footprint and mitigating climate change. Phase change materials (PCMs) have garnered significant attention in recent years because to their potential to enhance comfort and mitigate environmental impact by reducing greenhouse gas emissions. Between 2013 and 2023, research in this area experienced a substantial increase of 231.45%. This considerable rise reflects the technology›s notable advancements and growing interest among researchers. This article provides a comprehensive assessment of recent scientific studies investigating the effects of PCMs integrated into building envelopes to reduce heating and cooling energy consumption. The main characteristics and properties of PCMs, selection criteria, and integration methods are reviewed and discussed, then the main numerical tools as well as a method for determining the main thermo-physical properties of PCMs based on the results of previous studies are presented. Thus, all the recent research carried out locally (Morocco) was described, and finally, a thorough assessment was conducted to identify deficiencies and offer suggestions for future research.

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INTRODUCTION

We are currently experiencing the first global energy crisis. Pressures on markets had already been evident, but the actions of this crisis have transformed the rapid economic recovery that followed the pandemic and led to tensions across all global supply chains, including energy [1]. Fossil fuels and nuclear energy, both of which are limited and emit significant amounts of greenhouse gases, are the main sources of energy conversion and electricity generation. According to 2014 statistics, if current consumption rates continue, coal reserves will run out in about 130 years, natural gas reserves in about 60 years, and oil reserves in about 20 years. [2].

The construction sector contributes significantly to greenhouse gas emissions and is a significant energy consumer. It made up 132 EJ of energy consumption in 2021, or 30% of total final energy consumption worldwide. When indirect emissions from the production of heat and power are taken into consideration, the sector›s 3 Gt of CO2

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emissions in 2021 accounted for 15% of all emissions from end-use sectors, a percentage that doubles [1].

Currently, the global trend leans towards reducing greenhouse gas emissions, primarily through exploring various innovative technologies to reduce fossil fuel consumption and consequently technologies that have a positive impact on reducing greenhouse gases. Reducing energy demand in buildings and contributing to preserving fossil fuels are major challenges at the turn of the century. Building energy efficiency is part of the response to current energy challenges (resource economy, greenhouse gas reduction, carbon footprint reduction, renewable energy use, etc. It constitutes the primary pillar in the building sector's transition, particularly within the Net Zero Emissions (NZE) scenario. The NZE scenario by 2050 is a normative scenario from the IEA that outlines the path for the global energy sector to achieve zero net CO2 emissions by 2050. In this scenario, energy consumption will decrease by 24% by 2030, reaching approximately 100 EJ. Achieving this necessitates an annual improvement of about 5% in residential building energy efficiency between 2020 and 2030 [1].

There are significant opportunities for efficiency gains that can be introduced and studied to reduce the high energy consumption of buildings. This can be achieved through various passive and active techniques, whether through improving the thermal insulation of building envelope, energy storage for future utilization, heat pumps, energy-efficient appliances, and the utilization of renewable energy sources. Recently, various technical solutions have been introduced. The core of innovation focuses on research into intelligent materials based on latent heat thermal energy storage, able to lower energy consumption and manage thermal comfort in occupied structures. These materials are called phase change materials (PCM).

B. Duraković [2] has outlined the historical development of phase change materials for thermal energy storage in figure 1. The application of PCMs in buildings for thermal storage traces back to the late 1940s, with significant interest in research emerging only during the energy crisis of the late 1970s and early 1980s [2]. Extensive efforts have been devoted to exploring the utilization of PCMs in various domains, including solar heating systems [3-8], clothing, photovoltaic systems [9-14], lithium-ion battery systems [15-17], electronic devices [18, 19], as well as in active heating/cooling systems [20-24], wall panels, bricks, coatings, cement, plaster, concrete [25-32], glazing systems [33], infrastructure [32], etc.

To assess the effect of integrating phase change materials (PCMs) in the construction sector on energy savings and indoor temperature regulation, numerous research findings and significant experiments have been conducted. M. Prabhakar et al. [34] evaluated the impact of coupling macro-encapsulated PCM in bricks with natural ventilation and intelligent control on enhancing the energy efficiency of tertiary buildings. A simulation was conducted for 15 different cities worldwide. It was observed that in hot and arid conditions, the PCM passive cooling technology proved to be inefficient. However, energy savings were augmented by integrating PCMs with natural ventilation in such climatic contexts, although the benefits were comparable to those

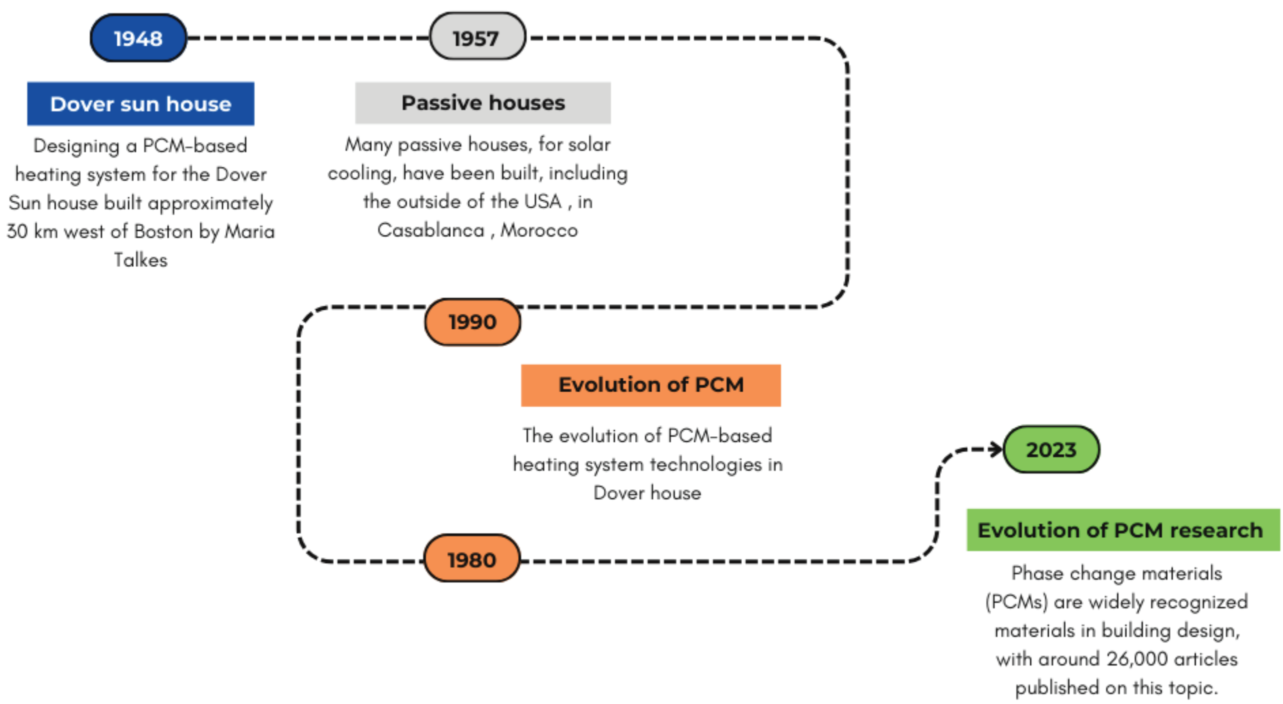

Figure 1. Historical Application of PCMs in Thermal Energy Storage (TES).

achieved through natural ventilation alone. Conversely, PCM efficiency increased from 3.32% to 25.62% in temperate conditions by coupling a passive PCM system with night ventilation. This was enhanced to 40% with the application of PCMs alongside temperature-controlled ventilation. Thus, it can be inferred that intelligent ventilation control has the potential to yield significant energy savings.

Xamán et al. [35] analyzed the effect of integrating phase change materials (PCMs) into a concrete roof on its thermal performance under the hot meteorological conditions of Mérida, Mexico. The results indicate that the installation of a 2 cm R-PCM1 resulted in a reduction of 57% compared with a normal roof. For an average building lifespan in México, approximately 30 years, the installation of R-PCM1 (paraffin wax - MG29) with a 2 cm PCM thickness is economically viable, with a payback period of 12.18 years.

The heat transfer within transparent structures containing PCM, such as windows, represent a highly complex process owing to the interplay of heat conduction, radiation, convection, phase change phenomena, and solar radiation buildup within the unit [33]. King et al. [36] carried out an empirical study on the thermal transfer properties of a double-glazed window integrated with paraffin RT 35 as a PCM. They demonstrated that the systematic integration of the appropriate phase change material into a double-glazed window can effectively mitigate solar heat gain into the room and substantially improve the building›s energy efficiency. Additionally, the PCM notably reduced temperature fluctuations within the interior space from 21°C to 11°C, the interior glass temperature by 8.5°C, and energy usage through the window by 3.76%.

The incorporation of phase change materials (PCMs) within a glazed roofing system, as opposed to air, leads to a substantial 47.5% reduction in energy consumption, with a payback period ranging from 3.3 to 6.2 years. Furthermore, this concept presents itself as a viable solution for renovating large spaces, such as gymnasiums, due to its easy implementation. [37].

Mabrouki et al. [38] investigated the impact of various factors influencing the use of PCM Trombe walls on heating and cooling loads in Ifrane, Morocco, characterized by a semi-oceanic climate. Their findings indicated a significant reduction in the annual energy consumption of the reference house, from 1,285.6 kWh to 733.18 kWh. A notable reduction in energy demand of 42.97% was also achieved by the addition of vents to the PCM Trombe wall.

Saikia et al. [39] introduced a new passive cooling system designed exclusively for high-temperature locations, harnessing the liquid-vapor phase change mechanism. Integration of the LVPCM technology into concrete slabs showed thermal performance equivalent to that of standard SLPCM systems. In the hottest daytime intervals, the use of LVPCM resulted in a reduction of 2.22°C in the temperature. Installation of the technology recorded an average reduction of 20.51% was attained, indicating a heat gain through concrete of 13.56%.

This article presents a comprehensive review of recent literature on phase change materials, considering their types, advantages, and disadvantages. It addresses some approaches to integration along with their benefits and drawbacks. It further addresses the simulation tools that have been applied to optimize and evaluate the impact of PCM integration into building envelopes on energy consumption reduction. The article also gives recommendations for selecting optimum PCM properties, such as type, thickness, and location, based on previous research findings. Subsequently, all recent local (Morocco) research is described, and a critical evaluation is conducted toward identifying gaps and providing recommendations for future studies.

Phase Change Materials (PCM)

Phase transition materials can store or release energy as latent heat. As the PCM temperature rises and the melting point is reached, the PCM absorbs thermal energy and changes phase through the stored latent energy, shifting from solid to liquid state. In the opposite process, when the temperature of PCM decreases, PCM crystallizes, releasing the stored energy. The phase change occurs at a constant temperature. Incorporating such materials into building envelopes provides potential energy savings and enhanced thermal comfort by reducing annual heating and cooling demands. In 1983, Abhat was the first researcher to propose classifying PCMs characterized by a solid-liquid phase change. He published one of the earliest articles describing the properties and potential use of these materials [40].

PCMs are categorized into three major families, organic compounds, inorganic compounds, and eutectics, according to their chemical characteristics, as illustrated in figure 2.

- **Organic PCMs**: These materials are divided into two subcategories based on their function, namely paraffins (C_nH_{2n+2}) and non-paraffins ($CH_3(CH_2)_{2n}$ COOH), including fatty acids and other substances such as alcohols and esters. Paraffin is the most widely used phase change material due to its high heat of fusion, chemical stability, lack of segregation tendencies, and minimal degradation of thermal properties after repeated melting/freezing cycles. Nevertheless, it has low thermal conductivity, is flammable, and undergoes significant volume change from solid to liquid, posing challenges in the design of the container. In addition, one requires caution when using plastic containers because paraffins can infiltrate certain containers and soften them.
- **Inorganic PCMs:** This category includes salt hydrates and metals. Salt hydrates consist of salt and water combining into a crystalline matrix upon solidification. They are heavily studied as energy storage materials due to their affordability, availability, high thermal conductivity and density, non-flammability, and minimal volume

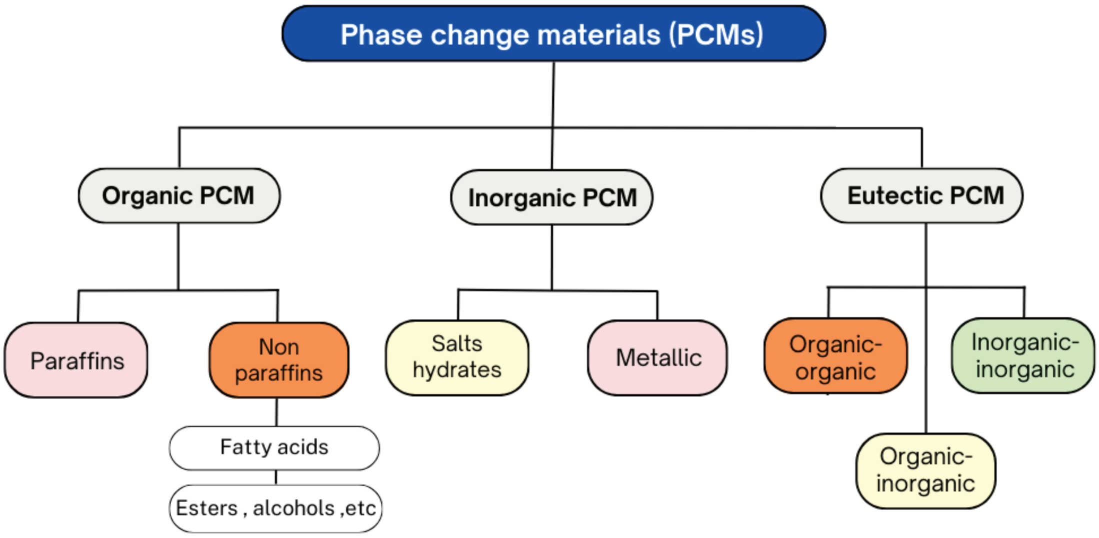

Figure 2. Classification of phase change materials (PCMs).

variation compared to other PCM types. However, the main drawback of salt hydrates is subcooling. Due to their weight, metals have not been extensively studied as PCMs for latent heat storage [2]. Although inorganic PCMs exhibit a sharper phase transformation (direct transition from solid to liquid without softening), they are two to three times more expensive than paraffins and slightly corrosive.

- Eutectic PCMs: refer to mixtures of two or more organic and/or inorganic compounds that consistently melt and freeze at a constant temperature without phase segregation, effectively acting as a singular component.

The diagram in figure 3 represents each PCM subgroup, illustrating the range of melting energy and the melting temperature interval.

To conclude, each of the aforementioned groups of PCMs has distinct properties, advantages, and disadvantages. selecting a suitable material necessitates thorough evaluation of multiple criteria specific to the application, such as buildings, batteries, photovoltaic systems, etc.

Criteria For Selecting a PCM

The selection of a PCM is contingent upon the specific application domain (building, transportation, food, textiles) as well as its environment (climatic conditions), hence the importance of defining the criteria for selecting a PCM

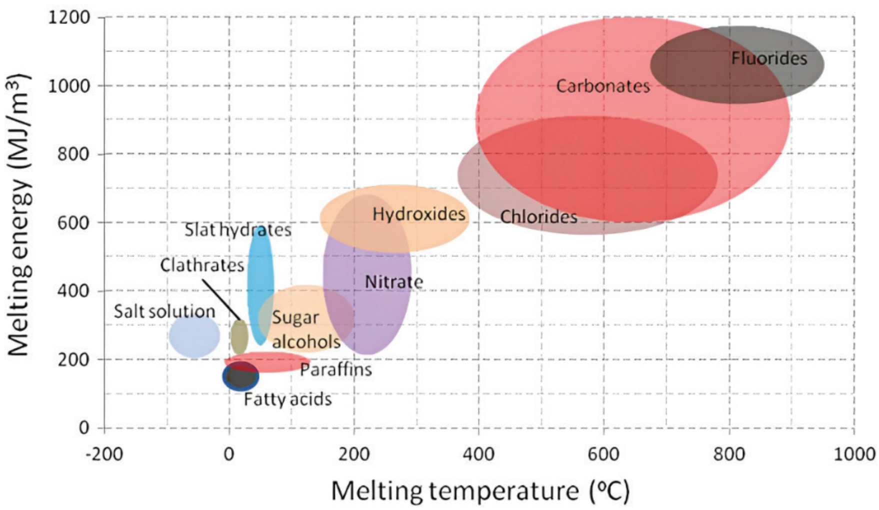

Figure 3. The latent heat and melting temperature of each PCM subgroup [From B.Duraković [2] , with permission from the author].

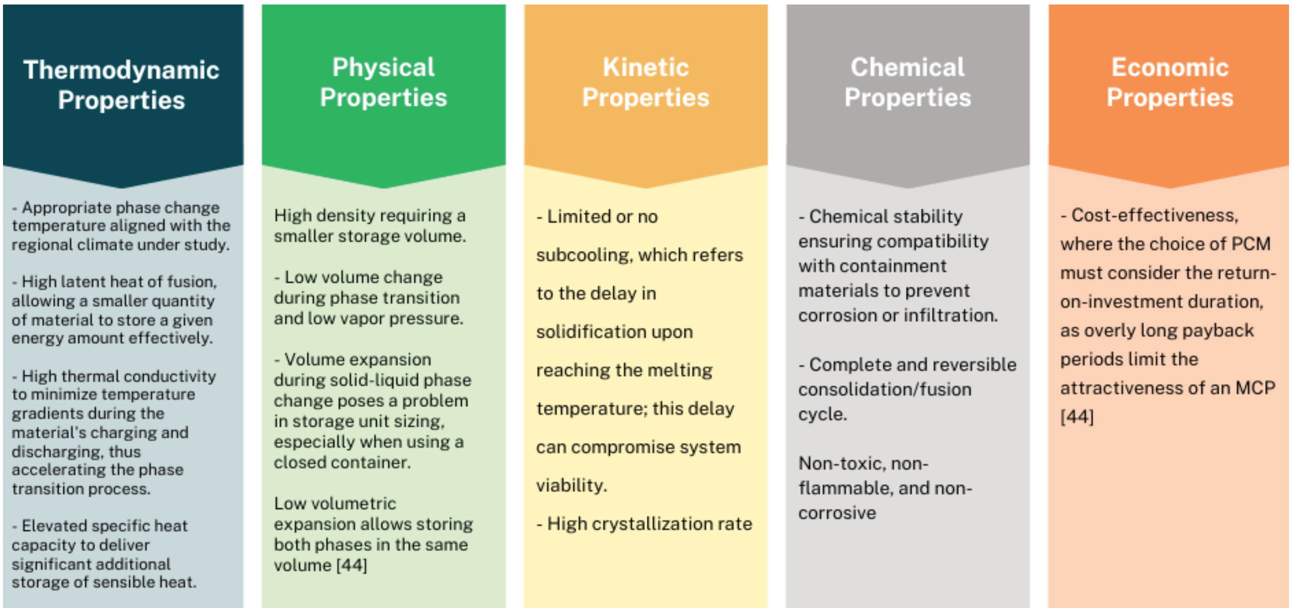

Figure 4. Phase change material's properties.

[41]. Abhat [40], Hawes et al. [42], and Pasupathy et al. [43] have defined the criteria for selecting a phase change material. To appropriately select a PCM for thermal energy storage in the form of latent heat, it is crucial to evaluate its thermodynamic, physical, kinetic, chemical, and economic characteristics. A proficient change material should have the following properties (Fig. 4).

No single material possesses all the required properties for ideal thermal storage. Selecting a PCM involves finding one that delivers optimal performance at minimal cost. Several researchers have affirmed that the melting temperature is one of the crucial thermo-physical properties that influence the performance of PCMs [2], [40-46].

Moreover, Yassine Chihab et al. [47] confirm that, for enhanced energy efficiency, a high heat of fusion and a low thermal conductivity are desirable properties for PCMs applicable in buildings. However, high thermal conductivity is recommended when using PCMs in heat exchanger systems [2].

The correlation among the heat of fusion, melting temperature, and thermal conductivity in various widely used commercial phase change materials used in construction applications is illustrated in figure 5.

In summary, the melting temperature, latent heat, cost, and stability are critical factors that will influence the market adoption of phase change materials (PCMs).

Since paraffins are widely recognized as the predominant phase change materials utilized in thermal energy storage applications due to their non-toxic nature, abundance, ease of microencapsulation, and other advantages, they are still derived from crude oil. This underscores the need to explore the development of biologically derived PCMs (bio-PCMs) as a sustainable alternative.

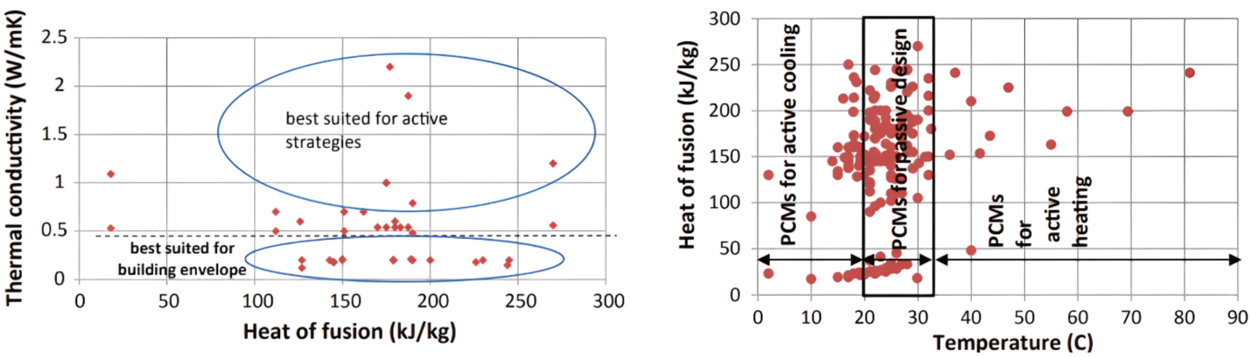

Figure 5. (**a**) Heat of fusion versus thermal conductivity, (b) Heat of fusion versus melting temperature for selected commercial PCMs [From B.Duraković [2], with permission from the author].

Bio-based PCM (BPCM)

Within the context of sustainable development, bio-origin phase change materials (BPCMs) offer an alternative to commercially available paraffin-based PCMs. They are renewable and environmentally friendly [48].

According to Duraković [2], paraffins are are the most commonly used as PCMs in thermal energy storage applications due to their non-toxic nature, abundance, and ease of microencapsulation. They are derived from petroleum, and their prices are sensitive to seasons and geopolitical scenarios. Consequently, there is a recognized necessity to explore other forms of bio-origin PCMs [2]. Several studies have been conducted for the development of a bio-sourced PCM capable of delivering comparable performance to conventional phase change materials.

The potential use of a bio-based PCM that is prepared from expired palm oil sourced from the food industry was investigated by Fabiani et al. [49]. Compared to petrochemical-based organic PCMs, it was found that, despite the low phase transition enthalpy, expired palm oil may serve as a potential, affordable, and environmentally friendly alternative for passive thermal storage systems. Such bio-based materials require further study in order to enhance the energy storage density and minimize subcooling to guarantee a more consistent material conducive to high performance while maintaining sustainability.

Boussaba et al. [50] explored the utilization of recovered coconut fat from underused feedstocks, cellulose fibers from recycled cardboard, natural clay, and graphite as a bio-based composite phase change material. The authors demonstrated that the latent heat fusion and freeze capacities were found to be 106.17 J/g and 107.34 J/g respectively, making the bio-based PCM suitable for passive solar TES building applications. It was found that the phase change temperatures aligned closely with human comfort levels (22.63 °C and 17.44 °C for the fusion and freeze cycles respectively), emphasizing its potential for practical application as a bio-based PCM. Thermal analysis TGA confirmed the material›s stability within operational temperature ranges, with thermal degradation starting above 200 °C., while spectroscopic analysis (FT-IR) verified its chemical stability.

Choi et al. [51], Jin Ong et al. [52], and Yoo et al. [53] examined the chemical composition, chemical, and thermo-physical properties of used coffee grounds (waste produced after using coffee as a beverage) to assess their viability as bio-based PCMs. Choi et al. [51] analyzed the morphological, thermal, and acoustic performances of a composite developed from degreased coffee waste with ethanol, urea-formaldehyde resin and bio-based micro-encapsulated PCM (MPCM). The results indicate that the developed composites present enhanced thermal performances (high thermal conductivity, thermal stability, etc.) and improved acoustic absorption properties. The composite can therefore be regarded as a sustainable building material, exhibiting significant thermal and acoustic properties.

Other PCMs have been evaluated by several researchers, including beeswax as a paraffin alternative as a durable, ecological, and potential PCM [54], [55], sugar alcohols [56], [57], [58], [59], [60], a eutectic mixture of ceramist sludge [61], grease waste from pork cooking processes confined in a polypropylene nonwoven mat derived from surgical mask filter waste and porous bio-silica (diatomite) [62], etc.

The bio-based products are developed from the renewable organic resources, presenting a more environmentally friendly, sustainable, and ecological option. These materials possess similar thermal properties, including latent heat capacity, phase change behavior, and thermal cycling durability, which make them suitable for equivalent thermal energy storage applications. However, research into biobased PCMs is still at the laboratory stage, so their use in building envelopes needs to be proven by experiments.

PCM Incorporation

To ensure optimal functionality, longevity, and mitigation of potential issues like corrosion or PCM leakage during its incorporation, various considerations are essential. Firstly, the storage system material must be suitable for the PCM, the container wall must also be thick enough for seal integrity and leak protection. Moreover, incorporation should be designed to withstand mechanical constraints arising from PCM volume changes during phase transitions. Therefore, selecting an appropriate incorporation method of PCM is crucial. There are several techniques for incorporating PCM into construction materials, such as direct incorporation, immersion, stabilized form, and encapsulation [63].

Encapsulation is the most widely used technique. It is a process that was invented and developed by Barrett K. Green of the National Cash Register Corporation (NRC) during the 1940s and 1950s [64]. This method entails encapsulating the PCM with an appropriate coating or shell material, in principle, maintaining the liquid and/or solid-phase of the PCM while isolating it from the outside environment [65].

Encapsulation provides multiple benefits, by decreasing PCM›s reaction to the environment, increasing flexibility in phase change process, and raising the thermal and mechanical stability of the PCM. Additionally, PCM encapsulation contributes to heightened heat transfer rates by increasing surface area, thereby increasing thermal conductivity. However, one of the main obstacles to commercializing an encapsulated PCM-based system lies in the considerable cost associated with encapsulation, which raises the overall system cost [66]. Encapsulations are classified based on their size into macro, nano, and micro-encapsulations [65].

- ✓ **Macro-encapsulation:** involves encapsulating phase change materials in large-scale containers, such as tubes, sachets, spheres, or panels, ranging from a few millimeters to several liters in volume. It is necessary that these containers be constructed from rigid materials with high thermal conductivity, such as aluminum or copper, to prevent leakage issues [37]. Additionally,

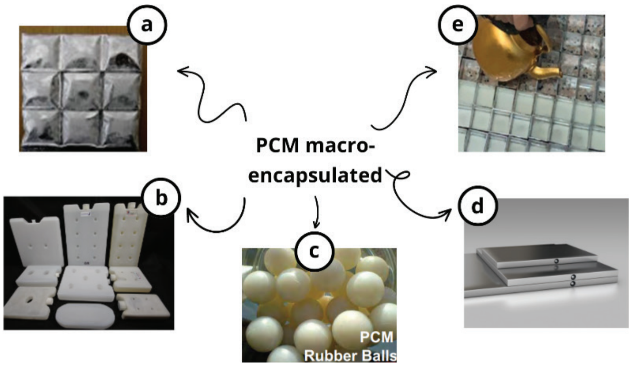

Figure 6. (a) Macro-encapsulation in sachets produced by PCM product company, (b) Macro-encapsulation in plastic containers as produced by PCM product company, (c) Macro-encapsulation in Rubber balls from PCM product company, (d) Macro-encapsulation in metal containers as produced by PCM product company [68]. (e) Macro-encapsulation in bricks for constructing a wall [From Q.Alyasiri et M.Szabo [67], with permission from Elsevier].

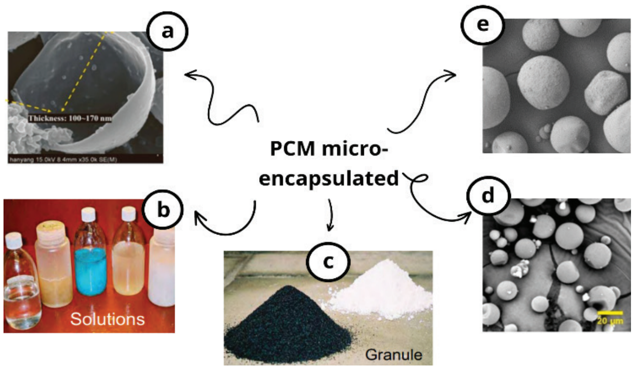

Figure 7. (a) Micro-encapsulation in a bio-sourced polymer shell (m-PCM) for incorporation into nano-modified cement composites [From X.Jin et al. [71], with permission from Elsivier]. (b) and (c) Microencapsulated PCM produced by PCM product company in fluid dispersion and granule forms respectively [68]. (d) PCM microcapsules are incorporated into asphalt coatings to regulate the temperature of asphalt pavements [From D.Bentacourt-Jimenez et al. [69], with permission from Elsevier]. (e) PCM microcapsules are incorporated into cement paste [From Y.Gu et al. [70], with permission from Elsevier].

when the container possesses sufficient rigidity, macro-encapsulation could also contribute to enhanced mechanical stability in the resulting system.

Figure 6 illustrates examples of macro-encapsulated PCM [67], [68].

✓ **Micro-encapsulation**: involves encapsulating the phase change material in spheres or capsules with diameters ranging from 1 μm to 1000 μm [46]. These PCM particles can then be incorporated into any matrix that is well suited to the encapsulated shell, such as construction materials. Microencapsulated PCM effectively avoids the drawbacks of macro-encapsulated PCM, such as handling issues, leakage risks, shape distortion, and maintenance complexities [67].

There are numerous commercial products of microencapsulated PCM, such as Micronal® PCM produced by the German company BASF. **Figure 7** depicts examples of microencapsulated PCMs [68-71].

✓ **Nano-encapsulation:** in certain applications, particularly in latent functional thermal fluids, microencapsulated phase change materials (PCMs) have demonstrated limited performance under repeated cycles. This limitation arises from the tendency of large particles in microencapsulated PCMs to increase fluid viscosity and susceptibility to being crushed during pumping. Consequently, there has been a focus on developing PCMs with particle sizes smaller than those found in microencapsulated forms [72]. Nano-encapsulation is an encapsulation technique introduced by Narty in the 1970s and widely used in medical dyes and fragrances [72]. It involves encapsulating the phase change material within capsules with diameters ranging from 1 nm to 1000 nm.

In light of the findings, it can be concluded that reducing capsule size enhances the thermal reliability and chemical stability of PCM. Nano-capsules exhibit superior structural stability compared to macro and microcapsules. However, research on nano-encapsulated PCMs is still at the laboratory level [65] .

Despite microencapsulated PCMs offering higher thermal reliability and chemical stability than macro-encapsulated materials, their production process remains more complex. They may also face subcooling issues due to hypothermia, retaining the liquid phase even below its freezing point [65]. In addition, they can present some leak issues caused by micro-encapsulation damage during handling or mixing processes at construction sites, which can deteriorate the properties of construction materials used for building. Encapsulating PCM in containers larger than 5,000 μm and then integrating it into the building envelope will minimize PCM leaks [66].

Rathore & Shukla [66] performed a comprehensive analysis of various approaches to integrate macro-encapsulated PCM into the building envelope. They demonstrated that macro-encapsulation is one of the simplest and most efficient methods to directly incorporate PCM into construction materials. Furthermore, macro-encapsulated PCM exhibits high resistance and durability relative to microencapsulated PCM and can be simply fabricated by filling PCM into the shell material of any desired shape.

Techniques for Enhancing The Thermal Properties of Phase-Change Materials

In the context of improving the energy efficiency of buildings, which has become a crucial concern, phase change materials have garnered substantial attention from researchers. Their incorporation is also potential for creating energy-saving building envelopes and reducing CO2 emissions in this sector. This is due mostly to their significant potential for storing and releasing heat energy, thus enhancing the latent heat storage potential of building envelope upon incorporation. However, PCM's drawback lies in their low thermal conductivity,resulting in suboptimal heat transfer rates and negligible effectiveness in heat storage and release. These limitations may inhibit their further usage as heat energy storage materials in building applications [73]. In order to overcome these setbacks, some methods could be implemented, such as incorporating high-conductivity materials, nano-encapsulation, forming composite PCMs, and shape stabilization [74].

- Forming a PCM -composite represents an approach aimed at enhancing the thermal performance of PCMs. It involves combining a PCM with other materials possessing high thermal conductivity to create a composite material with additional or modified properties. The integration of PCMs into another material's matrix is done at a microscopic level to preserve their thermal characteristics [42]. These composites can take the form of fibers/stearic acid, foams/polyethylene, or films [74]. Composites that establish a stable structure between a PCM and another material are commonly referred to as shape-stabilized PCMs [42].
- Shape-stabilized PCM: a technique for improving the thermal performance of PCMs, commonly adopted for organic PCMs known for their low thermal conductivity and leakage issues during phase change. This strategy involves utilizing two components: a porous material that prevents PCM leakage, such as porous carbon (derived from materials like cardboard, potatoes, succulents, activated carbon, etc.), expanded graphite, or polyurethane foam; and a nanomaterial that enhances the thermal properties of PCMs [73]. Additionally, the porous matrices enhance thermal performance through the provision of an extended surface area for heat transfer [74]. The loading PCMs into porous materials can be achieved through vacuum impregnation, ultrasonic oscillation, and melting adsorption methods [73].
- Nano-encapsulation: As mentioned in the earlier section, it encapsulates the phase change materials in tubular, cylindrical, spherical, or rectangular capsule, with diamters in the range of 1 nm and 1000 nm. It remains the most efficient technique for improving heat transfer rates [74], mostly by improving the thermal conductivity of PCMs and minimizing leakages while in their phase transition [75]. Metallic [76] and carbon-based [77] nanoparticles of high thermal conductivity are incorporated into PCMs for improved heat conductivity. Nonetheless, carbon-based nanoparticles demonstrate superior stability and dispersion within PCMs compared to metallic counterparts [2].

Numerous investigations have been implemented to evaluate the advantages of integrating nano-PCM in terms of energy savings and thermal comfort compared to conventional PCMs. Zhenjun et al. [78] demonstrated that the enhanced solidification/melting process of nano-PCM incorporated into a ventilation system, as opposed to the pure process, increased the heat charge and discharge rates by 8% and 25%, respectively.

Fateh Mbarek Oudina and Ines Chabani et al. [79] concluded that, from an economic perspective, the cost of this technique is relatively low in comparison to the substantial benefits conferred by the inclusion of nanoparticles and phase change materials on the overall thermal performance of systems. This represents an excellent solution for ensuring thermal comfort at a very low cost, enabling the phase transition to occur much more rapidly than in systems with pure PCM while capturing greater solar energy. Additionally, the use of nano-PCM leads to an increase in overall thermal capacity, resulting in significant thermal storage.

Nonetheless, it was reported by Ghalambaz et al. [80] that the cost of the nanoparticles is dependent on their type, as the copper nanoparticles were around 10 times higher in value as compared to the alumina nanoparticles. This highlights the interest in developing hybrid nano-PCMs, which are prepared by suspending various types of nanoparticles in a PCM. From numerical simulation of the melting process in nanoparticle-enhanced phase change materials, the authors that The melting process was improved by utilizing a hybrid nano-PCM. Specifically, the melting time of the single-component water/Ag–MgO nano-PCM was lower compared to that of the single-component water/MgO nano-PCM.

- Incorporation of High Thermal Conductivity Materials: This strategy is based on the incorporation of high thermal conductivity materials such as nano-metals, aluminum or carbon fins, carbon-based materials, or expanded graphite. Such fillers, through the formation of a conductive network within the PCM matrix, enhance thermal transfer as well as general thermal performance while preserving the inherent latent heat storage potential of the material [74].

Moreover, thermal conductivity improvement in PCMs can also be obtained through chemical modifications such as doping or grafting [81]. These chemical modifications considerably alter the composition and surface phase structure of the thermally conductive matrix, resulting in porous materials with doped components to improve the cyclic stability as well as the thermal conductivity of the PCM. Grafting, or post-synthesis modification, entails a chemical reaction that deposits organic groups onto the surface of the mesoporous canals. Doping, grafting, or incorporation of uniquely structured materials enhance the thermal conductivity, sensible heat, and latent heat of fusion of pure PCM [81].

Thermal performance can be improved through different methods. Nevertheless, the integration of some unknown elements may introduce adverse effects, such as a decrease in thermal stability. Therefore, additional research and development should be taken into account to improve the functionality of PCMs.

The Simulation Tools

The integration of phase change materials into lightweight constructions allows for improved thermal comfort and reduced energy consumption. Yet, to accurately evaluate and optimize the integration of phase change materials within building envelopes, numerical simulation becomes a necessary requirement. The simulation of building performance represents a key tool to choose the most effective solution to integrate [82]. Currently, several energy simulation tools are available and widely employed by researchers and designers, broadly categorized into two groups: Building Energy Simulation (BES) tools, including EnergyPlus as well as TRNSYS, and computational fluid dynamics packages, namely ANSYS Fluent and COMSOL Multiphysics.

According to Pandey et al. [83], Computational Fluid Dynamics (CFD) tools offer the capability to model spatially distributed solidification and complex PCM melting phenomena. However, they require considerable computational time to model and simulate the entire building system in combination with a PCM-based system. Additionally, CFD modeling necessitates accurate boundary conditions derived either from experimental data or prior knowledge of the system. Furthermore, these CFD models are not seamlessly integrated into building simulation frameworks.

Despite the relative simplicity of using Energy Plus as a Building Energy Simulation (BES) tool, which explains its extensive utilization in the literature to assess the impact of PCMs on enhancing thermal comfort and reducing cooling/heating energy demand, these BES tools reveal certain limitations [83]. For example, in the application of free cooling where PCM is charged with natural ventilation, meaning that external cold air is used to extract heat from the PCM, the use of BES tools to study the performance of the PCM TES system leads to under/over-prediction of results. This can be explained by the fact that these tools consider an air node in each zone as representing a volume of air with uniform thermal properties. Additionally, BES tools use uniform thermal properties to model a zone, whereas PCM solidification and melting phenomena are highly non-uniform, limiting their use in determining the efficiency of PCM-based systems. To address these challenges, Pandey et al. [83] developed a co-simulation model combining EnergyPlus as a BES tool and Ansys Fluent as a CFD tool to evaluate its relevance compared to EnergyPlus and to assess the impact of PCM-based systems on the built environment. The findings indicate that co-simulation outperforms existing BES tools, particularly in scenarios involving active use of PCM in the built environment and when passively applying PCM in forced convection. Indeed, a comparison of the predictive accuracy of the co-simulation model and EnergyPlus during forced convection reveals that EnergyPlus model underestimates the experimental data. However, for passive PCM application , the results indicate that there is no significant difference in predictive accuracy between the co-simulation approach and conventional BES models.

In the same context, Mazzeo et al. [82] assessed the predictive accuracy of the most widely used BES tools, namely TRNSYS, EnergyPlus, and IDA ICE, by comparing simulated outcomes with experimental measurements obtained under real operating conditions. Their findings underscored IDA ICE as a robust choice for dynamically modeling buildings incorporating Phase Change Materials (PCMs). Unlike TRNSYS and EnergyPlus, IDA ICE explicitly addresses PCM hysteresis phenomena. Moreover, the TRNSYS model exhibited the least precision due to its omission of both hysteresis effects and the temperature range associated with phase transitions, which are implemented in both IDA ICE and EnergyPlus. Even though TRNSYS yields the lowest precision, it allows for sufficiently accurate calculation of the total latent heat storage and release, with minimal thermo-physical input requirements and the lowest computational cost.

The selection of a simulation tool is contingent upon the specific model, simulation objectives, and the anticipated outcomes. TRNSYS and EnergyPlus are widely regarded as the most suitable and extensively utilized simulation tools for evaluating heating and cooling energy consumption in buildings that incorporate phase-change materials.

PCM Optimization

The annual thermal energy demand for heating and cooling in buildings with PCM integration is influenced by various factors, including the melting temperature, PCM thickness, and its location within the external envelope of construction [84].

a. Melting temperature

The melting temperature refers to the point at which a substance transitions from a solid to a liquid state, absorbing energy during this process and releasing it upon crystallization. Imghoure et al. [85] demonstrated through a simulation model that the melting temperature is one of the most crucial thermo-physical properties influencing PCM performance. Indeed, A suboptimal selection of the phase transition temperature could lead to increased cooling energy requirements during the summer months [86].

In a related context, Peippo et al. [87] introduced a method to calculate the optimal melting temperature for a phase change material:

$$T_{m,opt} = T_r + \frac{Q}{h\, t_{stor}} \quad (1)$$

$$avec\ T_r = \frac{t_n T_n + t_d T_d}{t_n + t_d}\ et\ t_{stor} = t_n + t_d$$

With $T_{m,opt}$ representing the optimal melting temperature of the PCM (°C), T_r the average room temperature (°C), Q the heat absorbed per unit area of a room surface (*J.m-2*), h the average transfer coefficient between the wall surface and its surroundings (*W.m-2K-1*), T_n room nighttime

Table 1. Results of PCM optimization from the literature

Climate zone	City	Optimal PCM	Thickness (mm)	Optimal placement of PCM	Optimal melting point (°C)	set-point temperature/ interior temperature (°C)	Ref
Am	Semarang (Indonesia)	PCM 29	20	Interior	29	20°C to 24 °C for winter 24°C to 26.5°C for summer	[88]
Aw	Brasilia (Brazil)	PCM28	20	Interior	28	20°C to 24 °C for winter 24°C to 26.5°C for summer	[88]
Af	Kisumu (Kenya)	PCM29	20	Interior	28	20°C to 24 °C for winter 24°C to 26.5°C for summer	[88]
Bsk	Makhachkala (Russia)	PCM26	20	Interior	26	20°C to 24 °C for winter 24°C to 26.5°C for summer	[88]
	Ceduna (Ausralia)	Rubitherm (CSM) RT 22	15	Interior	22	24°C	[89]
	Quetta (Pakistan)	Corda Therm 24	40	Interior	24	18 for heating 25 for cooling	[90]
Bsh	Luanda(Angola)	PCM29	20	Interior	29	20°C to 24 °C for winter 24°C to 26.5°C for summer	[88]
	Dakar (Senegal)	Rubitherm (CSM) RT 25	15	Interior	25	24°C	[89]
	Lahor (Pakistan)	Corda Therm 24	40	Interior	24	18°C for heating 25 for cooling	[90]
	Agadir (Morocco)	Infinite RTM 23 Based on hydrate salts	6 with a mechanical ventilation rate of 6 ACH	Middle, in the cavity of a double partition wall made of hallow clay bricks	23	set-point temperatures of 26°C in summer and 20 °C in winter	[91]
	Errachidia (Morocco)	40% polyethylene and paraffin (60%)	5	Exterior, next to the heat source	21,7-30	The test was conducted at controlled temperatures of 25.5 °C on the cold plate and 40 °C on the hot plate	[92]
Bwh	Cairo (Egypt)	PCM23	20	Interior	23	20°C to 24 °C for winter 24°C to 26.5°C for summer	[88]
	Abou Dabi (UAE)	Rubitherm (CSM) RT 26	15	Interior	26	24°C	[89]
	Marrakech (Morocco)	Infinite RTM 25 Based on hydrate salts	6 with a mechanical ventilation rate of 6 ACH	Middle , in the cavity of a double partition wall made of hallow clay bricks	25	set-point temperatures of 26°C in summer and 20 °C in winter	[91]
	Ouargla (Algeria)	Calcium chloride hexahydrate CaCl2.6H2O	PCM is inserted in the holes of the brick (12 cavities)	Middle	29,9	27 °C (imposed comfort temperature)	[93]
	Karachi (Pakistan)	Corda Therm 24	40	Interior	24	18°C for heating 25 for cooling	[90]
Bwk	Turpan (China)	PCM 28	20	Interior	28	20°C to 24 °C for winter 24°C to 26.5°C for summer	[88]
	Las Vegas (USA)	Rubitherm (CSM) RT 26	15	Interior	26	24°C	[89]
Cfa	Brisban (Australia)	PCM 26	20	Interior	26	20°C to 24 °C for winter 24°C to 26.5°C for summer	[88]
	Madrid (Spain)	Rubitherm (CSM) RT 25	15	Interior	25	24°C	[89]

Table 1. Results of PCM optimization from the literature (continued)

Climate zone	City	Optimal PCM	Thickness (mm)	Optimal placement of PCM	Optimal melting point (°C)	set-point temperature/ interior temperature (°C)	Ref
Cfb	Hamilton (New zealand)	PCM 24	20	Interior	24	20°C to 24 °C for winter 24°C to 26.5°C for summer	[88]
	Paris (France)	Rubitherm PCM24	20	Interior	24	20°C to 24 °C for winter 24°C to 26.5°C for summer	[94]
	Bilbao(Spain)	Rubitherm PCM22	20	Interior	22	20°C to 24 °C for winter 24°C to 26.5°C for summer	[94]
	Melbourne (Australia)	Rubitherm PCM25	20	Interior	25	20°C to 24 °C for winter 24°C to 26.5°C for summer	[94]
Csa	Naples (Italy)	PCM 24	20	Interior	24	20°C to 24 °C for winter 24°C to 26.5°C for summer	[88]
	Tehran (Iran)	Rubitherm (CSM) RT 26	15	Interior	26	24°C	[89]
	Fes , Tangier (Morocco)	Infinite RTM 25 Based on hydrate salts	6 with a mechanical ventilation rate of 6 ACH	Middle, in the cavity of a double partition wall made of hallow clay bricks	25	set-point temperatures of 26°C in summer and 20 °C in winter	[91]
	Istanbul (Turkia)	Infinite PCM	33,6 (3 Layers of 11,2)	Interior	21	20°C to 24 °C for winter 24°C to 26.5°C for summer	[84]
Csb	Bursa (Turkey)	PCM 26	20	Interior	26	20°C to 24 °C for winter 24°C to 26.5°C for summer	[88]
	Ifrane (Morocco)	Infinite RTM 25 Based on hydrate salts	6 with a mechanical ventilation rate of 6 ACH	Middle, in the cavity of a double partition wall made of hallow clay bricks	25	set-point temperatures of 26 and 20 °C throughout the summer and winter season, respectively	[91]
	Antofagasta (Chile)	Rubitherm (CSM) RT 24	15	Interior	24	24°C	[89]
Cwa	Busan (Korea)	PCM 26	20	Interior	26	20°C to 24 °C for winter 24°C to 26.5°C for summer	[88]
	Hong Kong (China)	Rubitherm (CSM) RT 25	15	Interior	25	24°C	[89]
Cwb	Johannesburg (South of Africa)	PCM 26	20	Interior	26	20°C to 24 °C for winter 24°C to 26.5°C for summer	[88]
	Islamabad (Pakistan)	Corda Therm 24	40	Interior	24	18 for heating 25 for cooling	[90]
Dfa	Chicago (USA)	PCM 26	20	Interior	26	20°C to 24 °C for winter 24°C to 26.5°C for summer	[88]
Dfb	Montreal (Canada)	PCM 25	20	Interior	25	20°C to 24 °C for winter 24°C to 26.5°C for summer	[88]
	Ottawa (Canada)	An aluminum honeycomb matrix with 60% microencapsulated paraffin	20	Interior	23	24°C	[95]

temperature (°C), T_d the daytime room temperature (°C), t_n the PCM discharging time night (s), t_d charging time day (s), and t_{stor} the diurnal storage time (s).

Several studies conducted in different cities worldwide aimed to determine the optimal melting temperature [88-95]. Table 1 summarizes some literature studies investigating the effect of integrating PCMs into buildings on reducing heating and cooling energy consumption. The table specifies the type of PCM used by each author, its optimal melting temperature, location, and thickness. These studies are classified, according to the Köppen-Geiger climate classification system, based on monthly average outdoor temperatures and precipitation data. This classification divides the world into five major climatic regions (A: equatorial, B: arid, C: temperate, D: continental, E: polar). These climatic zones are further divided based on precipitation and temperature data.

The analysis of the table regarding the optimization of melting temperature leads to conclusions similar to the study conducted by Saffari et al. [96]. In climates with high energy demand (A and B), PCM melting temperatures are generally close to the maximum of 26°C (ranging from 24 to 28°C). Conversely, in climates where heating predominates (C and D), PCM transition temperatures vary from 18°C to 22°C, except for select cities where the optimal melting temperature may exceed these values, for example, Paris which has an optimal melting temperature of 24°C [94]. According to Saffari et al. [96], this difference can be explained by other climatic factors such as altitude.

In general, for enhanced energy efficiency, several researchers affirm that the optimal melting temperature of a phase change material should closely align with the average indoor heating and cooling setpoints [47], [95], [97]. Neeper (2000) considers that the optimal melting temperature of a phase change material should be close to the interior temperature to minimize thermal loads. The indoor temperature of a room is heavily contingent on the outdoor temperature, which fluctuates across seasons.

It is pertinent to mention that in studies where the set-point temperature is unspecified, we referred to ASHRAE standard 55 (American Society of Heating, Refrigerating, and Air-Conditioning Engineers), which recommends a comfort temperature of 20°C to 24°C for winter and 24°C to 26.5°C for summer.

Cities in the same climatic region, such as Bilbao and Paris (Cfb), won›t necessarily have the same optimal melting point of phase change materials (PCMs), since different climatic conditions apart from the Koppen climatic classification are also involved. Some of the climatic conditions that dictate the selection of the PCMs are wind velocity, intensity of solar irradiance on the exterior surfaces, humidity ratio, and precipitation intensity [98].

For instance, Paris, situated at an altitude of 15 meters, has an optimal PCM melting temperature of 24°C as determined by Bozzhigitov et al. [94]. Conversely, in Bilbao, located at an altitude of 19 meters, the optimal melting temperature is 22°C. This indicates that comfort temperature, a key parameter for determining the melting temperature of a phase change material, depends on the outdoor temperature, which in turn varies with altitude. Outdoor temperature decreases with altitude.

In the context of the RP884 research initiated by ASHRAE in 1995, aimed at formulating an international adaptive comfort standard to complement the American ASHRAE Standard 55, several scholars (Humphrey 1978, de Dear 1986, Nicole Rejal 1995, de Dear and Brager 2002) have demonstrated, through on-site investigations, that indoor comfort temperature is influenced by outdoor temperature. The adaptive approach involves determining thermal comfort conditions from empirical data and field studies. It was introduced by de Dear and Brager in 1998 based on extensive data collected from 160 global office buildings [100], this methodology enables the establishment of linear regressions for comfort temperature in relation to outdoor temperature for both air-conditioned and naturally ventilated buildings [99].

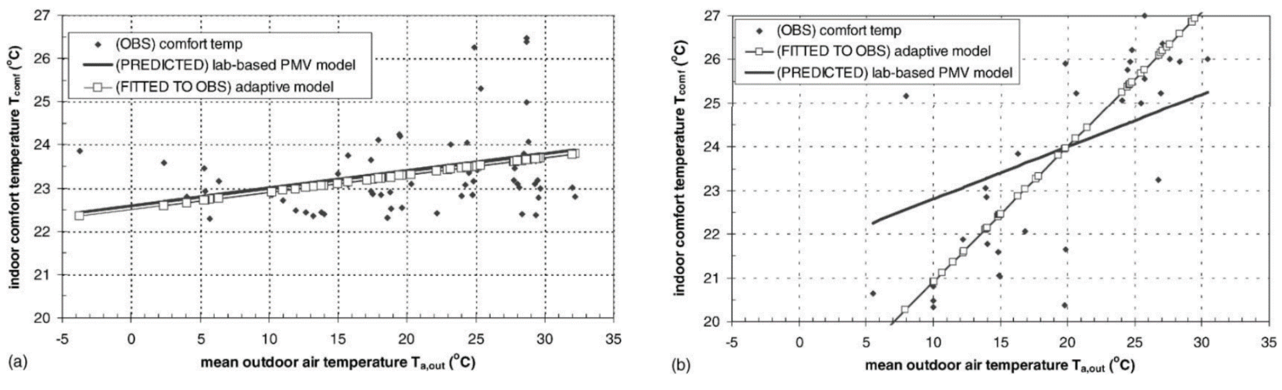

Figure 8. Adaptive model proposed by the RP-884 project for air-conditioned buildings and naturally ventilated buildings [From R.De Dear and G.Brager [99], with permission from Elsevier].

The results obtained by de Dear are illustrated in figure 8. Through this figure, it can be concluded that as altitude decreases, the average outdoor temperature increases, leading to higher comfort temperatures and consequently higher melting temperatures.

Within the framework of optimizing the phase transition temperature of PCM, Dardouri et al. [86] conducted a study aimed at evaluating the PCM›s efficacy, in conjunction with thermal insulation, in reducing annual energy consumption. The results revealed that for both single and double walls, PCM 23 demonstrated superior energy savings in heating, while PCM 29 exhibited higher benefits in cooling energy. This can be attributed to PCM23›s ability to maintain thermal comfort during summer months due to its lower melting temperature compared to outdoor temperatures, thereby keeping the PCM mostly in a liquid state, posing a risk of overheating. A PCM with a fixed melting temperature proves inadequate for simultaneous heating and cooling applications [101].

Liu et al. [46] emphasized, based on previous studies, the necessity of considering the fluctuations in solar radiation received by various building elements such as walls, roofs, and floors. Given that the roof receives the majority of solar radiation, it is advisable to use a PCM exhibiting a higher phase change temperature compared to walls to mitigate heat influx, especially during cooling periods. Therefore, the integration of a single PCM within a building envelope fails to maximize its thermal potential to control the internal temperature as well as to minimize the consumption of energy.

Overcoming this challenge, Wang et al. [102] proposed a strategy to improve the energy efficiency of PCMs integrated into building structures. This includes the use of adaptive dynamic building envelope integrated PCM (ADBEIPCM), in which the location of the PCM and the insulation vary with the outdoor temperature. Their research showed that, in comparison with a static envelope, such innovative walls considerably reduced annual cooling loads by between 15% and 72% and heating loads by 7% and 38%. However, no actual practical experience in the use of ADBEIPCM in buildings to evaluate the technical viability exists, as their complex maintenance makes their application challenging. Another potential method to increase the storage of energy within the building envelope involves utilizing cascaded thermal storage PCM, also known as cascaded latent thermal energy storage. This method consists of integrating various PCMs in decreasing order of their melting temperatures.

PCM placement

The potential of phase change materials (PCMs) to enhance thermal comfort and energy efficiency of buildings is contingent upon the location where the PCM is incorporated within the exterior envelope. The optimum location to integrate PCM can be reliant on certain factors such as heat source temperature, exterior surface temperature, thermal flux density through the wall, and thermal flux stored within the walls [92]. Several numerical and experimental studies recommend the adoption of internal wall placement of PCMs, as given in Table 1.

Khan et al. [90] conducted a numerical simulation using Energy-plus software to study the effect of PCM integration in residential building envelopes in five major cities located in different climatic zones in Pakistan (Islamabad, Karachi, Lahore, Quetta, Peshawar). The study aimed to optimize several parameters such as PCM melting temperature, its location, and thickness. The results indicate that annual energy consumption in the configuration where PCM is positioned on the inner surface of the wall diminishes by 6.04%, compared to a reduction of 5.5% when it is placed on the exterior side.

Ben Zaid et al. [92] carried out an experimental study to assess the thermal performance of clay-straw walls incorporating PCM in the Drâa-Tafilalet region (Errachidia Province), Morocco. Using a scaled laboratory cavity, the study made clay-straw walls with PCM integration in the form of panels made of two aluminum sheets, one with 40% polyethylene and the other with 60% paraffin. Keeping the internal temperature at 40°C, the results show that when the PCM is next to the heat source, the surface temperature drops by 1°C compared to when it is away from the source. Similarly, Gouni et al. [103], employing wooden walls, observed a 2°C decrease in exterior surface temperature when the material is placed near the heat source as opposed to a distant placement. The commonality between these two studies is that the impact of the PCM layer placed close to the heat source on reducing the exterior surface temperature is more pronounced. This observation can be elucidated, on one hand, by the PCM›s complete fusion under conditions where the melting temperature is lower than the internal temperature, which reduces the exterior surface temperature. On the other hand, the wall containing PCM in the internal layer exhibits a slower heat release compared to the wall with PCM in the external layer [92]. Furthermore, PCM placement on exterior wall surfaces facilitates nocturnal dissipation of stored heat, thus not negatively affecting occupant thermal comfort [96].

It is pertinent to note that cavity studies are conducted exclusively under warm climatic conditions, with the test cell›s exterior simulating the building's indoor environment. Nevertheless, to select the optimal position for a phase change material (PCM), it is crucial to study its impact on annual heating and cooling energy consumption.

In the presence of insulation, integrating PCM into building walls improves its energy efficiency, offering potential benefits for renovating old buildings [86]. Multiple investigations have been undertaken to assess the integration of thermal insulation compared to phase change materials [85], [86], [90], [104]. The synthesized findings are summarized as follows:

- Roof insulation integration yields superior energy savings compared to PCM [86]. Consequently, PCM›s impact on reducing cooling and heating loads becomes more pronounced in the absence of insulation, as the latter may impede PCM›s phase transition process. Khan et al. [90] demonstrated that total annual energy consumption is reduced by 44% when PCMs are installed in the building envelope and by 28% when incorporating expanded polystyrene.

- The optimal position of PCM, in the presence of insulation, recommended by Dardouri et al. [86] and Imghoure et al. [85] during the summer period is when PCM is placed on the interior side after the insulator. However, Alyasiri et al. [104] examined the impact of EPS insulation on PCM (paraffin wax) thermal performance during six summer months in the city of Almarah in Iraq. Their findings clarified that placing the EPS layer after the PCM layer on the inside guarantees effective fusion and solidification phases, as evidenced by the liquid fraction. Notably, the melting temperature range of paraffin wax, as adopted by Alyasiri et al. [104] due to its local availability in Iraq, spans between 40°C and 44°C. This represents a fairly high value compared to that adopted by the other two aforementioned studies. In this context, placing EPS after PCM on the exterior side proves advantageous in averting overheating during discharge periods. Consequently, it is advisable to conduct a comprehensive study on optimizing the phase change temperature before determining the optimal location of PCM conjoined with insulation. Additionally, the impact of this placement should be evaluated during all heating and cooling periods throughout the year.

b. PCM thickness

The decrease in heating and cooling energy demand is heavily dependent on the PCM thickness. As more volume of PCM is utilized, the energy storage capacity increases. However, it reaches a saturation point once the PCM has absorbed its maximum capacity [90]. Moreover, a greater volume necessitates a longer period for the PCM to fully activate its latent potential [46].

The thickness of a PCM panel can be calculated using the formula proposed by Peippo [87]:

$$D_{opt} = \frac{t_n\ h}{\rho\ \Delta H}\ (T_{m,opt} - T_n) \qquad (2)$$

Where D_{opt} represents the optimal thickness of the PCM slab (m), ΔH denotes the latent heat of fusion of the PCM (*J.kg-1*), and ρ signifies the density of the PCM (*kg.m-3*).

Several other factors influence the selection of PCM thickness. Notably, the thicker the PCM layer, the more costly its integration into building walls becomes affecting its economic viability, as already mentioned in Section 4.

In summary, the optimal phase change material (PCM) should possess a melting temperature aligned with the average set-point temperatures for both heating and cooling within the building envelope. For optimal thermal regulation, it should be positioned near the heat source, minimizing the surface temperatures of both external and internal walls during summer and winter, respectively. In the case of an insulated structure, placing the PCM on the interior side, after the insulation layer, is most effective during the summer. Nevertheless, a thorough evaluation across all seasonal heating and cooling periods is required to determine its most effective position throughout the year.

The State of The Art of Articles Published in Morocco

Phase Change Materials (PCMs) have garnered substantial attention from researchers globally over recent decades, spanning various continents. Their integration into construction materials and building structures is viewed as a viable strategy to enhance building thermal inertia. PCMs are instrumental in improving energy efficiency, managing energy demand, improving occupant thermal comfort, and reducing greenhouse gas emissions, which are major contributors to climate change.

According to the Global Climate Risk Index (CRI 2021) compiled by the non-governmental organization Germanwatch, developing nations face heightened vulnerability to climate change impacts due to their limited adaptation capacities, despite being more exposed to hazards. Notably, Mozambique and Zimbabwe were the two African countries most affected in 2019, with CRI scores of 2.67 and 6.17, respectively [105].

However, few studies are focusing on PCM technologies to reduce energy consumption and shift away from fossil fuels. In contrast, Europe and Asia are at the forefront of research on thermal energy storage technologies that offer greater resilience against climate change impacts.

Based on a sample of 6000 articles published between 1984 and 2023, Asia surpasses other continents according to the number of scientific research articles written about phase change materials, with a percentage of 68.6%, with China leading the pack. In contrast, Africa contributes only 5.35% of articles distributed among Egypt, Morocco, Ethiopia, Ghana, Nigeria, South Africa, Tunisia, Algeria, and Sudan. These findings are visually represented in figure 9.

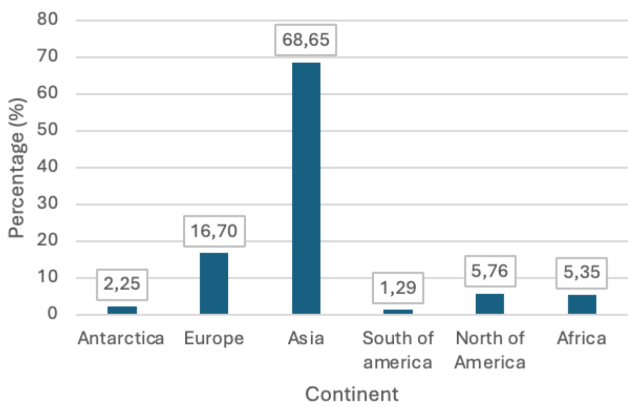

Figure 9. Percentage of PCM articles published by continent.

Table 2. Surveys on the integration of PCMs into building envelopes under Moroccan climatic conditions

Localization	Study objective	Climate region	Study type	PCM used	Main Results	Ref
Bricks	Studying the thermal effects of incorporating PCMs into the solid components of HCB (Hollow Clay Brick microencapsulation)	Hot regions with drastic climates (Ouarzazate, Marrakech, Erfoud, etc.)	Numerical simulation using ANSYS Fluent software	n - Nonadecane	The phase shift induced by HCB-3, HCB-6, HCB-8, and HCB-12 is approximately 1 hour, 1 hour 43 minutes, 2 hours 27 minutes, and 4 hours, respectively. The volume of HCB has decreased by as much as 30%, and material savings have been estimated at 35%.	[108]
	Studying the energy performance of a wall integrating PCM through the examination of its placement within a double wall constructed of hollow bricks	The city of Er-Rachidia (Morocco)	Numerical simulation using COMSOL software	PCM-Paraffin RT26	Placing the phase change material close to the internal surface can conserve up to 97% of the energy needed to maintain internal thermal comfort at a set temperature of 26°C.	[109]
	Evaluate the energy performance of three types of buildings: single-family homes, collective housing, and hotel housing, constructed with hollow bricks, incorporating and excluding PCMs to mitigate cooling requirements.	Al Hoceima (Morocco), Malaga (Spain),Marseille (France), Taher (Algeria), Naples (Italy), Tripoli (Libya), Ankara(Turkey), and Port Said (Egypt).	Numerical simulation using COMSOL software	RT-Line (from Rubitherm) and capric acid	In Northeast Mediterranean cities , energy savings can achieve 56% through the application of a PCM with a melting temperature of 26°C, while no energy savings were observed for Southeast cities.	[110]
	Studying the impact of integrating PCMs into a hollow brick structure (12 cells) on the thermal efficiency of exterior walls	Er-Rachidia,Fes, Marrakech (Morocco)	Numerical simulation using ANSYS Fluent software	n – Nonadecane	The incorporation of PCM into the hollow brick improves both the storage capacity and insulating efficiency of this construction element. This is evidenced by a notable decrease in amplitude and a substantial phase shift of the thermal wave through the PCM-wall.	[111]
Ceiling	Studying the energy and thermal advantages of implementing PCM in a controlled cooling ceiling system within a ventilated room	Fez (Csa climate), Ifrane (Csb climate), and Marrakech (BSh climate)	CFD simulation	Paraffin C13	The application of paraffin C13 as PCM in cooling ceilings yielded notable energy savings in Fez (17.07%) and Ifrane (16.30%) respectively), while the effect was minimal in Marrakech (2.23%).	[112]
Trombe wall	Evaluate the 3E performance (energy, economic, and environmental) of thermal, electrical, and hydrogen storage systems. This evaluation aims to guide stakeholders in identifying the most appropriate storage systems for achieving NZEB.	Ouarzazate, Tangier, and Ifrane	Numerical simulation using Energy-plus software	BioPCM	The studied PCM strategy allows for total annual thermal energy savings of 45.45%, 64.29%, and 43.06% in hot desert, Mediterranean, and cold climates, respectively. With Trombe wall integration, additional savings reached 9.56%, 4.18%, and 18.09%. While all analyzed storage systems exhibit environmental advantages, the trombe wall approach presents a comparatively higher CPBP and a lower LCEB, especially in the Mediterranean climate of Tangier.	[113]
Walls	Providing guidelines for designing office buildings integrated with PCM in the Mediterranean region	Tangier	Numerical simulation using Energy-plus software	BioPCM	Selecting an appropriate PCM fusion temperature improves thermal performance by 9.87% in free-running buildings and 20.5% in air-conditioned buildings over a 30-year lifespan. A fusion temperature of 28°C is identified as the optimal option for enhancing summer thermal performance in free-running office buildings throughout their lifespan.	[114]

Table 2. Surveys on the integration of PCMs into building envelopes under Moroccan climatic conditions (continued)

Localization	Study objectives	Climate region	Study type	PCM used	Main Results	Ref
Walls	Analyzing the influence of building volume, window orientation, and air infiltration on PCM performance.	All 12 regions of Morocco	Numerical simulation using Energy-plus software	Commercial panels Rubitherm RT28HC	The lightweight square building, featuring a south-facing window and no air infiltration, resulted in a total temperature fluctuation reduction of 1303.3 °C for the 10 m building located in a semi-arid climate. Furthermore, the PCM-enhanced building with a south-facing window and an air infiltration rate of 0.5 air changes per hour achieved significant energy savings of 69.56%.	[115]
	A multiparametric analysis is conducted to assess the impact of placing PCM on the inner side of exterior walls on energy savings and indoor thermal comfort.	Benguerir	Numerical simulation using Energy-plus software	Commercial panel CSM from Rubitherm	HW construction achieved maximum energy savings of 13.1% for PCM 28. The square-shaped building demonstrates effective performance across aspects, including energy savings, temperature regulation, and energy consumption. The optimal solution includes PCM 28 with LW construction for summer and PCM 22 with HW construction for winter. The recommended building configuration achieved a maximum PCM activation of 26.63%.	[116]
	A numerical investigation is conducted on building walls integrating PCM under semi-arid climate conditions to define the main parameters for their efficient utilization.	The city of Benguerir with a hot semi-arid climate	Numerical simulation using Energy-plus software	RT-18 HC RT-21 HC RT-25 HC RT-28 HC RT-35 HC (34–36°C).	The RT-28 HC PCM is appropriate for a semi-arid climate. Exterior placement provides heating energy savings of 101 kWh, while interior placement yields the highest cooling energy savings, reaching up to 317 kWh, and demonstrates improved performance in terms of annual energy savings. The south-facing PCM wall is more energy-efficient than other orientations. The optimal configuration was RT21–RT25–RT28 HC, achieving an annual energy savings rate of 15.21% and the shortest payback period of 12.94 years. Moreover, a triple layer of PCM combined with mechanical ventilation in summer maintains a comfortable indoor temperature, although indoor temperature fluctuations are more pronounced when mechanical ventilation is applied.	[117]
	Eight building configurations are assessed regarding indoor air temperature fluctuation reduction, PCM energy savings, PCM activation, and payback period	Benguerir	Numerical simulation using Energy-plus software	Compact Storage Module (CSM) containing paraffin wax, type RT 28HC	Placing PCM on walls, roofs, and ceilings results in the highest annual energy savings. However, placing PCM on the wall envelope alone exhibits the shortest simple payback period, at just 22.38 years. Implementing PCM on all interior envelope surfaces results in a maximum reduction in indoor temperature fluctuations of 110.2 °C during August.	[118]
	Emphasize the advantages of incorporating PCM into clay walls rather than cement wall	Errachidia	Numerical simulation using COMSOL software	Paraffin 5913 Capric acid n-Eicosane	Straw–clay construction incorporating PCM24 and PCM32 reduces the indoor thermal flux density by 72.72% in winter and 73.68% in summer, respectively, compared to cement construction.	[119]
	Develop adaptive exterior walls containing thermochromic (TC) material and phase change materials (PCM) to adopt dynamic responses to external climatic conditions	Marrakech, Dubai, Nice, London, Tianjin, Mexico, and Ottawa	A numerical code is developed.	RT18 and a hydrated salt	Combining PCM1 (T_m = 26 °C) with W-doped VO_2 in a structure during summer does not yield as many benefits as using PCM alone. The configuration with two PCMs delivers the best thermal comfort compared to the reference wall and other setups throughout both summer and winter.	[120]

Morocco is ranked among the top ten performing countries in terms of climate according to the Climate Change Performance Index (CCPI) 2023 report by Germanwatch, the International Climate Action Network, and the Climate Institute [106]. The country is actively involved in climate policy, especially through a national strategy that focuses on developing renewable energy sources such as wind farms, photovoltaic solar, hydropower, and biomass. This strategy aims to get 20% of its energy from renewable sources by 2025, reducing Morocco's reliance on fossil fuels. The CCPI report [106] highlights that Morocco has high scores for greenhouse gas emissions and energy use, mostly because it uses fossil fuels, which account for over 75% of anthropogenic emissions. Petroleum covers 35% of energy needs, coal 23%, natural gas 21%, nuclear 4%, and hydropower 4%. In many African countries, biomass is still a major source of energy, contributing 12% to overall energy production. However, new renewable energies like solar and wind currently comprise less than 1% of total energy consumption [107].

The objectives outlined during the United Nations Framework Convention on Climate Change (COP28) held in Dubai in 2023 centre on peaking the world's greenhouse gas emissions by 2025 and reducing them by 43% by 2030 and 60% by 2035 compared with 2019 levels. The goal is to limit global warming to 1.5 °C. To accomplish these goals requires transitioning away from fossil fuels, adopting renewable energy, and improving energy efficiency by 2030 (COP 28, 2023).

To meet these goals, Morocco could greatly improve its climate performance and lower its overall energy use by exploring innovative approaches such as phase change materials (PCMs). The building industry in Morocco uses 33% of the country›s energy because it consumes a lot of energy and releases a lot of greenhouse gases. This includes 7% in commercial buildings and 26% in residential buildings (AMEE, 2024). This consumption is expected to increase due to population growth, the development of new cities, and greater reliance on air conditioning and heating systems in Morocco.

Although in recent years more comprehensive studies have been carried out on PCM-based latent heat storage systems, the optimization of thermal performance and comfort using PCM-integrated building envelopes, based on their parameters across diverse Moroccan climates, has not been extensively explored in the literature.

A summary of studies conducted in Morocco from 2020 to 2023 regarding the impact of integrating phase change materials into building envelopes on reducing energy consumption is provided in Table 2. Most prior research has considered only the cooling or heating season. However, decisions regarding PCM integration into the building envelope should account for its annual impact rather than a single season.

Moreover, the selection of PCM materials for integration within building infrastructures necessitates thorough consideration of their impact on structural mechanical integrity in conjunction with their hygrothermal characteristics. The mechanical comportment of PCMs refers to their behavior and response to external mechanical forces, constraints, and deformations. While the mechanical aspects may not constitute the primary focus of PCM development, they merit meticulous consideration when integrating PCMs into construction applications.

During the integration of PCMs, moisture constraint specifications must be considered, and necessary measures must be adopted in order to avoid moisture-induced problems. For instance, if any PCM is used for a building with thermal energy storage, it is essential that the PCM be encapsulated and protected against the penetration of humidity. Moisture ingress can potentially degrade PCM performance or cause unintended phase changes, subsequently leading to inefficiencies or structural damage. Hence, it is essential to evaluate the suitability of the PCMs with other materials to ensure long-term durability and effectiveness. Therefore, the choice of PCM must be undertaken with careful deliberation, and its lifespan should be rigorously analyzed before determining its economic viability and potential for reducing energy costs.

CONCLUSION

The integration of phase change materials (PCMs) within building structures serves as a viable approach to reducing energy consumption and managing thermal comfort in indoor environments. This article provides an overview of the different types of PCMs, integration methods in the construction sector, their limitations, proposed solutions to improve their thermo-physical properties, and a structured approach for selecting optimal materials based on literature results. Antecedent studies have shown that the effect of integrating phase change materials into the building envelope on energy savings depends on several factors including architectural design, climatic conditions, type, as well as the nature and volume of PCM deployed. Hence, there is a need to make the right PCM choice to take advantage of their benefits in terms of reducing energy consumption. Based on the aforementioned literature, the following conclusions can be inferred:

- ✓ Building envelope integration of phase change materials (PCMs) also presents the potential to decrease yearly energy consumption to a large extent. The saving potential of such energy varies between 10% and 97% based on several factors such as the climatic area, the thermophysical properties of the PCM, and compositions of the material in the building envelope among others.
- ✓ The melting temperature, latent heat, cost, and stability are critical factors that will influence the market adoption of phase change materials (PCMs).
- ✓ Bio-origin phase change materials (BPCMs) offer an alternative to commercially available paraffin-based PCMs. They possess similar thermal properties,

including latent heat capacity, phase change behavior, and thermal cycling durability, which make them suitable for equivalent thermal energy storage applications.

- ✓ Reducing capsule size enhances the thermal reliability and chemical stability of PCM. Therefore, nano-capsules exhibit superior structural stability compared to macro and microcapsules.
- ✓ TRNSYS and Energy-Plus are widely regarded as the most suitable and extensively utilized simulation tools for evaluating heating and cooling energy consumption in buildings that incorporate phase-change materials.
- ✓ The thicker the PCM layer, the more costly its integration into building walls becomes affecting its economic viability. Furthermore, a greater volume of phase change material necessitates a longer time to completely activate its latent heat potential.
- ✓ the optimal phase change material (PCM) should possess a melting temperature aligned with the average set-point temperatures for both heating and cooling across the building envelope.
- ✓ For optimal thermal regulation, the phase change material (PCM) should be positioned near the heat source.
- ✓ In the case of an insulated structure, positioning the PCM on the inner side, after the insulation layer, is most effective during the summer. A year-round analysis throughout the year for all heating and cooling seasons is required in order to determine the optimum position throughout the year.

RECOMMENDATIONS

Further studies must be carried out in order to enhance the thermal performance of phase change materials (PCMs) integrated in building envelopes. The following recommendations are proposed for future studies:

- Future investigations should further study the performance of PCMs through experiments on real buildings and propose solutions for renovating existing buildings to enhance their energy efficiency.
- It is necessary to incorporate PCMs in buildings considering passive and bioclimatic solutions and analyzing their impacts in order to achieve appropriate findings in terms of energy savings, indoor thermal comfort, and financial feasibility. For example, evaluating the use of a Canadian well combined with PCMs for reducing energy consumption in cooling-dominated climates.
- The application of evolutionary algorithms for optimizing the thermo-physical properties of PCMs, notably the metaheuristic algorithm, or using an artificial neural network to predict the important parameters (melting temperature, thickness, …) of an optimal PCM.
- It is recommended to analyze the effect of integrating PCM with latent heat energy storage in cascade within the outer envelope of buildings.

It is essential to consider the variation in outdoor temperature caused by climate change for optimizing PCM properties. Therefore, it is important to study their effect on reducing energy consumption, improving thermal comfort, and reducing greenhouse gas emissions under prospective climatic scenarios.

It is important to assess the entire life cycle of PCMs to evaluate their durability and environmental performance.

NOMENCLATURE

ACH	Air changes per hour
ADBEIPCM	Adaptative dynamic building envelope integrated with PCM
BES	Building energy simulation
BPCM	Bio-based phase change material
BPS	Building performance simulation
CCPI	Climate Change Performance Index
CFD	Computational fluid dynamics
COP	Conference of parties
CPBP	Carbon payback period
CRI	Global climate risk index
EJ	Exajoule
EPS	Expanded polystyrene
FT-IR	Fourier transform infrared spectroscopy
GHG	Greenhouse gas
Gt	Gigaton
HCB	Hallow clay brick
HW	Heavy weight
IEA	International energy agency
LCEB	Life cycle carbon emissions benefits
LVPCM	Liquid-Vapor PCM
LW	Light weight
MPCM	Microencapsulated PCM
MWI	Mineral wool insulation
NRC	National cash register corporation
NZE	Net zero emissions
PCM	Phase change material
RP	Research Project
RT	Rubitherm
SLPCM	Solid-Liquid PCM
TES	Thermal energy storage
TGA	Thermos gravimetric analyzer
VO2	Vanadium dioxide
W	Tungsten

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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