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Review

Energy Efficiency in Buildings Through the Application of Phase Change Materials: An In-Depth Analysis of the Integration of Spent Coffee Grounds (SCGs)

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Abstract

Energy demand in the building sector has drastically increased due to rising occupant comfort requirements, accounting for 30% of the world's final energy consumption and 26% of global carbon emissions. Thus, to improve building efficiency in heating and cooling applications, phase change material (PCM)-based passive thermal management techniques have been considered due to their energy storage capabilities. This study provides a comprehensive review of the research on PCM applications, types, and encapsulation forms. Various solutions have been proposed to enhance PCM performance. In this review, the authors suggest new methods to improve PCM efficiency by using the multilayered wall technique, which involves employing two layers of a hybrid bio-composite—specifically, the hybrid hemp/wood fiber-reinforced composite with a polypropylene (PP) matrix—along with a layer of PCM made from spent coffee grounds (SCGs). Previous studies have shown that oil extracted from SCGs demonstrates good thermal and chemical stability, as it contains approximately 60–80% fatty acids, with a phase transition temperature of approximately 4.5 ± 0.72 °C and latent heat values of 51.15 ± 1.46 kJ/kg.

Keywords: buildings' energy efficiency; thermal energy storage; phase change materials; cooling and heating; spent coffee grounds

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1. Introduction

For the first time in centuries, five megatrends are concurrently impacting the world: climate change, demographic shifts, technological disruption, a fracturing world, and social instability. As we move into the future, organizations must strategically address each of these areas. In particular, demographic shifts and urbanization have made significant contributions to the excessive use of primary energy and massive emissions of carbon dioxide (CO_2), leading to energy depletion, global warming, and climate change. Nowadays, investigations are being conducted worldwide on various energy production, energy storage, and renewable energy technologies [1].

Energy production accounts for around three-quarters of global greenhouse gas emissions. Moreover, not only is it the largest driver of climate change, but the burning of fossil fuels as well as biomass has also come at a large cost to human health [2]. In addition, projections indicate that CO_2 emissions could increase by more than 50% by 2050 [3]. Among the most energy-consuming sectors is the building sector. In fact, it accounts for 30% and 26% of the world's final energy consumption and global carbon emissions, respectively [4–6]. Furthermore, as shown in Figure 1, building systems, particularly heating, ventilation, and air conditioning (HVAC), along with lighting, account for up to 60% of the total building energy consumption—a percentage that continues to rise through the years [1,7,8]. In particular, the energy demand for cooling is projected to increase significantly in 2040 and 2060, driven by the growing need for indoor comfort and the effects of climate change [9].

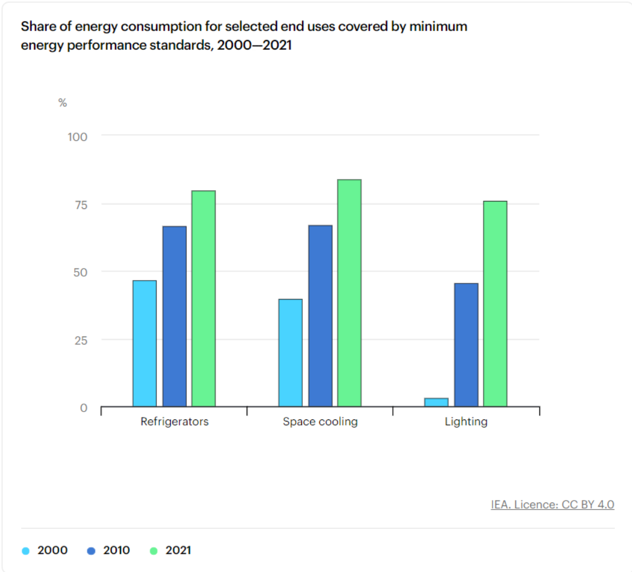

Figure 1. Trends in rising energy consumption in the building sector: a comparative analysis from 2000 to 2021 [5].

According to the 2022 Outlook of the International Energy Agency (IEA) [10], global building energy consumption is projected to increase by an average of 1.5% per year between 2012 and 2040 [11]. This trend is expected to accelerate between 2025 and 2027 due to the growing energy demand from data centers and digital networks within the building sector [4]. Besides, one-third of global energy and process-related CO_2 emissions originate from both direct and indirect emissions in the building sector, resulting in a large carbon footprint. In total, 10 Gt of emissions were attributed to building operations, marking an increase of 2% compared to 2019 and 5% compared to 2020. These emissions are distributed as follows: 8% result from the direct use of fossil fuels in buildings, 19% from the generation of electricity, heating, and cooling for buildings, and 6% from the manufacture of cement, steel, and aluminum used in construction operations—an activity that saw a 34% rise between 2010 and 2021 [5,12].

Thus, the transition toward more sustainable, cleaner, efficient, and renewable energy technologies in the building sector remains a necessity for seeking potential solutions to achieve Net Zero Emissions in Buildings (ZEB) by 2050. Therefore, the next few years will be critical for implementing the necessary measures in both new and existing buildings to reach the zero-carbon-ready target as early as 2030 [5,7]. As shown in Figures 2 and 3, this alarming situation made many countries take action and invest in the clean green sector, which saw a 15% increase in 2021. As a result, over 1828 related policies, strategies, and scenarios have been suggested worldwide to reach the 2030 target [13] and to align with the UN's Sustainable Development Goals, including the "Clean Growth Strategy" adopted by the UK, the "13th Five-Year Plan" by China, and the "2030 Energy Strategy" by EU states [14–16].

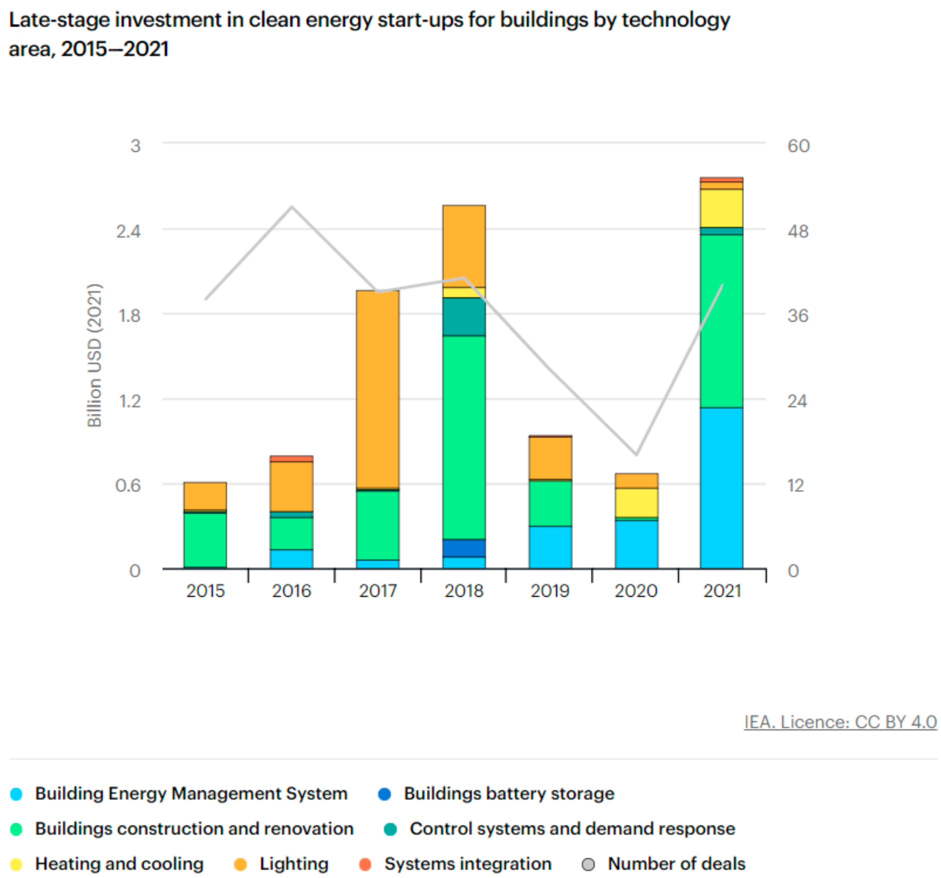

Figure 2. Investment driving clean energy transformation in the building sector: a 2015–2021 analysis [5].

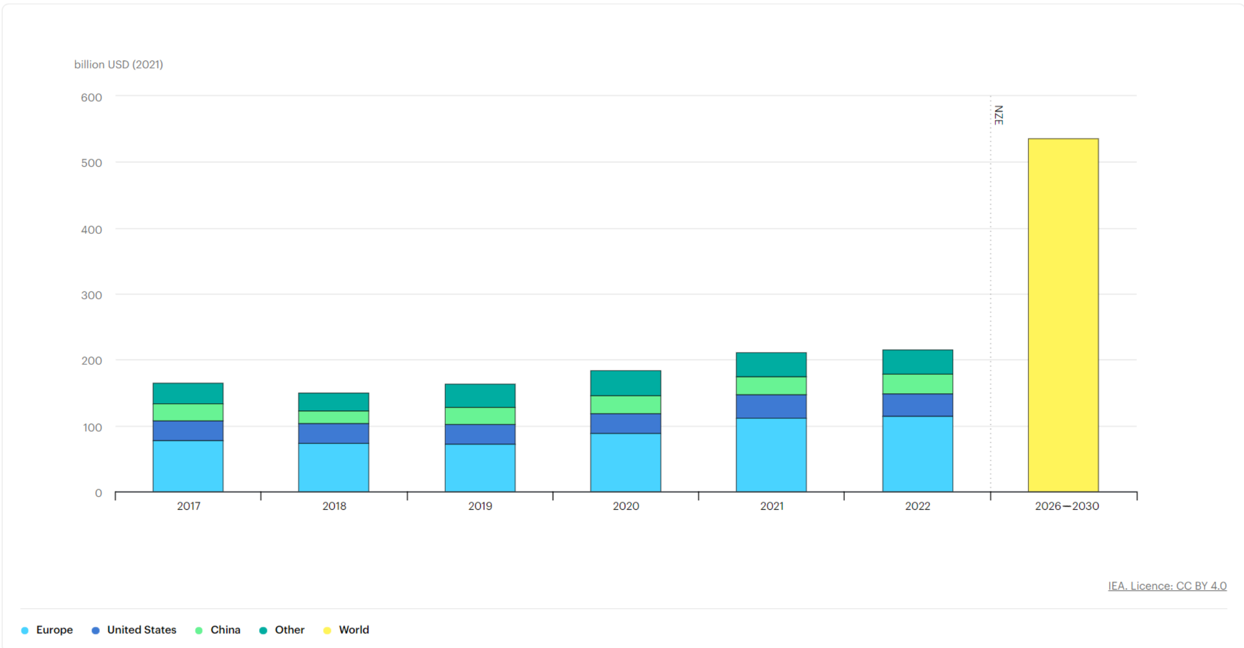

Figure 3. Predicted evolution of global investment trends in energy efficiency and clean technologies in the building sector [5].

This review aims to investigate the importance of latent heat thermal energy storage technology by using phase change materials, specifically spent coffee grounds (SCGs), as a storage material. The proposed study focuses on using multilayered techniques, specifically a double layer of a hybrid PP-MAPP/hemp/wood composite, to enhance the performance of the PCM incorporated into the building envelope.

2. Thermal Energy Storage (TES) Technology

Researchers have conducted various investigations on renewable energy-based systems, each within their respective field of expertise, to reduce heating and cooling peak load. Among them, Hmida et al. [17] investigated the use of photovoltaic–thermal (PVT) systems to produce heat, cooling, and electricity for buildings. The authors concluded that the photovoltaic–thermal (PVT) double-pass collector can achieve an annual electrical power of up to 194.58 kWh/m^2 and a thermal power of 811.37 kWh/m^2. In comparison, a conventional PV system produces approximately 194.76 kWh/m^2 of electricity per year. This significant additional thermal contribution makes the PVT system highly advantageous for heating and cooling applications in buildings. Yuan et al. [18] suggested the use of biomass to produce heat during the winter season and found that energy consumption significantly reduced throughout the heating period. Chen et al. [19] recommended the use of wind turbines, reporting that their system generated 1960 kW, 336.1 kW, and 183.3 kW of power, heating, and cooling, respectively. Other researchers, like Ruan et al. [20] and Huang et al. [21], developed a white reflective paint that reflects 98% of the sunlight, allowing the building to reduce air-conditioning use by up to 40% during the summer season (Figure 4).

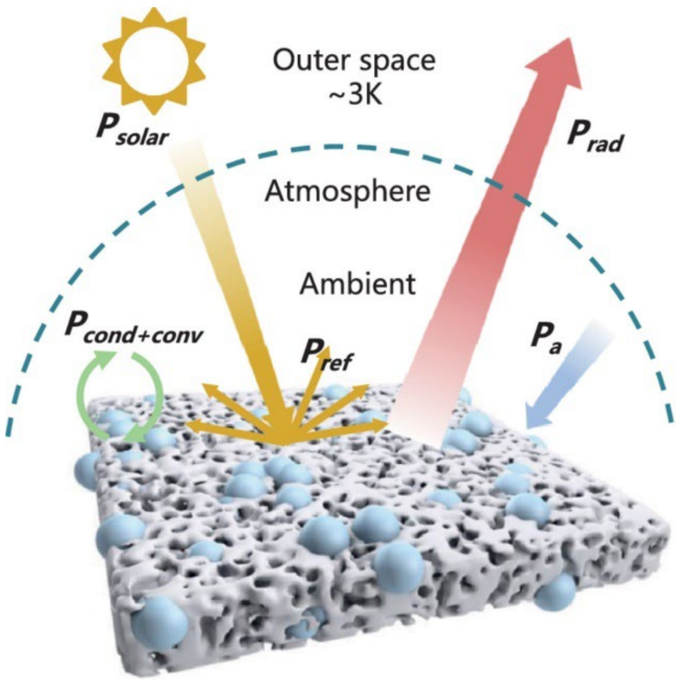

Figure 4. Schematic representation of passive radiative cooling paint [21].

However, for commercial applications, cost has always been a concern. Thus, researchers have adopted new strategies to achieve higher comfort levels and efficiency through the application of advanced techniques, such as active systems (e.g., HVAC systems, heat pumps) [22] and passive measures (e.g., Trombe walls, greenhouses, solar chimneys, etc.) [16,23–26]. Passive systems, such as thermal mass integration in buildings, rely on natural heat storage and release without external energy input, whereas active systems, including air conditioning and evaporative cooling, require mechanical or electrical assistance to enhance heat transfer.

Among the most widely tested passive technologies for reducing peak heating and cooling loads and storing energy are the integration of solar thermal energy storage (TES) technology systems [7,27,28]. Incorporating TES technologies into buildings can reduce peak demand by 20–40%, lower energy usage by 14%, cut energy costs by 10–20%, and decrease emissions by 5% [27].

Three types of TES technologies have been widely investigated—sensible heat storage, latent heat storage, and thermochemical heat storage—as detailed in Table 1. Sensible and latent heat storage are the most commonly used technologies in building envelopes due to their safety characteristics and ease of use [28]. Furthermore, for the same storage volume, latent heat storage (LHS) systems offer a higher energy storage density than sensible heat storage (SHS) systems, as a large amount of energy is absorbed or released during the phase change at a constant temperature. Thus, LHS can improve system efficiency while maintaining a stable target temperature [29].

Table 1. Classification of a thermal energy storage system [29–34].

Types of TES	Characteristics	Phases
Sensible heat	• Associated with the temperature rise, until the initialization of PC. • Classified based on storage media.	L/S
Latent heat	• Higher energy storage density associated with PC. • Sustains a small difference in temperature between the release and storage of heat.	L–S S–S L–G
Thermochemical heat	• Due to shifts in equilibrium caused by changes in P and T, a large amount of chemical energy is absorbed and released.	L–G S–G G–G

PC: phase change; **P**: pressure; **T**: temperature; **L**: liquid; **S**: solid; **G**: gas.

Researchers have focused on phase change materials (PCMs) based on latent heat energy storage as a solution to address energy crisis problems, reduce environmental pollution, and ensure human thermal comfort. PCMs are used to effectively store energy and manage temperature variations, maintaining temperatures within a specific range. This capability enables enhanced thermal regulation and improved energy efficiency in various applications.

3. Operational Processes of Phase Change Materials (PCMs)

The latent TES (LTES) system using phase change materials (PCMs) stores and releases thermal energy through phase transition, which can occur in the form of solid–liquid (S-L), liquid–gas (L-G), or solid–solid (S-S) transformations during charge and discharge cycles [34–36].

During the charging cycle, the PCM absorbs heat energy and changes its phase from solid to liquid, with the reaction being endothermic. During the discharging cycle, when energy is needed and released, the material returns to its solid phase (Figure 5), with the reaction being exothermic. Due to the slight volume change, the S-L and S-S phase change materials are the most favored [29,35].

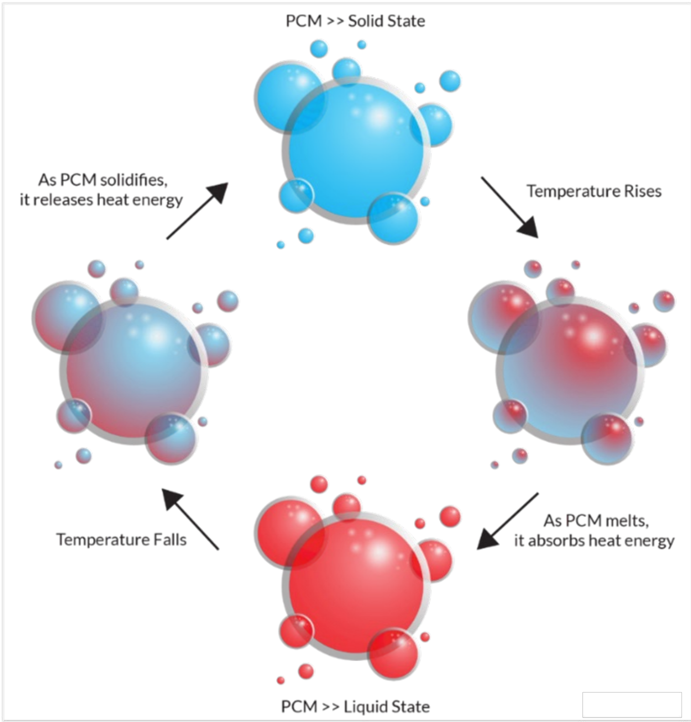

Figure 5. Mechanisms and processes of phase change materials [36].

PCMs are classified based on their chemical composition and temperature range and are categorized into organic, inorganic, and eutectic materials. Figure 6 provides a list of PCMs available in both organic and inorganic forms [35].

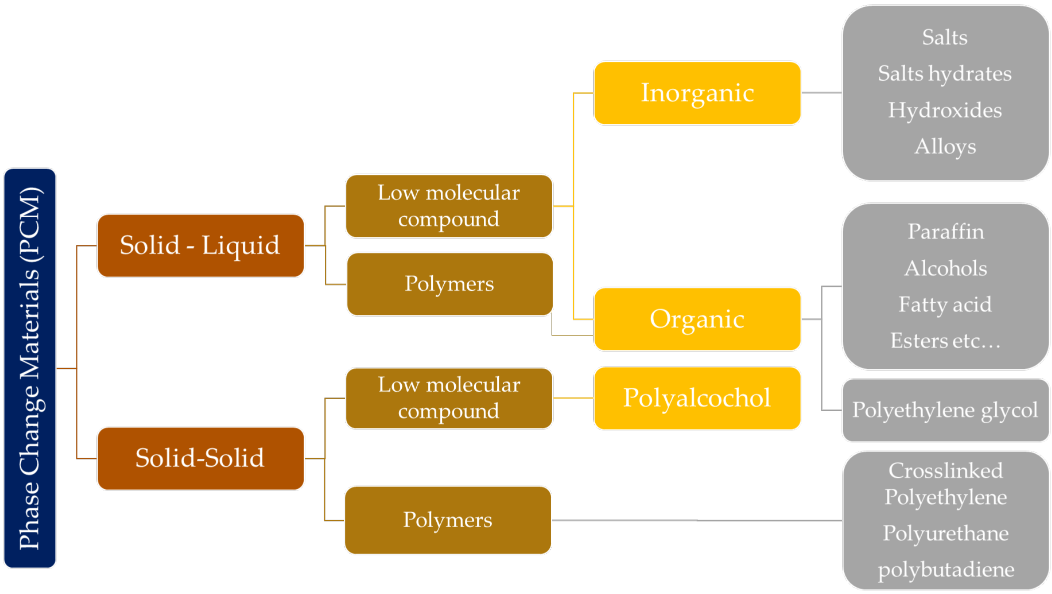

Figure 6. Potential PCMs widely used for building cooling and heating purposes [29,37].

3.1. Integration of Phase Change Materials

As depicted in Figure 7, PCMs can be integrated into various parts of a building, depending on the application. This includes PCM-impregnated floors, roofs, wallboard bricks, ceilings, gypsum panels, windows/façades, solar collectors, etc. [38–41]. Li et al. [16] provided a detailed illustration showing all possible PCM incorporation points within a building (Figure 8).

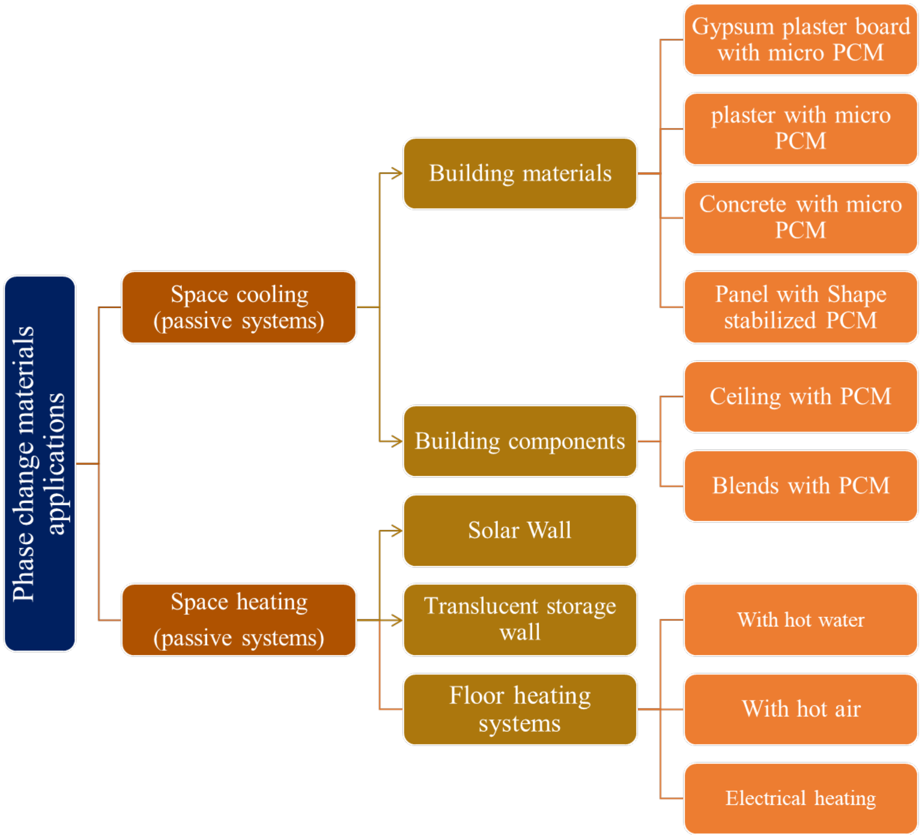

Figure 7. Various applications of phase change materials in building construction [31].

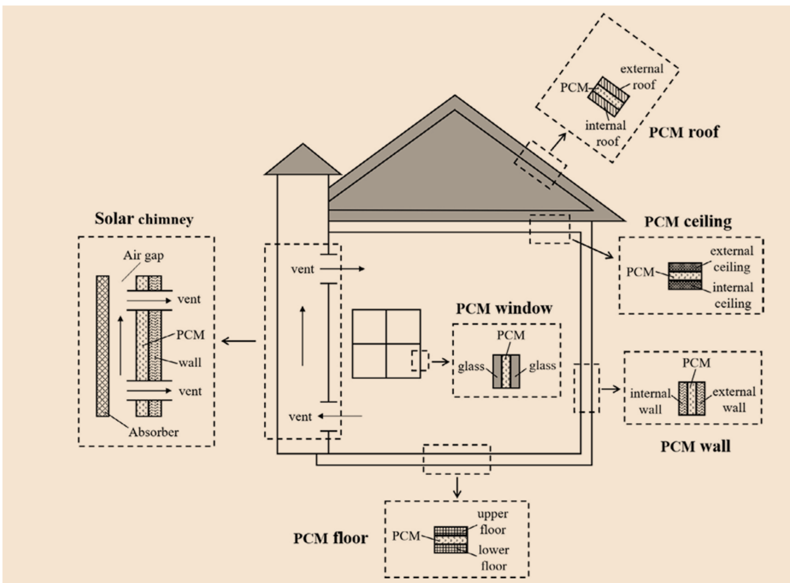

Figure 8. Potential approach for incorporating phase change materials [39].

3.2. Fundamental Properties of Phase Change Materials

Selecting the optimal PCM for a particular building application is indeed a challenging task, as each material has unique thermal properties that may or may not be suitable for different structural elements: roofs, walls, windows, etc. Table 2 highlights the advantages and limitations of each type of PCM used in building applications [31]. Organic PCMs appear to be very promising due to their favorable melting temperature range and stability. However, it is clear that further enhancements are still needed, especially in areas like thermal conductivity and cost-effectiveness. The use of nanoparticles to improve thermal conductivity and bio-based PCMs as a pathway to reach net-zero CO_2 emissions is particularly promising, as these solutions have the potential to make phase change material technology both efficient and sustainable. That said, balancing performance with affordability and environmental impact will remain crucial as we continue to refine these materials for widespread building applications.

Table 2. Core characteristics of phase change materials (PCMs) [31,37].

PCM	Advantages	Weaknesses
Organic	• Available in a wide range of temperature • High heat of fusion • No subcooling • No segregation • Stable after many transitions cycle • Chemically and physically stable • Compatible with many types of containers • Environmentally safe, nonreactive • Recyclable	• Low thermal conductivity • Large volume change during transitions • Instability at high temperatures • Low enthalpy • Flammability • Incompatibility with plastic containers • Expensive in pure form • Different toxicity levels
Inorganic	• High thermal storage capacity • High thermal conductivity • Availability • Sharp melting points • Low vapor pressure • Non-flammable • Low cost	• Subcooling • High change in volume • Phase segregation • Incompatible with metallic containers • Corrosive • Not stable thermally • Toxic

The appropriate PCM depends heavily on its thermophysical properties and operating temperature range, along with other desired characteristics. As depicted in Figure 9, each type of PCM has a specific working temperature range, making some more suitable for certain applications than others [35].

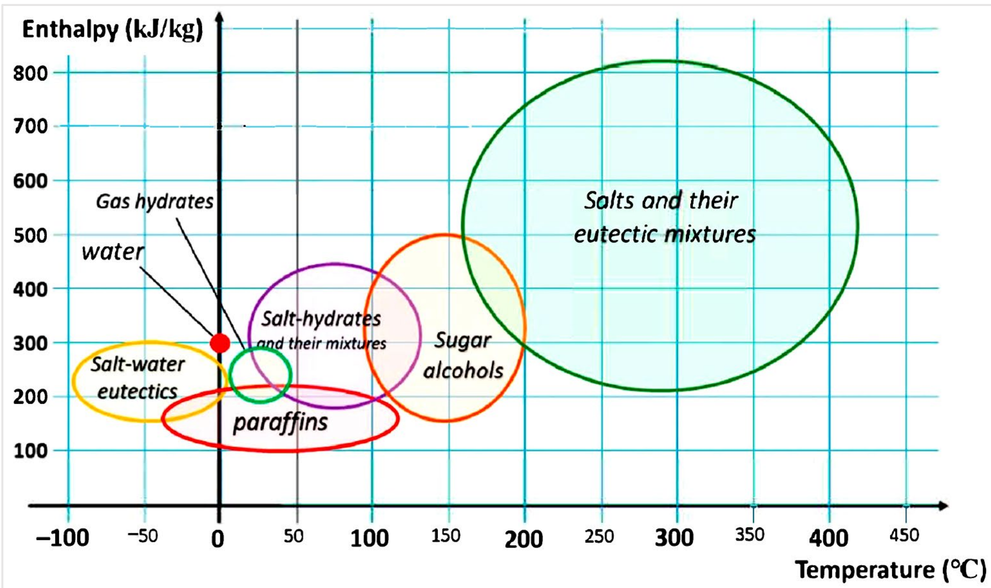

Figure 9. Operating range of enthalpy and temperature of various PCMs [37].

Before any application, a thermophysical test should be conducted to ensure the suitability of the PCM chosen for the building under study. Different technologies can be used, but the most widely adopted method is the differential scanning calorimetry (DSC). This technique provides information on the PCM's melting and solidification temperatures, specific heat, enthalpies, and heat storage capacity. Table 3 yields the thermal properties of PCMs commonly used in building applications [35], while Table 4 depicts the most used paraffins and fatty acids for cooling and heating purposes. It can be concluded that for cooling applications in buildings, integrated PCMs should have a melting temperature between 19 °C and 28 °C, whereas for heating applications, the optimal range is between 28 °C to 40 °C [28]. Furthermore, other factors should be considered, like weather conditions—especially in regions with variable climates—building structure, insulation degree, ventilation rate, inner recesses, occupancy profile and number of people, direct solar radiation, heating profile, and more [37,42].

Table 3. Thermophysical properties of phase change materials [37,43].

PCM	Melting Point (°C)	Heat of Fusion (kJ/kg)	Thermal Conductivity (W/m·K)	Density (kg/m^3)	Specific Heat (kJ/kg·K)
			(L/S)	(L/S)	(L/S)
Paraffin	27–29	245	0.2 (L)	770/880	2 (L)
Bio-PCM	28.85	219	0.2/0.2	860/860	1.97/1.97
OM32	31.85	200	0.145/0.219	870/928	2.3/1.95
Pure-Temp 23	22.23–24.17	170.71	0.15/0.25	830/910	2.06/1.56
OM35	35	160	0.16/0.2	870/900	2.71/2.31
Eicosane	36–38	202	0.15/0.39	780/815	2.46/1.92
Paraffin wax	44	174.12	0.13 (L)	783/830	2.53/2.44
Paraffin PT 27	28	147	0.2 (L)	750/870	-
OM37	26–29	218	0.13 (L)	860	-
HS29	26–29	190	0.55/1.05	1530/1681	2.62 (L)
GR27	28	72	0.15	710	1.125
Water	0	334	0.6	1000	4.179

L: liquid; S: solid.

Table 4. Different types of PCMs: insights into paraffin and fatty acids [27].

PCM	Melting Temperature (°C)	Heat of Fusion (kJ/kg)	Thermal Conductivity (W/m·K)	Density (kg/m^3)
Paraffin				**L/S**
n-Heptadecane	19	240	0.21	777
Paraffin C17	21.7	213	0.2	817/754
Paraffin C13–C24	22–24	189	0.21 (L)	760/900
Paraffin RT-27	28	179	0.2	800
Paraffin RT-18	15–19	134	0.2	756
Paraffin C18	28	244	0.148 (L)	-
n-Octadecane	28	179	0.2	750/870
Fatty acids				
Capric Acid–Palmitic Acid	26.2	177	2.2	784
Capric Acid	30	142.7	0.2 (L)	815 (L)
Capric Acid and 1-Dodecanol	26.5	126.9	0.12(S)	752 (S)
MeP + MeS	23–26.5	180	0.2 (L)	817 (L)
Butyl Stearate-Palmitate	17–20	137.8	0.12 (S)	754 (S)
Eutectic Capric Acid–Myristic Acid	21.7	155		
Eutectic Capric Acid–Stearic Acid	24.7	179		
Capric Acid–Lauric Acid	19.2–20.3	144–150	-	550
Glycerin	17.9	198.7	-	-
Lauric Acid–Myristic Acid–Stearic Acid/Expanded Graphite	29.05	137.1	-	-
Capric Acid–Palmitic Acid–Stearic Acid	19.93	129.4		
Myristic Acid–Palmitic Acid Stearic Acid/Expanded Graphite	41.64	153.5		

L: liquid; S: solid.

Based on their phase transition temperature, fatty acids have proven to be suitable as PCMs for different applications at both low and medium temperatures. For low phase transition temperatures ranging from −20 °C to 5 °C, PCMs are particularly effective in commercial and domestic refrigeration applications. In the range of 5 °C to 40 °C, they can be used for both passive and active cooling and heating applications [42]. However, while fatty acids demonstrate promising thermal properties, challenges such as supercooling, phase segregation, and low thermal conductivity may limit their long-term efficiency and performance.

3.3. Advanced Incorporation Techniques for Phase Change Materials

The incorporation of PCMs into building envelopes contributes to improving thermal comfort and energy management by reducing heat peak and indoor temperature fluctuation. This is owing to their energy storage density, which is 5–10 times higher than that of standard walls, ultimately leading to reduced electricity costs [43]. As depicted in Figure 10, there are four main methodologies for integrating PCMs into building envelope elements: direct incorporation, impregnation, encapsulation, and stabilization [33,44–46], each with its own advantages and disadvantages.

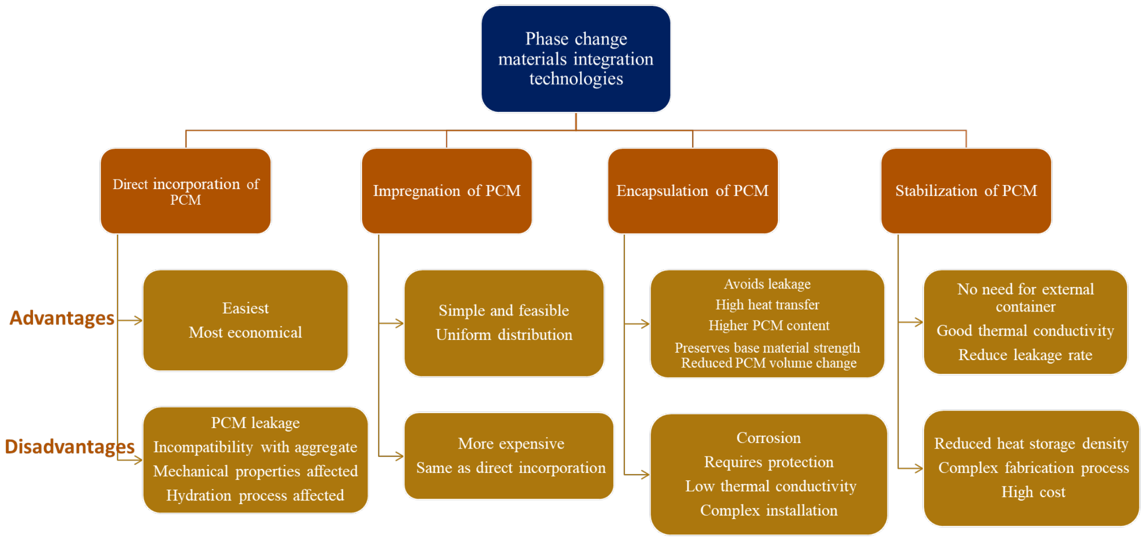

Figure 10. Advanced technologies for incorporating phase change materials.

Figure 11 shows that PCMs can be integrated into porous construction materials such as bricks or building blocks, or encapsulated in metal or plastic containers through macro-encapsulation [33,45,47–53]. In some applications, PCMs can be filled into brick cavities or added as one or more separate layers to the wall with proper encapsulation. In this context, Mukram and Daniel [31] investigated various methods for incorporating PCMs into building structures, including using PCM as a separate layer, inserting them into brick cavities, and integrating them into cement mortar for concrete or plastering. They concluded that for optimal thermal performance, the PCM layer should be placed closer to the heat source. However, while this approach enhances heat absorption, it also raises concerns regarding structural integrity, potential leakage, long-term durability, and compatibility with traditional building components. Thus, further studies are needed to balance thermal regulation with material stability for more effective PCM integration.

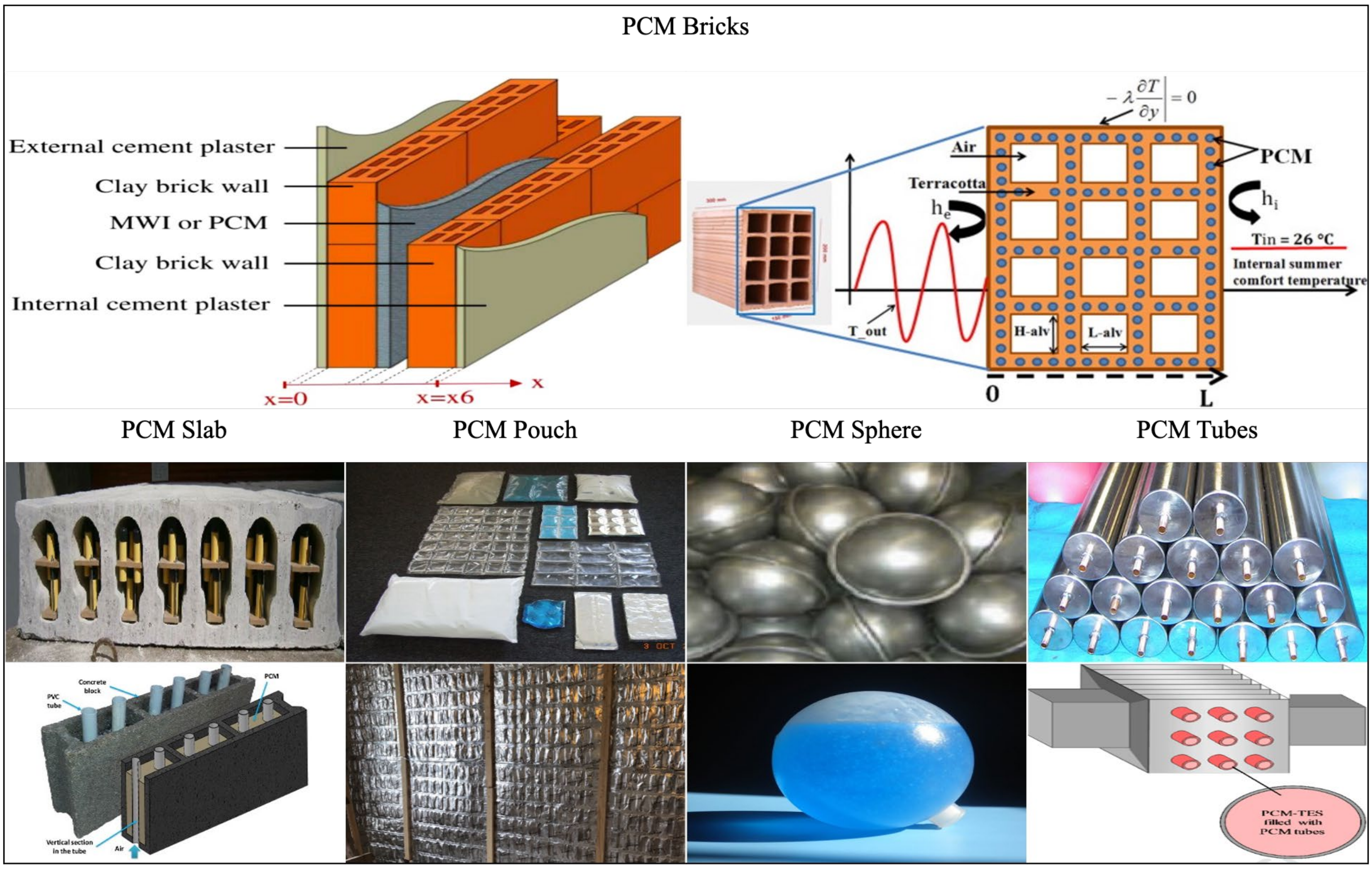

Figure 11. Exploring different forms of phase change material integration [33,45,47–53].

Phase change materials can be incorporated into various applications using different chemical and physical methods to enhance their efficiency and adaptability. They can be integrated through microencapsulation, direct incorporation, or shape stabilization [33,37,54].

3.3.1. Direct Incorporation Methods of Phase Change Materials

Direct integration of PCMs into building materials (e.g., concrete, cement mortar, or gypsum) is considered the simplest, easiest, and most cost-effective integration technique. Feldman et al. [53] proved that directly adding 21–22% organic PCMs to gypsum sheets, along with some additives, significantly enhanced energy storage—up to 10 times more compared to conventional gypsum wallboard. However, the main drawback of this technique is the risk of PCM leakage and the degradation of the mechanical properties of building materials. In particular, it was noticed that leakage could increase the risk of fire [31,43,54,55]. To address these drawbacks, Sun et al. [56] explored a double-layer radiant floor system integrating $Na_2HPO_4 \cdot 12H_2O$ and $CaCl_2 \cdot 6H_2O$ composite PCMs as high- and low-temperature layers, respectively (Figure 12). They concluded that the incorporation of the PCM layer significantly improved thermal comfort in the test room [1].

Antar et al. [28] also conducted a numerical simulation using ANSYS 2020 to examine the thermal behavior of a building wall under different weather conditions, testing multiple types of PCMs and placement configurations. The highest thermal performance was achieved using RT-35HC, optimally positioned 1.5 cm from both sides of the wall. Besides, they registered a 3.4 °C decrease in indoor wall temperature and a 66% reduction in overall energy gain during the summer season.

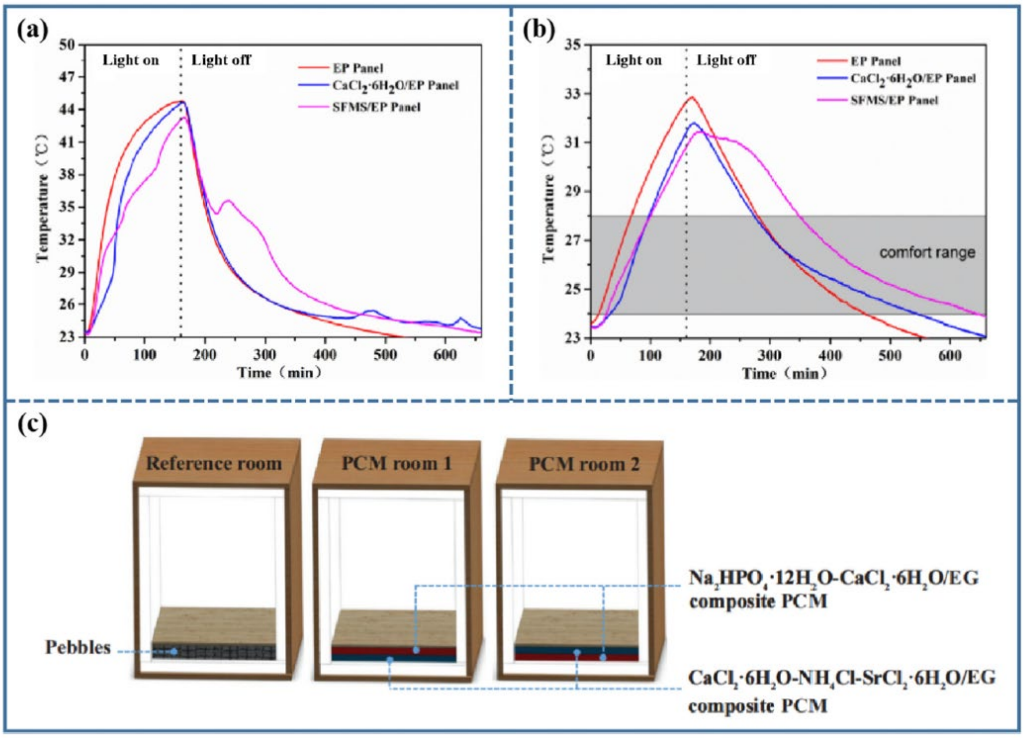

Figure 12. Experimental model of PCM integrated into the floor [1]. (**a**) in the indoor center; (**b**) in the roof of the tested room; (**c**) schematic of the three tested rooms.

Despite its simplicity, direct incorporation compromises structural integrity, while optimal placement requires precise engineering. These challenges raise concerns about long-term durability and safety—particularly with regard to fire risks and leakage problems. Therefore, future research should focus on enhancing stabilization, encapsulation, and fire resistance to make PCMs more practical and reliable solutions.

3.3.2. Impregnation Technique for PCM

In this technique, building materials such as bricks, concrete, or gypsum board are dipped in a liquid PCM. As a result, the PCM is absorbed through capillarity, permeating the pores of the materials. Although impregnation is still subject to the same risks as direct integration, it is considered a more effective technique [31,43,55,57].

3.3.3. Encapsulation Technique for PCM

To overcome leakage and compatibility problems, the encapsulation technique was developed, in which PCM is enclosed within a protective shell before incorporation. This containment prevents the liquid phase from leaking and isolates it from its surroundings. To ensure compatibility with the construction materials, the shell (or core) must meet specific criteria like corrosion resistance, flexibility, and sufficient strength to prevent the leakage of molten PCM and contamination of the core material. Thus, the heat transfer area and thermal conductivity increase, leading to improved PCM effectiveness. Despite improvements in heat transfer efficiency and PCM performance, encapsulation also introduces complexities, such as reduced thermal storage density, increased costs, and challenges in large-scale applications.

Based on their size, capsules are classified as follows: macro-capsules (diameter larger than 1 mm), including shells, tubes, panels, containers, and plastic bags [58]; micro-capsules (diameter ranging from 1 to 1000 μm), typically used in applications with a temperature range of 10–80 °C; and nano-capsules or nano-spheres (diameter ranging from

1 to 1000 nm) [31,43,55], which have been proven to offer higher thermal stability but face challenges related to degradation and fabrication.

3.3.4. Stabilization Techniques for Phase Change Materials

Shape-stabilized PCM (SSPCM) and foam-stabilized PCM (FSPCM) are two advanced methods developed to enhance PCM integration.

SSPCMs are obtained by impregnating PCMs into porous matrices like expanded vermiculate (EV), expanded perlite (EP), expanded graphite (EG), and carbon nanotubes. Capillary forces, surface tension, and interactions between the PCMs and the matrix stabilize the material, preventing leakage during the phase change process. This method is preferred due to its ability to maintain structural integrity over multiple cycles while also improving thermal conductivity and energy storage performance.

The infiltration of liquid/solid PCMs can be elaborated on using two different techniques: the two-step impregnation method (direct impregnation or vacuum impregnation) and the one-step in situ synthesis technique. Studies have shown that vacuum impregnation enhances the retention rate by up to 50% compared to only 30% with non-vacuum treatment [59].

FSPCM, a newer approach, provides complete retention of the PCM during the melting process, preventing leakage and allowing the retention of a wider variety of PCMs. FSPCMs can be produced either through the natural immersion method or through vacuum incorporation. Although the natural immersion technique is the easiest, its low capacity to retain stored thermal energy makes it less recommended compared to vacuum impregnation. FSPCMs utilize porous inorganic matrices—such as silica-based material, silicon dioxide, clay materials diatomite, perlite, etc.—to contain the PCM during phase transitions [31,43].

Despite their advantages in enhancing stability and thermal performance, both methods are relatively expensive, limiting their adoption in large-scale applications. Therefore, the high material and processing costs raise concerns about their commercial viability.

Shohan et al. [60] gathered the most relevant studies where PCMs were incorporated into various building materials, including bricks, mortar, and concrete. Their analysis, summarized in Table 5, explores different integration methods such as encapsulation and immersion. Shohan et al. [60] highlighted the transition temperature range of each PCM and summarized the key findings of each study, including thermal performance, efficiency, and limitations in large-scale applications (Table 5).

Table 5. Techniques of PCM integration in buildings [60].

Constructive Localization	Method of PCM Integration	Constructive Solution	Temperature Transition of PCM (°C)	Most Relevant Conclusions
Walls	Immersion	Gypsum Boards	50	Cost reduction of the energy consumed by HVAC systems, aiming to minimize peak electricity demand.
			20	The system assisted in decreasing the temperature to its maximum level and increasing it to the minimum level.
	Microencapsulation	Gypsum Boards	22	Relatively low changes in temperature.
			18	Enhanced performance of the PCM was obtained when it was placed close to the surface of the gypsum board, which resulted in an increase in the minimum temperature.
		Concrete	22	Air temperature reduction and lagging latency.
			25	Enhanced thermal inertia and heat efficiency.
		Bags	34	The bags reduce the peak demand period of the heat.
		Mortar	24	Increase in the minimum temperature and decrease in the maximum temperature along with reduction in the cooling and heating requirements and lag time.
	Macroencapsulation	Brick	35	The system can reduce heat flux and inner temperature.
			25	Reduction in electricity utilization along with decrease in the highest temperature and daytime thermal gradients.
		Panels	30	Enhanced energy storage capacity.
			21	Decrease in the temperature intensity.
	Microencapsulation (Hybrid solution)		10, 24, 26, and 28	Greater thermal amplitude attenuation.

Table 5. *Cont.*

Constructive Localization	Method of PCM Integration	Constructive Solution	Temperature Transition of PCM (°C)	Most Relevant Conclusions
Ceiling	Macroencapsulation	Metallic panel	46	Reduction in the cooling load and thermal flow.
			22	Grater internal temperature control system.
	Shape-stabilization	Ceiling	21	Energy conservation during daylight hours.
		Concrete	26	Increase in the minimum temperature and decrease in the maximum temperature
	Microencapsulation	Panels	18	Decrease in volume flows.
	Macroencapsulation (Hybrid solution)	Metallic panels	26–28	Reduction in the interior temperature fluctuation and improvement in thermal comfort
Floor	Macroencapsulation	Concrete	20	Extended periods at constant temperature.
			23	Increase in the minimum temperature and decrease in the maximum temperature.
	Shape-stabilization	Boards	52	Increase in the temperature inside without increasing the temperature gradient.
	Macroencapsulation (Hybrid solution)	Panels	14, 16, 18, 20, 22, 30, 34, 38, 42, and 46	Decrease in surface temperature variability as well as heat flows.
Glazed	Macroencapsulation	Shutter system		Maintaining the internal temperature at a consistent level.
	Macroencapsulation (Hybrid solution)	-	18, 26, and 32	Thermal efficiency enhancement of the glazed unit when incorporating PCM.

3.4. Change Materials: A Sustainable Approach to Heating and Cooling in Buildings

Phase change materials have gained attention for thermal storage due to their ability to exchange heat with the environment, regulate indoor temperature fluctuations, and enable 24 h energy supply from renewable sources [32]. As summarized in Table 6, their desirable characteristics, such as availability, chemical stability, corrosion resistance, high durability, and higher heat storage capacity, make them a good alternative for energy-efficient applications. Besides, the range of phase transitions often aligns with the range of thermal comfort and offers high energy density with a small storage volume [1,26,28,61–64].

For cooling purposes, PCMs can be integrated into various systems to enhance energy efficiency and reduce temperature fluctuations. In this regard, Chandel and Agarwal [65,66] summarized the integration of PCMs for cooling photovoltaic panels to enhance system efficiency and improve economic benefits. Maccarini et al. [67] investigated a thermal plant configuration with a heat exchanger integrated with PCM, revealing that it could eliminate conventional cooling systems and reduce energy consumption by approximately 67%. Similarly, Garg et al. [68] tested the PCM-incorporated heat exchanger in a rig chamber, registering a 50% reduction in heat gain and a decrease in average air temperature by over 6 °C while maintaining indoor temperature fluctuation stability. Saffari et al. [69] investigated PCM-based cooling techniques in buildings. As expected, they found that the effectiveness of a specific PCM is highly dependent on climatic conditions, its melting temperature, and occupant behavior. Stritih et al. [67] found that PCM-filled walls can significantly decrease building energy consumption, supporting the goal of zero-energy buildings (ZEB). Meanwhile, Ahangari and Maerefat [70] demonstrated that adding a layer of PCM enhanced thermal comfort by 27.39% in dry climate and 19.04% in semi-arid climate conditions in Iran, based on the Fanger comfort model. Similarly, Ascione et al. [69] evaluated the contribution of PCM integrated into various building components in reducing cooling demand in Mediterranean climates, finding a reduction of up to 11.7% in energy consumption during summertime. Evola et al. [71] assessed the effectiveness of PCMs in improving thermal comfort within lightweight structures during the summer season. They concluded that organic PCMs are more appropriate for temperate climate regions than for hot Mediterranean climate regions. Jin et al. [70] investigated the optimal placement of a thin layer in frame walls to increase thermal mass and reduce peak heat flux through the wall [27]. All the previous research underscores that the effectiveness of PCMs is influenced by various factors, including climatic conditions, PCM thickness, surface area, melting point, etc. Based on these findings, Pasupathy and Velraj [72] and Kuznik et al. [73] emphasize that an appropriate PCM should have a phase change temperature range aligning with the indoor comfort zone, typically between 20 °C and 28 °C.

Canim et al. [33] investigated the integration of PCM-paraffin wax in pumice blocks with distinct percentages of 5%, 10%, and 15%. The optimum results in terms of total energy loads were found when using pumice blocks with 15%. This configuration improved indoor temperature fluctuations by 25% and the average wall time delay by 30%. Also, they registered a decrease in the maximum indoor temperature of 1.5 °C. They ultimately recommended pumice blocks containing PCM as a valuable building material, highlighting its potential to significantly improve energy efficiency. Besides, the use of PCM in building components has shown a quite clear improvement in human thermal comfort, but in most cases, the PCM layer was incorporated into the external wall of the building; thus, limited data was available about cooling energy savings that could be achieved by using PCMs in different parts of the building [63,74].

To facilitate the selection of the proper PCM for a specific application, researchers gathered the main characteristics, as presented in Table 6.

Table 6. Chemical, thermophysical, and environmental requirements of PCM [31,75].

Thermophysical Properties	Kinetic Properties	Chemical Properties	Economic and Environmental Properties
• Suitable phase change temperature. • Higher heat storage capacity: ○ High latent heat of fusion. ○ High specific heat. • High thermal conductivity of solid and liquid phases. • High energy density. • Congruent melting of the PCM. • Cycling stability. • Low vapor pressure at operating temperatures. • Low volume changes during transitions. • No sub-cooling during freezing. • No segregation.	• High nucleation rate. • No/little super cooling. • High rate of crystallization.	• Chemically stable. • Reversible cycle (freezing/melting). • High durability: no degradation after charging/discharging cycles. • Corrosion resistivity. • Non-flammable, non-toxic, and non-explosive materials for safety.	• Abundantly available. • Cost-effective. • Non-polluting. • Low environmental impact. • Recyclable. • Low embodied energy. • Facility for separation from other materials. • Compatible with the container.

4. Phase Change Materials: Addressing Drawbacks and Potential Enhancements

Depending on the solidification or melting temperature of the PCM, most research investigating the integration of a single PCM layer has faced the problem of suitability for only one specific season, i.e., either cooling or heating, but not both. Thus, ongoing investigations aim to find solutions that address both applications. Some researchers have suggested using natural ventilation at night to ensure PCM discharge. Others have studied the concept of integrating two PCM layers into different parts of a building, where each layer is designed to meet the operating conditions of a specific season.

Jin and Zhang [76] conducted a numerical simulation in which they proposed a new double-layered PCM incorporated into the building floor. They revealed that compared to a floor without the PCM, the energy released by the PCM-enhanced floor increased by 41.1% during heating and 37.9% during cooling at peak time.

Likewise, the work of Pasupathy and Velraj [69] highlighted the benefits of using double-layer PCM in roof design. The mathematical model, based on the finite volume method, showed a significant improvement in thermal performance: a single layer of

PCM reduced heat gain by 17–26%, whereas a double layer achieved a reduction of 25–35% [73]. However, incorporating a second layer of PCM also induced additional costs and implementation complexity. Rehman et al. [77] also highlighted the effectiveness of multiple layers of phase change materials (PCMs) in improving thermal comfort in buildings. They conducted a numerical study on the integration of a double-layer PCM configuration into brick walls, simulating weather conditions in Islamabad during January and June. By selecting PCMs with melting temperatures of 29 °C and 13 °C, they demonstrated that this configuration improved thermal comfort throughout the year compared to a single-layer system. Similarly, Almeida et al. [72,78] used the ESP-r simulator to model a building wall incorporating multiple PCM layers. Their results confirmed that the addition of several layers improves the building's thermal performance compared to a single-layer design.

Although these studies demonstrated the positive effect of multilayer PCMs on thermal regulation, they remain limited to specific climatic conditions, numerical simulations, material types, and building configurations. Further experimental validation is required to confirm these results under real-life conditions. In addition, the increased thickness of the roof may pose challenges in terms of architectural integration and compatibility with current building standards [79]. Moreover, the economic impact and technical feasibility of such an approach are not discussed, despite being critical for its adoption in the building sector. Finally, the long-term stability and resistance to repeated thermal cycles of PCMs must be thoroughly examined to ensure the reliability and durability of this solution.

Besides, for thermal management applications in buildings, some researchers have used commercially available PCMs, yet the desirable TES properties are not always achieved during incorporation. Challenges often arise related to the melting point, leakage during the charging process, volume changes, and the compatibility of the PCM container with the wall material. To address these issues, the investigations were divided into two main approaches. The first group of studies reported that these impediments could be overcome by mixing different materials in a certain proportion to obtain a composite PCM with improved thermophysical properties [1,31].

In this context, Sheikholeslami [80], in his research on air conditioning machines using porous media, incorporated a PCM to improve the material's thermal conductivity. He used paraffin (RT27) combined with nano-sized ZnO particles and found that the required operating time was reduced by 37.15% through the use of porous media.

Mehrizi et al. [29] gathered the most relevant results involving enhancements to building walls using bio-composite PCMs. These results are shown in Table 7.

Table 7. Enhancements of integrated PCM with bio-composite [29].

Sample	Components	Absorbed PCM (wt%)	Thermal Conductivity (W/m·K)	Melting Temperature (°C)	Melting Latent Heat (J/g)
Base PCM	Hydrogenated palm kernel vegetable fat (HPKVF)	-	0.2	26.53	74.35
Composite PCM	HPKVF + cellulose fibers + natural clay + graphite	53	0.86	27.33	40.27
Base PCM	Coconut oil	-	0.182	22.63	106.17
Composite PCM	Coconut oil + 50% cellulose fibers + 50% natural clay +10% graphite	44	0.53	23.73	46.70
	Coconut oil + 42% cellulose fibers + 33% natural clay + 25% graphite	46	0.71	23.66	48.39
	Coconut oil + 0.38% cellulose fibers + 31% natural clay + 31% graphite	55	0.81	23.57	58.03
	Coconut oil + 29% cellulose fibers + 29% natural clay + 42% graphite	56	1.06	23.79	59.10

Table 7. *Cont.*

Sample	Components	Absorbed PCM (wt%)	Thermal Conductivity (W/m·K)	Melting Temperature (°C)	Melting Latent Heat (J/g)
Base PCM	Non-cocoa vegetable fat	-	0.2	34.94	108.83
Composite PCM	Non-cocoa vegetable fat + cellulose fibers + natural clay + graphite	56	0.83	34.83	62.39
Composite PCM	Core (palmitic acid) + shell (polylactic acid) micro encapsulated PCM	24.3 core content 35.8 core content 41.9 core content	- - -	61.9 62.3 62.1	40.7 59.9 70.1
Base PCM	Beeswax	-	-	62.28	141.49
Composite PCM	Beeswax + 3% graphene	-	2.8	62.42	186.74
Base PCM	Stearic acid	-	0.16	69.23	208.16
Composite PCM	Stearic acid + carbonized maize straw	77.22	0.3	67.62	160.74
Base PCM	Capric-stearic acid	-	0.19	24.65	175
Composite PCM	Capric-stearic acid + sugar beet pulp	70	0.34	24.4	117
Base PCM	Lauric-stearic acid	-	0.228	37.5	199.6
Composite PCM	Lauric-stearic acid + carbonized biomass waste corn cob	77.9	0.441	35.1	148.3

The second group of investigations focused on using double-layer PCMs combined with composites to enhance thermal conductivity. In this regard, Sun et al. [56] examined a radiant floor system using a PCM based on two hydrated salts mixed with expanded graphite. The investigation was carried out under both winter and summer weather conditions. The heat storage layer in the floor systems was made from an $Na_2(HPO)_4{\cdot}12(H_2O)$-based composite with a melting temperature of 31.3 °C and the cold storage layer was made from a $CaCl_2{\cdot}6(H_2O)$-based composite with a melting temperature of 20.2 °C. The results showed that compared to the reference room, the radiant floor system achieved 2.2 times longer thermal comfort duration during the winter season [78].

5. Commonly Adopted Fundamental Assumptions in Leading Research Studies

These assumptions are commonly used in phase change material (PCM) studies [78], but they have certain limitations that can affect the accuracy of the results:

- Liquid PCM is considered an incompressible and Newtonian fluid.

This simplification is reasonable for many PCMs; however, it may be inaccurate for materials that exhibit non-Newtonian behavior, especially near the melting point. A more detailed examination of the rheological properties of such materials could help refine the models.

- Natural convection of a liquid PCM is neglected.

Natural convection plays an important role in the distribution of heat within the liquid phase of a PCM. By ignoring this, the heat transfer and, therefore, the actual thermal performance of the system may be underestimated. While this assumption might be acceptable for very thin PCM layers, it becomes problematic for larger thicknesses.

- PCM envelope layers are assumed to be thin and have high thermal conductivity, allowing us to overlook their thermal resistance.

Although this assumption simplifies the calculations, it does not always reflect reality—especially when the envelope has significant thermal resistance. In real-world applications, the nature of the encapsulation material can significantly influence thermal storage efficiency.

- Volume changes during solid–liquid phase transitions, heat loss from the TES system, and radiative heat transfer are neglected.

Volume changes during solidification and melting can affect the structure and durability of storage materials. Neglecting these factors could lead to inaccurate predictions of long-term performance.

Thermal losses in the thermal energy storage (TES) system can have a significant impact, especially on long-term storage efficiency. Integrating a thermal loss model improves the accuracy and representativeness of the simulations.

Although these assumptions simplify models and facilitate numerical simulations, they must be carefully justified based on the specific conditions of each study. Experimental validation is essential to evaluate the impact of these approximations and to ensure that the simulation results remain reliable for real-world applications.

6. Ground-Breaking Insights and Practical Recommendations

Due to rapid population expansion and increasing energy demand, the energy crisis remains a major concern for modern society. Projections indicate that fossil fuels will continue to account for 70 to 80% of the world's primary energy supply, leading to environmental issues like frequent disasters, iceberg melting, global warming, and climate change—problems that are expected to worsen in the coming years. As a result, various research methodologies are being promoted to tackle current environmental and energy challenges. Since the building sector is one of the largest energy consumers—accounting for 30% of the world's energy consumption [5]—many countries have implemented regulations aimed at enhancing energy efficiency in buildings and reducing the carbon footprint. This has been achieved through the development of low-carbon technologies [60,81] and the use of bio-based products. One proposed solution is to replace or integrate conventional materials with more efficient, eco-friendlier, and biodegradable alternatives [82,83].

Thus, the authors of the present paper advocate a multilayer wall design for buildings that goes beyond the traditional use of multiple layers of PCM or PCM combined with bio-composites. Instead, they suggest an innovative configuration consisting of a single PCM layer sandwiched between two layers of hybrid bio-composite. This arrangement, illustrated in Figure 13, is intended to improve the control of heat propagation through the wall structure.

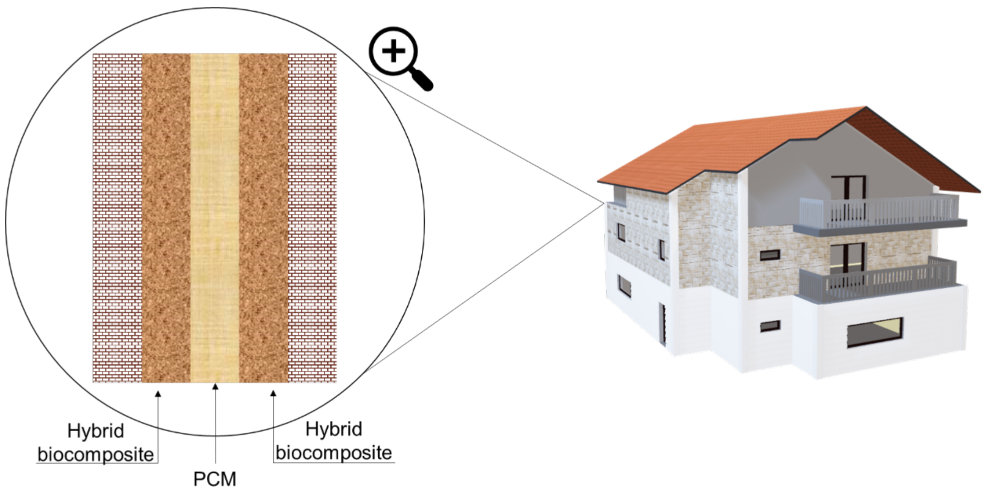

Figure 13. Shape of the wall suggested by the authors.

The logic of this approach lies in the complementary thermal and environmental benefits offered by PCM and bio-composites. The core layer of PCM functions as an effective thermal energy buffer, storing and releasing latent heat during phase transitions to regulate indoor temperature. The bio-composite outer layers not only serve as structural and insulating elements but also contribute to environmental sustainability by using natural or recycled materials such as coffee grounds.

This multilayer system should

- Improve the thermal inertia of the wall, delay heat transfer, and stabilize indoor temperatures;
- Increase energy efficiency, thereby reducing heating and cooling demands;
- Reduce greenhouse gas emissions by reducing reliance on mechanical HVAC systems;
- Promote waste recovery by incorporating organic by-products into building materials.

This approach is particularly relevant in the context of green building strategies and low-carbon construction solutions.

6.1. Spent Coffee Grounds as PCM

Containing a significant amount of fatty acids, spent coffee grounds (SCGs) have attracted attention as bio-based phase change materials (PCMs) that can be integrated into building walls, ceilings, or roofs.

Coffee is one of the largest agricultural commodities and remains one of the most consumed beverages across the globe. It is deeply integrated into daily human routine. In fact, more than 2.25 billion cups of coffee are consumed every day worldwide, which has resulted in an escalation of coffee production to satisfy market demand. Coffee is considered a natural composite, containing crude fiber (lignin, cellulose, hemicellulose, poly-oligo- and mono-saccharides), lipids (free fatty acids, triacylglycerides, and sterols), nitrogenous compounds, and minerals [84]. Freshly brewed coffee served in cafés, restaurants, and pubs and by coffee producers generates spent coffee grounds (SCGs) as a byproduct of the brewing process. It has been found that one ton of green coffee beans results in approximately 550 to 670 kg of SCG, which is usually sent to landfills, causing environmental issues [42,85]. Indeed, landfilling increases the risk of leaching active biochemicals into the environment. Considering the high organic content of SCGs, disposing of untreated excessive quantities could induce spontaneous combustion, leading to high CO_2 and methane emissions, as well as unpleasant odors due to the fermentation process [42].

However, recent studies have shown that compared to conventional organic and inorganic PCMs, SCGs are a promising green alternative to bio-based PCMs. Oil can be extracted from SCGs through different methods such as supercritical fluid extraction (SFE), Soxhlet extraction, ultrasound-assisted extraction (UAE), and microwave-assisted extraction (MAE). The UAE and MAE methods significantly reduce extraction time and solvent consumption. UAE, in particular, has been shown to improve oil yield by disrupting the SCG matrix and facilitating solvent penetration. UAE-derived oils have demonstrated latent heat capacities similar to Soxhlet (~49–50 kJ/kg), but with greater energy efficiency and shorter processing times (~30 min). MAE methods also promise high yields, but can lead to localized overheating that can degrade heat-sensitive compounds. These emerging methods proved that SCGs contain a high value of fatty acids (81.7%), which predominantly consist of linoleic, palmitic, stearic, and oleic acids, making coffee oil a good source of bio-based PCM [42,84]. Fatty acids are considered among organic non-paraffin PCMs, represented by the formula $CH_3(CH_2)_{2n}COOH$, and exhibit significant promise for applications due to their cost-effectiveness, biodegradability, and renewable nature. Compared with paraffins, fatty acids have excellent solid–liquid phase change properties, but they are about three times more expensive [80].

As reported in Table 8, the melting temperature of fatty acids ranges from −5.6 °C to 79 °C, and their latent heat varies between 102 kJ/kg and 212 kJ/kg [80,86]. In this context, the differential scanning calorimeter (DSC) thermograms of the oil extracts (from SCG) analyzed by [42] exhibited relatively broad melting and cooling curves, with a peak melting temperature (T_m) of 4.5 ± 0.72 °C, and a peak freezing temperature (T_f) of −0.98 ± 0.59 °C. Besides, the enthalpy was determined to be 51.15 ± 1.46 J/g. Additionally, the heat capacities of the coffee oil extracts were determined based on temperature variations for both solid ($C_{p,s}$ (T)) and liquid ($C_{p,l}$ (T)) phases. It was found that $C_{p,s}$ (T) varied from 1.3 to 1.5 kJ/kg·K, while $C_{p,l}$ (T) was nearly temperature-independent at 1.8–1.9 kJ/kg·K. Furthermore, to assess their thermal reliability and stability, the coffee oil extracts were subjected to 100 melt-freeze cycles; the DSC curves displayed endothermic and exothermic peaks identical in shape to those of their uncycled counterparts, indicating that the extracts were thermally stable with largely similar peak positions and intensities. These DSC results support the further exploration of coffee oil as a potential phase change material for thermal energy storage applications. A comparative analysis of SCG-derived PCM with commercialized paraffin and fatty acids has been established and is presented in Table 9. As seen, SCG performance depends on the processing route: pure coffee oil targets cold chain applications (≈5 °C), while SCG/beeswax or SCG-fatty acid composites are suited for building comfort ranges (20–30 °C).

Table 8. Thermophysical properties of some fatty acids used as latent heat storage [80,86].

Acid	T_m (°C)	H_f (kJ/kg)	Cp (kJ/kg·K)	k (W/m·K)	ϱ (kg/m^3)
Enanthic	−7.4	107	-	-	-
Butyric	−5.6	126	-	-	-
Caproic	−3	131	-	-	-
Propyl palmiate	10	186	-	-	-
Pelargonic	12.3	127	-	-	-
Isopropyl stearate	14–18	140–142	-	-	-
Caprylic	16	148.5	-	0.149 (L)	862 (L)
	16.5	149		0.148 (L)	1033 (S) 981 (S)
Butyl stearate	19	140 123–200	-	-	-
Dimethyl sabacate	21	120–135	-	-	-
Undecylenic	24.6	141	-	-	-
Vinyl stearate	27–29	122	-	-	-
Undecylic	28.4	139	-	-	-
Capric	31.5	153	-	0.149 (L)	886 (L)
	32	152.7		0.153 (L)	878 (L)
Tridecylic	41.8	157	-	-	-
Methyl-12 hydroxy-stearate	42–43	120–126	-	-	-
Lauric acid	42–44	178	1.6	0.147 (L)	870 (L)
	44	177.4			862 (L)–1007 (S)
Elaidic	47	218	-	-	851 (L)
Myristic	54	187	1.6 (S)	-	844 (L)
	58	186.6	2.7 (L)		990 (S)
	49–51	204.5			
Pentadecanoic	52–53	178	-	-	-
Margaric	60	172.2			
Palmitic	63	187	-	0.165 (L)	874 (L)
	61	203.4	-	0.159 (L)	874 (L)
	64	185.4	-	0.162 (L)	850 (L)
Stearic	70	203	2.35 (L)	0.172 (L)	941 (L)
	69	202.5			
	60–61	186.5			848 (L)
	69.4	199			
Nonadecylic	67	192			
Arachidic	74	227	-	-	-
Heneicosylic	73–74	193			
Phenylacetic	16.7	102			
Acetamid	81	241	-	-	-
SCG	4.50	50.89	1.3–1.5 (S) 1.8–1.9 (L)	0.2	919.2–927.7

Table 9. Comparative overview: SCG-derived PCM vs. commercial paraffin- and fatty acid-based PCM [42,80,87].

	SCG-Based PCM	Paraffin PCM (RT 25)	Fatty Acid PCM (Pure Temp 25)
Primary feedstock	Spent coffee grounds (coffee oil or SCG/bio-wax composite)	Petroleum-derived Paraffin wax	Vegetable oil–fatty acid blend
Phase change temperature (°C)	✓ 4–5 (pure coffee oil) ✓ 24–27 (beeswax/SCG composite)	24–26	25
Latent heat (kJ/kg)	✓ 51 ± 15 (pure coffee oil) ✓ 127–137 (composite)	148–170	185
Cost of bulk material (USD/kg)	0.12–0.38 (ultrasound-assisted extraction, pilot scale)	✓ 2.5–4 (crude) ✓ >8 (purified building grade)	1.4–1.7
Embodied carbon and circularity	Very law net GHG when credits for avoided disposal in landfill are counted	High fossil carbon footprint No circular benefit	Renewable raw material, but concerns about land use and food versus fuel
Commercial readiness	✓ Laboratory to early demo scale ✓ Encapsulation and long-term cycling still under study	Widely commercialized Proven 10,000 + cycles	Commercialized for building and cold chain
End-of-life	Biodegradable/compostable (Can enter organic waste streams)	Non-biodegradable (disposal or recycling needed)	Biodegradable under controlled conditions

The study conducted by Jin et al. [42] demonstrated the potential of commonly discarded spent coffee grounds (SCGs) as a promising bio-based PCM for thermal energy storage applications. However, as previously reported, the major drawback of this material is its low thermal conductivity. Thus, the heat transfer properties of PCMs can be improved using various methods such as fins, heat pipes, or the incorporation of beeswax. In this context, the authors of the present paper suggest exploring the multilayer technique using hybrid composites due to their favorable thermal characteristics.

6.2. Hybrid Composite

The term "hybrid composite" typically refers to a matrix that is reinforced with two or more types of materials. This approach aims to enhance certain properties of the composite material while reducing production costs by incorporating less expensive reinforcements [88]. In this context, Ben Hamou et al. [89] explored the use of hemp fibers as reinforcements in the production of bio-based (thermoplastic) composites. The increasing interest in such techniques is due to several factors, including the material's abundance, biodegradable nature, durability, thermal stability, and applications in the aerospace and automotive industries, as well as its recent use in the construction industry. Polypropylene (PP) is the most commonly used thermoplastic (matrix) in natural fiber composites due to its low density, strong mechanical properties, dimensional stability, and high-temperature resistance [88]. Mutjé et al. [90] investigated the polarity of PP and hemp fibers and concluded that both showed hydrophilic behavior. Besides, they found that the surface morphology of hemp fibers improved fiber–matrix adhesion. Khoathane et al. [91] studied the thermal and mechanical properties of hemp fiber-reinforced 1-pentene/PP copolymer composites. The results showed that the thermal stability of the composite surpassed that of both the fiber and the matrix when considered separately.

Thus, hemp fibers have emerged as a strong contender to replace glass fiber due to their superior thermal and mechanical properties. Indeed, Ben Hamou et al. [87] assessed the thermal and mechanical behavior of hybrid hemp/wood fiber-reinforced composites compared to pure hemp fiber and pure wood fiber-reinforced composites. The DSC results are provided in Table 10, which exhibits the melting temperature (Tm) and enthalpy (ΔHm), as well as the crystallization temperature (Tc) and enthalpy (ΔHc). Notably, the melting peak for pure PP was observed at 165 °C and remained largely unchanged in the presence of hemp fibers. However, there was a significant increase in the Tc of the PP matrix from 111 °C to 121 °C, which can be attributed to the nucleating ability of the fibers. This increase in the crystallization rate of hemp fiber-reinforced PP bio-composites further indicates a strong interfacial interaction between the surface of the hemp fibers and the PP molecular chains, facilitated by the coupling agent PP-g-MA [88].

Table 10. DSC parameters of PP, PP/hemp fiber composites, and hybrid bio-composites [88].

PP-MAPP/Hemp/Wood Weight Ratio	Melting Process		Crystallization Process	
(wt.%)	T_m (°C)	ΔH_m (kJ/kg)	T_c (°C)	ΔH_c (kJ/kg)
100:0:0	165	81	111	84
80:20:0	164	66	119	64
60:30:10	164	53	121	47
80:10:10	163	75	120	66

7. Outlook and Emerging Trends for Future Research

To further improve the energy performance of buildings, current research continues to explore advanced techniques for integrating PCM into various structural components. The focus is on optimizing thermal regulation, improving the sustainability of PCM, and developing bio-based or waste-derived materials such as coffee grounds. Emerging trends also focus on multilayer configurations, encapsulation methods, and adaptive thermal systems adapted to climate variability. However, several key factors must be considered to ensure their effectiveness:

- Temperature range suitability

PCMs are effective within a specific temperature range, meaning that their performance is highly dependent on climatic conditions. Some PCMs are better suited to warm climates for passive cooling applications, while others perform more effectively in cold climates for heating purposes. Therefore, it is essential to choose a PCM with an appropriate phase transition temperature that aligns with a building's thermal requirements.

- Appropriate PCM selection for each application

The efficiency of PCMs depends on several parameters, such as melting and solidification temperature ranges, thermal conductivity, durability, and leak resistance. For instance, materials used for passive cooling must have a phase change temperature that aligns with summer comfort levels, whereas those used for heating applications must be able to efficiently absorb and release heat during the winter.

- Efficient heat transfer during charge and discharge cycles

One of the major challenges in using PCMs is ensuring efficient heat transfer during the charging and discharging phases. Poor heat distribution can reduce storage efficiency and lead to uneven thermal performance throughout the building.

- Managing leakage problems

PCMs can infiltrate adjacent building materials, resulting in thermal losses and structural degradation. To overcome this problem, the use of additives, encapsulation, or bio-based composites can stabilize PCMs and improve their long-term durability.

- Stability and sustainability of PCMs

To ensure efficient use in buildings, PCMs must retain their thermal properties after numerous cycles of melting and solidification. Degradation during repeated thermal cycling could reduce their effectiveness, making encapsulation and chemical stability crucial for sustainable applications. To overcome this problem, incorporating advanced methods like embedding sensor technologies would enable continuous monitoring of the PCM's thermal performance and structural integrity over time. Such an approach would provide valuable real-time data to help predict degradation and ensure the practical viability of SCG-PCMs for building applications [92].

- Improved thermal conductivity

The low thermal conductivity of many PCMs limits their ability to store and release heat effectively. To remedy this, various strategies can be applied, such as the addition of fins, metal foams, or heat pipes, to optimize heat transfer and maximize PCM efficiency. Also, techniques from semiconductor packaging (micro- or nano-structural heat spreaders) could be adapted in SCG-PCM composites to enhance heat transfer [93].

- Strategic location for optimal efficiency

The placement of PCMs in the building structure plays a key role in their performance. To maximize thermal benefits, they are recommended to be positioned near heat sources (such as sun-exposed surfaces in passive solar heating systems) or in areas with high temperature fluctuations. This ensures efficient heat absorption and release to regulate indoor temperatures.

The integration of PCMs into building materials represents an innovative and effective strategy to improve energy efficiency and reduce reliance on conventional heating and cooling systems. However, the selection of appropriate PCMs and their placement, stability, and thermal conductivity improvement are essential aspects to ensure long-term performance. Future advancements in PCM composites, encapsulation techniques, and thermal management will further optimize their application in the design of sustainable and energy-efficient buildings.

8. Conclusions

Energy security and environmental concerns are driving numerous research initiatives aimed at enhancing energy efficiency, reducing strain on energy infrastructure and cutting carbon dioxide (CO_2) emissions. One of the most notable areas of progress is the efficiency enhancement of building heating and cooling systems, achieved through advanced technologies such as heat pumps, solar collectors, chimneys, and thermal energy storage (TES). One of the most promising TES technologies is the integration of phase change materials (PCMs) into various parts of buildings—including walls, floors, ceilings, etc.

This paper provides a summary of research conducted on various PCM applications, offering insights into different types of PCM, methods of encapsulation, their respective weaknesses, and enhancement techniques using additives (such as bio-composites), while also addressing environmental concerns. The aim is to optimize the use of PCMs in building applications. Through this review, it can be concluded that selecting the appropriate PCM for a particular application—whether cooling or heating—requires careful consideration. This choice depends on various factors such as occupancy profile, climate, PCM melting and freezing temperature ranges, thermal conductivity, durability, the building's insulation properties, and compatibility with construction materials. Incompatibility may lead to leakage or inadequate performance when there is direct contact.

To improve PCM performance, several solutions have been proposed, like incorporation of bio-composites or addressing the encapsulation technique, which help prevent leakage, improve stability, and enhance thermal performance by enclosing the phase change material in a protective core. In the present paper, the authors suggest a new approach involving the use of a multilayered wall. This approach combines two layers of a hybrid bio-composite—specifically, the hybrid hemp/wood fiber-reinforced composite with a PP matrix—along with a layer of PCM made from spent coffee grounds (SCGs).

This review explores the potential of using coffee waste residues as a green and sustainable resource for thermal energy storage, addressing environmental concerns related to landfill disposal. Previous studies on valorizing spent coffee grounds (SCGs) have shown promising results, indicating that coffee oil extracts from SCGs can serve as potential bio-based phase change materials. The extracts contain approximately 60–80% fatty acids with a phase transition temperature of approximately 4.5 ± 0.72 °C and latent heat values of 51.15 ± 1.46 kJ/kg, as determined by differential scanning calorimetry (DSC). FTIR and DSC analyses were conducted on coffee oil extracts following thermal cycling and demonstrated good thermal and chemical stability.

Building on this, an innovative configuration-based multilayer design was suggested, consisting of a single layer of PCM sandwiched between two layers of a hybrid bio-composite. This arrangement aims to improve the control of heat propagation through the wall structure. Although the phase transition of the SCG-PCM (5 °C) seems unsuitable for passive cooling in hot climates (typically requiring 19–28 °C), ongoing research is exploring enhancements to the thermophysical properties of the SCG-PCM by blending it with materials like palm wax (PW), beeswax (BW), or golden soy wax (GW).

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Abbreviations

The following abbreviations are used in this manuscript:

Abbreviations	
DSC	Differential scanning calorimeter
DTG	Derivative thermogravimetric machine
EG	Expanded graphite
EP	Expanded pearlite
EV	Expanded vermiculate
FSPCM	Foam-stabilized PCM
FTIR	Fourier transform infrared spectroscopy
GDP	Gross domestic product

HVAC	Heating, ventilation, and air conditioning
LHS	Latent heat storage
LTES	Latent thermal energy storage
MUFA	Monounsaturated fatty acid
PCM	Phase change material
PUFA	Polyunsaturated fatty acid
PVT	Photovoltaic–thermal
SCG	Spent coffee ground
SDG	Sustainable Development Goals
SFA	Saturated fatty acid
SHS	Sensible heat storage
SSPCM	Shape-stabilized PCM
TES	Thermal energy storage
TG	Thermogravimetric
ZEB	Net Zero Emissions in Building
Nomenclature	
Cp	Specific heat capacity (kJ/kg·K)
K	Thermal conductivity (W/m·K)
Tm	Melting temperature (°C)
W0	Weight of extracted oil (g)
Wd	Weight of the dried SCGs (g)
α	Thermal expansion coefficient
ΔH	Latent heat for fusion (kJ/kg)
ϱ	Density (kg/m^3)

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