construction materials

Review

Incorporation of Phase Change Materials in Buildings

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Abstract: This review paper explores the integration of phase change materials (PCMs) in building insulation systems to enhance energy efficiency and thermal comfort. Through an extensive analysis of existing literature, the thermal performance of PCM-enhanced building envelopes is evaluated under diverse environmental conditions. This review highlights that PCMs effectively moderate indoor temperatures by absorbing and releasing heat during phase transitions, maintaining a stable indoor climate. This paper also delves into the detailed concepts of PCMs, including their classification and various applications within building insulation. It is noted that different types of PCMs have unique thermal properties and potential uses, which can be tailored to specific building requirements and climatic conditions. Furthermore, cost–benefit and environmental assessments presented in the reviewed studies suggest that incorporating PCMs into building materials offers significant potential for reducing energy consumption and mitigating environmental impacts. These assessments indicate that PCMs can lead to substantial energy savings by decreasing the reliance on heating and cooling systems, thereby lowering overall energy costs and carbon emissions. However, despite the promising outlook, this review identifies a need for further research to optimize PCM formulations and integration methods. This optimization is essential for overcoming current challenges and facilitating the widespread adoption of PCMs in the construction industry. Addressing issues such as long-term durability, compatibility with existing building materials, and cost-effectiveness will be crucial for maximizing the benefits of PCMs in enhancing energy efficiency and sustainability in buildings. Overall, this review underscores the transformative potential of PCMs in building insulation practices. By providing a comprehensive overview of PCM classifications, applications, and their impacts on energy efficiency and environmental sustainability, this paper lays the groundwork for future advancements and research directions in the field of PCM-enhanced building technologies.

Keywords: PCM; building; heating; thermal energy

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1. Introduction

We must use energy wisely and put some energy-saving techniques into place in order to balance the demand–supply ratio, because as we all know, energy consumption is rising daily while our energy sources are constant and also running out. This will allow us to continue using our energy sources unhindered for a longer period of time. A large portion of the world's environmental problems are caused by buildings and the activities that take place inside of them [1]. Building energy use is a significant factor in the energy-related issues that hinder sustainable development, such as indoor cooking-related deaths, a lack of energy resources to support economic growth, universal access to modern energy services, and climate change [2–4].

More specifically, the building sector used about 115 EJ globally in 2010, which accounted for 30% of energy-related CO_2 emissions and 24% of the world's final energy demand. Heating, ventilation, and air conditioning (HVAC) systems consume 42–68% of all the energy in a building, followed by the domestic hot water system (14–26%) and lighting and appliances (16–32%) [5]. Additionally, the building industry is accountable for 25–33% of black carbon emissions and approximately two-thirds of halocarbon emissions. In addition, the building industry consumes 30% of the world's electricity and 23% of the world's primary energy [6]. The efficiency of the building's insulation plays a key role in lowering the building's indoor energy usage because it directly affects how well the building transfers heat. Facades, roofs, doors, and windows are all parts of the building's exterior structure, and they all have an impact [7]. Using the building envelope may be a viable option for energy efficiency and thermal comfort. A building's envelope serves as nothing more than a shield to regulate the temperature inside. Building envelopes have the purpose of physically separating interior spaces from outside environments [8,9].

As a result, they provide the interior environment with external protection while also facilitating climate control. By preventing direct solar radiation from entering the interior, reducing glare, minimizing water penetration, allowing for natural ventilation, lowering external reflection, allowing for views, and acting as thermal barriers, building envelopes aid in lowering energy consumption [10]. The building envelope design affects how much energy the HVAC system and lighting use, while other components' energy use is influenced by their inborn design features and occupant behavior [11]. Numerous studies have been conducted to find ways to reduce the energy used by lighting and HVAC systems by designing an energy-efficient building envelope while taking into account a variety of factors. For instance, depending on the climate, increasing the thermal resistance, thermal storage, and solar absorptivity of the building envelope reduced the energy consumption of the HVAC system by 20–80%, 35–56%, and 2–46%, respectively.

As with lighting load, upgrading window type and glazing decreased HVAC energy use by 17–47% and 39–56%, respectively [12]. The main elements of an opaque envelope are the insulation materials, phase change materials (PCMs), and coating materials. They guarantee energy efficiency and thermal comfort in buildings, while visual comfort is dependent on the transparent envelope's glazing qualities. Buildings must reduce their energy use, guarantee an acceptable level of thermal, acoustic, and visual comfort, and enhance indoor air quality. Building energy conservation is influenced by a number of factors, such as design, environmental factors (indoor and outdoor), and selection criteria, as shown in Figure 1.

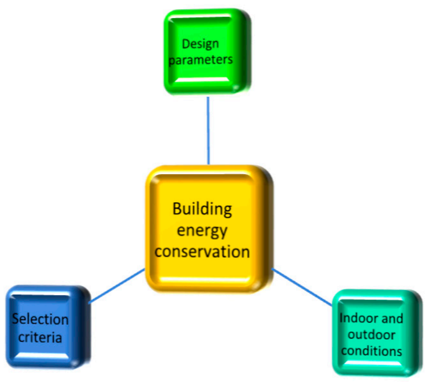

Figure 1. Building energy conservation consideration.

To design an energy-efficient building that meets the needs and preferences of stakeholders, a variety of design criteria and selection criteria are used [13]. By increasing the heat capacity of light-weight buildings, particularly steel structures, and by adding more thermal mass to concrete and brick structures, thermal energy storage (TES) is an efficient way to improve energy efficiency in buildings. By utilizing materials with a high energy storage capacity to store energy in the form of sensible heat and latent heat, these systems are promising ways to reduce energy consumption. Phase change materials (PCMs) are substances that can store latent heat. When incorporated into a building's envelope, PCMs significantly increase the thermal mass of the structure because of their high latent heat capacity, which allows them to store a large amount of energy in a limited range of temperatures [14]. Phase change materials (PCMs) are substances that, as a result of the latent heat they produce during the phase change, have the capacity to store energy. As an alternative to be used in building applications' constructive envelopes, these materials have undergone extensive research. In order to store thermal energy efficiently, phase change materials (PCMs) are used in latent heat storage systems, which have the advantages of high energy density and isothermal storage. PCM and thermal insulation work together to lower the building's energy use, which smooths out temperature fluctuations [15].

A total of 109 peer-reviewed journal articles on phase change materials (PCMs) and their integration with energy-saving technologies were reviewed. In this paper, we will discuss thermal energy in buildings, techniques for minimum thermal loss through the building, the Trombe wall, phase change materials (PCMs), types and characteristics of PCMs, applications of PCMs, the PCM-incorporated building envelope, selection criteria of PCMs, various incorporation methods of PCMs in buildings, parameters for PCMs performance in buildings, melting temperature, thickness, the location of PCMs, modeling of a PCMs-incorporated building envelope, and the assessment of a PCM-incorporated building. Based on the literature review, the research focus was refined to address the key practical challenges identified in large-scale applications of PCMs, such as thermal efficiency and integration with renewable energy systems. This informed the development of the methodology, ensuring it addressed these challenges in real-world scenarios.

Previous reviews about PCMs for building applications have been carried out that provide broad knowledge with respect to thermal properties, methods of incorporation, and theoretical benefits. However, practical challenges, large-scale applications, or real-world scenarios relating to integration with other energy-saving technologies have not been addressed by most of the reviews.

For instance, Zalba et al. (2003) conducted an overall review of state-of-the-art progress in PCM applications, emphasizing mainly on theoretical benefits and practical implementation and integration challenges that had been overlooked [16].

Similarly, while Sharma et al. (2009) gave an in-depth review of latent heat and thermal properties of PCMs, they typically failed to discuss any challenges in real-life applications, large-scale performance, and synergistic effects with other energy-saving technologies [17].

A review by Kenisarin and Mahkamov (2016) focused on recent advances made in integrating PCMs into building concretes, yet they did not provide any real-world performance data on combined effects with other building energy technologies [18].

Farid et al. (2003) offered a deep review of thermal energy storage using PCMs along with several applications; however, they did not take into consideration practical challenges or large-scale applications [19].

Tyagi and Buddhi (2007) considered the theoretical performance of passive cooling using PCMs as a potential means of sustainable passive cooling in building envelopes not taking into account real-world factors such as climatic variations and occupant behavior [20].

Cabeza et al. (2011) also reviewed state-of-the-art PCMs in construction from the point of view of application and research, but still, their review did not cover challenges in practical implementation or actual performance in real life [21].

Khudhair and Farid (2004) reviewed the integration of PCMs in building walls for energy saving but did not consider large-scale performance data or the combined effects with other energy-saving technologies [22].

Castell et al. (2012) provided an overview of PCM applications in buildings and their potential energy-saving ability but did not consider practical application issues along with the feasibility of large-scale use [23].

Al-Saadi and Zhai (2015) conducted parametric studies on the enhancement of the thermal performance of PCMs but did not discuss the challenges of real-life application issues or large-scale performance assessments [24].

These reviews indicate that further research studies are needed concerning practical challenges, applications at scale within real-world settings, and other integration activities with complementary energy-saving technologies that can enhance the overall energy performance of buildings.

The objective of this review is to fill these gaps by discussing the performances of PCMs in real building environments taking into account all factors that may influence their activities, such as climatic variations, occupant behavior, and building design. We will probe into the interactive effects resulting from integrating PCMs with other energy-saving technologies, like advanced insulation materials, smart HVAC systems, and renewable sources of energy. The next stage will be cost–benefit assessments and environmental impacts of building envelopes incorporating PCMs, thus providing a full view of their feasibility and sustainability. Our review envisions new ways that PCMs can be integrated into building materials and structures to enhance thermal storage capacity for energy efficiency. We will further discuss models and simulation software that can be used in optimizing the performances of PCMs in various building scenarios, thereby allowing for the design of energy-efficient building envelopes.

Therefore, by covering these areas, this review offers a general yet practical overview of the aspects of using PCMs in building envelopes with regard to their ability to achieve efficient and sustainable buildings for researchers, designers, and policymakers.

2. Methodology

The methodology utilized to develop the literature survey and the bibliometric analysis is reported in this section. VOSviewer software (Version 1.6.20) was employed to generate a bibliometric map, with data collection facilitated through Dimensions.ai. A search query using keywords relevant to the research area on the incorporation of phase change materials (PCMs) in building envelopes was conducted on Dimensions.ai, and the bibliometric data were subsequently downloaded in CSV format. Titles, abstracts, and keywords of the documents were extracted from the dataset for analysis and review purposes.

VOSviewer was downloaded and installed from its official website. The software was opened, and the option ‘Create a map based on text data’ was selected. The downloaded data file from Dimensions.ai was imported into VOSviewer. The software then evaluated the text data to generate a map, which was adjusted for term frequency by eliminating stop words and defining fields to be analyzed, such as title or abstract.

Parameters for the selection of terms were customized by setting up a threshold value for the number of times a term should appear. Upon completing these parameters, the map was created. VOSviewer generated a term co-occurrence map based on the chosen parameters, displaying clusters of terms often found together in the dataset as shown in Figure 2. The layout, colors, and labels were adjusted according to different visualization settings to enhance readability. By examining the clusters, the main topics and their interlinking were identified, providing insight into the prominent themes within the research area. A comparative table for phase change material implementation in building envelope is shown in Table 1. Here is the comparative table of several terms belonging to different clusters with the help of the co-occurrence map relating to the incorporation of PCMs in building envelopes:

Comparing the data extracted from Dimensions.ai with other databases, such as Web of Science and Scopus, revealed striking similarities and differences in clusters of terms and thematic areas:

Dimensions.ai: Thematically focused on the practical applications of PCMs in building envelopes, highlighting relevant terms such as ‘thermal energy storage’, ‘insulation’, and ‘thermal comfort’.

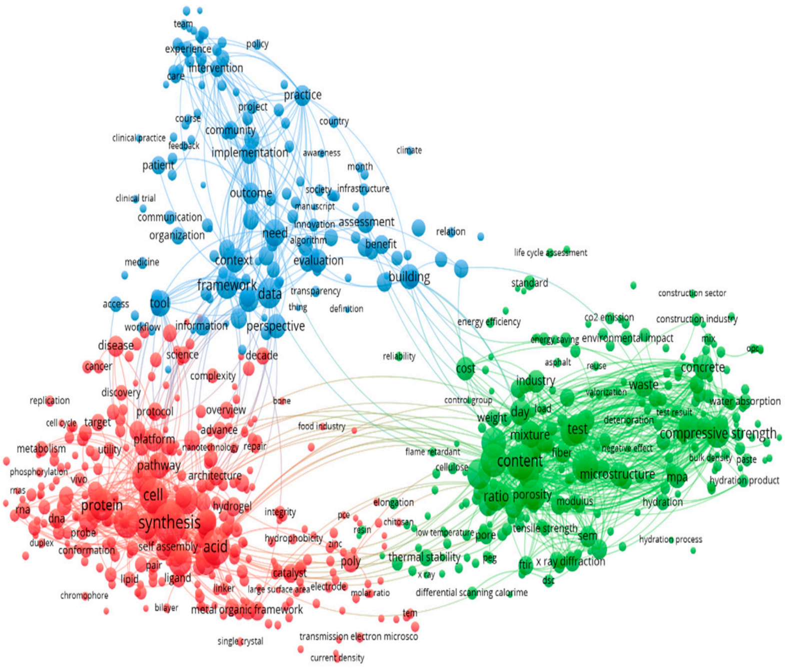

Figure 2. A co-word (keyword co-occurrence) network visualization using VOSviewer.

Table 1. Comparative table of terms of the co-occurrence map.

Cluster 1 (Red)	Cluster 2 (Blue)	Cluster 3 (Green)
Thermal Energy Storage	Energy Efficiency	Building Envelope
Phase Change Material (PCM)	Renewable Energy	Insulation
Latent Heat	Energy Consumption	Thermal Comfort
Melting Point	Energy Saving	Heat Transfer
Solidification	Sustainable Building	Thermal Conductivity
Heat Capacity	Energy Performance	Passive Design
Encapsulation	Smart Materials	Temperature Regulation
PCM Integration	Energy Management	Building Materials
Thermal Regulation	Environmental Impact	Construction Techniques
Energy Optimization	Energy Policy	Durability

Web of Science: Accentuated a greater number of themes related to energy efficiency and sustainability, particularly renewable energy and energy policy.

Scopus: Presented a mix of technical and application-oriented topics, with considerable overlap between themes related to thermal regulation and building materials.

While Dimensions.ai was particularly strong in detailing aspects of integration and practicality for PCM in building envelopes, Web of Science and Scopus provided a better overview of energy efficiency and policy implications. This multi-source comparison provided a holistic overview of the entire amount of research on PCMs encompassing basic science, applied engineering, and policy considerations.

The co-occurrence map offered a valuable visualization of the relationships between key terms in the research data derived from Dimensions.ai. The clusters revealed different thematic areas, with each color representing a unique cluster: red for biological and chemical processes; blue for frameworks and data implementation; and green for materials science, particularly concerning concrete and its properties. Utilizing VOSviewer for this analysis significantly aided in exploring major trends and connections within this research field, thereby furthering the understanding of the landscape of literature.

3. Thermal Energy in Buildings

In terms of whether someone is feeling too hot or too cold, the term thermal comfort refers to a person's psychological state of mind [25]. The thermal comfort level of the residents is influenced by a number of indoor environmental factors. The requirements for the thermal environment and the room temperature are provided using the operative temperature as a reference in all current indoor environmental standards. The temperature at which a person would exchange the same amount of heat by radiation and convection as they would in a non-uniform environment is known as the operative temperature. Operative temperature is also known as comfort temperature and represents the mean of the indoor air temperature T_a (degree Celsius) and the mean radiant temperature T_r (degree Celsius). This means that the temperature of the air and the mean radiant temperature both have an equal impact on the degree of thermal comfort in a space and as a result of the creation of suitable thermal conditions. Particularly, there is not an even distribution of the mean radiant temperature throughout the room, which affects the operative temperature. When using radiant surface heating and cooling systems, the mean radiant temperature is strongly influenced by the surface temperatures of the heated/cooled surfaces, but it is also affected by the angles that the human body (inhabitant's position) makes with the surfaces of the room as well as by the surface emissivity [26].

A building envelope is the best solution for minimizing energy consumption in buildings. Trombe walls, thermally activated buildings, and PCM integration in buildings are a few common methods used to reduce energy consumption. Our primary concern in this review paper is the PCM-incorporated building.

The Trombe wall is a dark south-facing wall with significant thermal mass and glazing material. Brick, quarry rock, reinforced concrete or water containers can all be used to create a freestanding wall or a load-bearing wall as shown in Figure 3. The operating premise of the Trombe wall is that a large wall is heated by solar radiation. Radiation and convective heat exchange from a large heated wall warm the air in the space. The massive wall has air vents in the upper and lower portions that are used to ensure the necessary air circulation. Trombe walls work by absorbing sunlight and transforming it into energy. When energy demand is at its highest, a Trombe wall stores it and releases it when a building's occupants need it [27]. A Trombe wall, also referred to as a thermal storage wall and a solar heating wall, can cut a building's energy use by up to 30% while also providing thermal comfort in the winter and transitional seasons. An essential green architectural element that helps with building ventilation, heating, and cooling is a Trombe wall [28].

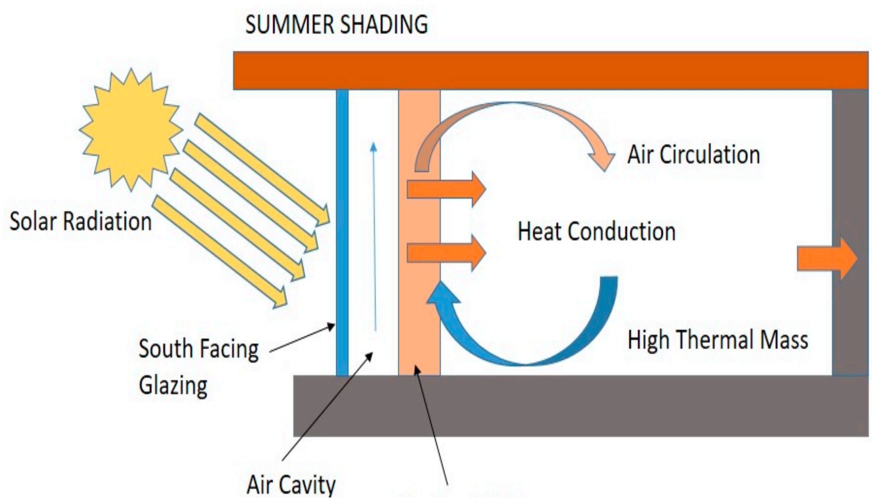

Figure 3. Details of Trombe wall (Redrawn from [28]).

The traditional Trombe wall offers benefits like easy configuration, high efficiency, no operating costs, etc. The conventional Trombe wall can use clean energy to enhance indoor thermal comfort, enhance indoor air quality, and decrease energy consumption for cooling in the summer and heating in the winter [29]. The conventional Trombe wall, however, has a number of drawbacks such as a low aesthetic value, low thermal resistance, reverse thermo siphon phenomenon, and heat transfer that is always uncertain. The traditional Trombe wall system with a single function has thus been unable to meet the performance requirements of buildings, and numerous types of Trombe wall systems have been proposed. This is due to the improvement of the requirements of structural transformation, material selection, design optimization, and engineering practices [30].

A modified Trombe wall, a zigzag Trombe wall, a solar water wall, a solar trans-wall, a Trombe wall with venetian blinds (VBTW), a composite Trombe wall (Trombe–Michel wall), a fluidized Trombe wall, and a photovoltaic Trombe wall (PVTW) are some of the nine different types of the proposed Trombe wall that can be classified based on configurations. The nine configured walls can be divided into two types, heating type and cooling type, each serving the primary purpose of a Trombe wall [31].

4. Phase Change Material

Renewable energy sources must be developed in order to meet our power requirements and to consistently supply energy in order to lessen our reliance on fossil fuel energy sources. Some renewable energy sources like the Sun and wind have intermittent availability which is a problem. When the wind is too strong or not strong enough, wind turbines cannot operate. When there is a lot of cloud cover or at night, photovoltaic (PV) panels cannot produce electricity. By charging charge-storage devices such as batteries and fuel cells during peak hours to store energy for later use, direct electricity-generating technologies can overcome the intermittent nature of the power source. Thermal energy storage (TES) materials can be used to store heat for uses involving the thermal energy of the Sun. Chemical storage and physical storage are the two broad categories into which TES can be divided. Chemical storage involves a reversible chemical reaction with a significant enthalpy change, which breaks and forms chemical bonds. The system is charged as a result of the reaction that produces high-energy products when heated by the Sun or another thermal source. The reaction moves in the opposite direction during discharge, releasing heat. This review is focused on physical storage, which makes use of the TES materials' thermal characteristics to store heat. Sensible heat storage and latent heat storage are the two types of physical TES [32]. Sensible heat storage, latent heat storage, and thermochemical energy storage are the three main types of thermal energy storage [33]. The process of changing a storage material's phase typically between solid and liquid phases, although solid–gas, liquid–gas, and solid–solid phase changes are also possible, is known as latent heat storage [34]. Due to the isothermal nature of the phase change process, as well as its lower weight per unit of storage capacity and compactness, latent heat storage has received a lot of attention recently [35]. Its development is also aided by its superior thermal characteristics over sensible heat storage materials, such as a stable phase change temperature and a high latent heat. Paraffin waxes, esters, fatty acid and salt hydrates, eutectic salts, water, and other PCMs are frequently used as storage media [36]. The four categories of PCMs are solid–solid, solid–liquid, solid–gas, and liquid–gas; of these, a solid–liquid PCM has excellent thermal energy storage potential, which could be eutectics, organic PCM, or inorganic PCM [37].

Many industries including the construction, automotive, textile, and solar energy installation sectors use PCM. Its range of applications, which also include traditional industries like construction, electronics, and pharmaceuticals, as well as advanced thermal energy storage materials for textiles and thermo-regulated biomaterials, is expanding in recent years [37].

4.1. Concept of PCMs

The term PCMs refers to a class of materials that can be either organic, inorganic, or eutectic mixtures and which have the inherent ability to absorb and release heat during phase transition cycles as shown in Figure 4. PCMs primarily refer to the composite between two or more materials that can overcome the performance shortcomings of a single material, and which frequently give the material some new excellent properties. According to the phase change method, PCMs can be classified as solid–solid, solid–liquid, solid–gas, and liquid–gas types. The solid–solid PCMs' small volume changes have led to quick advancements in research and application [38]. While the liquid system must be kept in a container during the phase change process, which increases the cost and limits the use of this type of PCM, the solid–liquid PCMs have the advantage of having a high latent heat of phase change. Additionally, PCMs can be used in temperature control systems because their temperature remains essentially constant throughout the phase change process. Due to their exceptional qualities including a high latent heat storage capacity, a suitable solid–liquid phase change temperature, thermal reliability, and low cost, PCMs have recently attracted increasing attention [39].

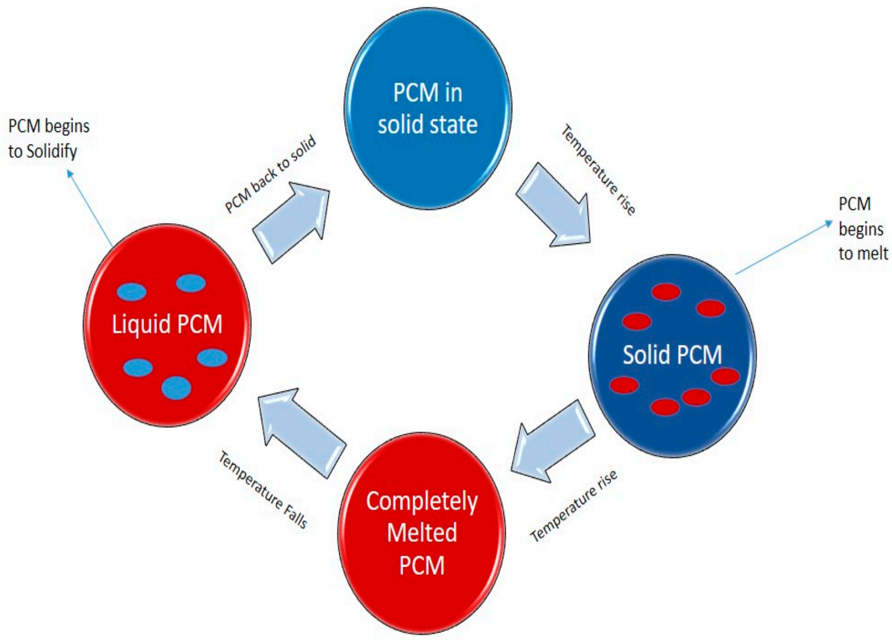

Figure 4. Concept of phase change materials.

PCMs are sustainable energy storage materials with a wide range of potential commercial applications, including temperature control and heat storage [40]. However, issues like poor thermal conductivity and liquid PCM leakage have hampered its widespread application. Researchers have been working hard recently to identify the technical challenges that stand in the way of PCM application and to encourage the quick development of phase change energy storage materials. Coordination bond breaking is used by the majority of low-temperature inorganic PCMs to absorb and release energy. The same drawbacks apply to them, including phase separation, easy corrosion, and supercooling. Solid–liquid phase change technology is used by high-temperature PCMs to absorb and release energy [41].

4.2. Types and Characteristics of PCMs

PCMs can be categorized into three groups based on the phase transition temperature as shown in Figure 5:

1. Low-temperature PCM, with a phase transition temperature below 15 °C, is typically used in air conditioning applications and the food industry [42].

2. Medium-temperature PCM, which is the most popular, has a phase transition temperature between 15 and 90 °C and has applications in solar energy, medical, textile, and electronic fields [43].
3. High-temperature PCM, with a phase transition temperature greater than 90 °C, is primarily used in industry and aerospace fields [44].

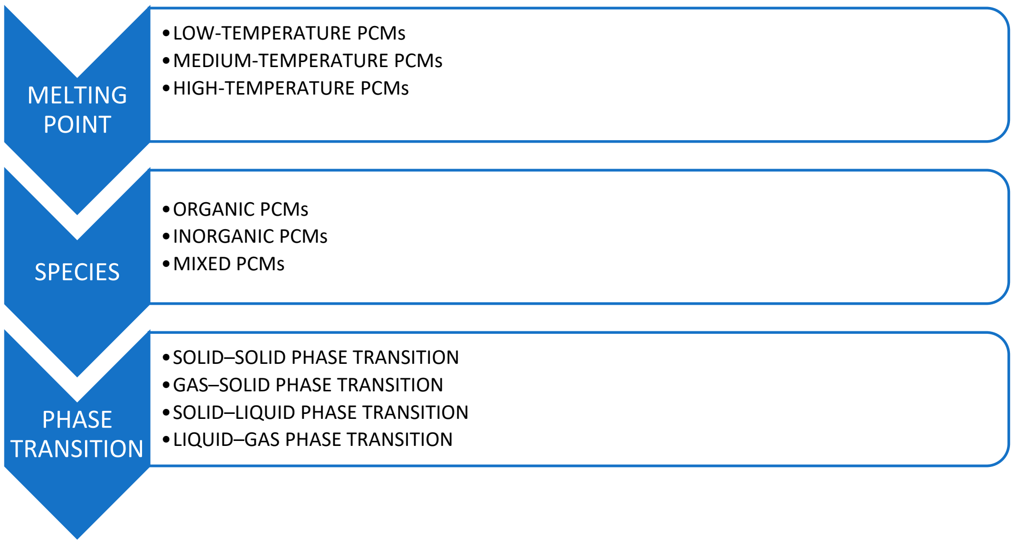

Figure 5. Types of PCMs based on melting point and phase transition temperature.

The phase change mode of PCMs can also be used to categorize them as solid–solid, solid–liquid, liquid–gas, and solid–gas phase change materials [45]. The benefits of materials with solid–solid phase changes include no liquid production, minimal volume change, no corrosion, and long service life. However, they do have drawbacks such as high phase change temperatures and low latent heat of phase changes. Both solid–gas and liquid–gas phase change materials have a high latent heat of phase transition. However, they are not commercially viable for large-scale TES because of the drawback of large-volume changes. Materials with large latent heats of phase change and small volume changes are known as solid–liquid phase change materials; however, when heated, they leak easily [46]. TES systems have limited use for PCMs with a solid–gas or liquid–gas phase transition because of the substantial volume changes involved in the transition, even though the latent heat of phase transition is high. In general, solid–solid PCMs have a lower heat of phase transition than solid–liquid PCMs. However, using the former group of materials can prevent the significant technical issue with solid–liquid PCMs, which is PCM leakage at temperatures above the phase transition temperature [47].

Desirable thermo physical, kinetic, and chemical characteristics should be present in the PCM used in the design of TES systems [48]. The primary qualities needed for a good PCM are in Table 2 [49].

Phase change materials can also be classified into organic, inorganic, and eutectic PCMs. Paraffin and non-paraffins (fatty acids, eutectics, and mixtures) are additional categories for organic materials as shown in Figure 6. They crystallize with little to no sub-cooling and are typically non-corrosive and very stable according to experiments (melting and freezing cycles) using these materials [50].

Table 2. Various characteristics of PCMs.

Property	Thermal Characteristics	Chemical Characteristics	Economics
Melting Point	Within the preferred operating temperature range	Stable chemical structure within operating temperature	Lower energy costs due to optimal temperature range
Latent Fusion Heat Capacity	High latent fusion heat capacity per volume	Consistent phase change properties over multiple cycles	Reduces the amount of material needed, lowering costs
Specific Heat Capacity	High specific heat capacity for significant additional sensible heat storage	Chemical stability under varying thermal loads	Enhances energy efficiency, reducing operational costs
Thermal Conductivity	Both solid and liquid phases have high thermal conductivity	Non-reactive with encapsulating materials	Minimizes material degradation, reducing replacement costs
Vapor Pressure	Minimal vapor pressure at operating temperature and minimal volume change during phase transformation	Non-volatile, ensuring safety and longevity	Low maintenance costs due to stability
Uniform Melting/Freezing	Uniform melting and freezing points, maintaining the material's storage capacity	Consistent phase change temperatures	Reliability reduces operational disruptions
Reversibility	Ensures efficient thermal energy storage and release	Full reversible cycle of freezing and melting	Long-term cost savings through reusable cycles
Durability	Long-term thermal stability	No deterioration even after numerous freeze/melt cycles	Reduces replacement frequency, saving costs
Non-corrosive	Compatible with thermal systems	The materials used in construction and encapsulation are not corrosive	Low maintenance and replacement costs
Safety	Safe under operating conditions	Not explosive, flammable, or toxic	Reduces safety management costs
Availability	Widely available for various applications	Chemical composition easily sourced	Abundantly available and reasonably priced
Treatment and Recycling	Easily integrated into existing systems	Simple chemical treatment and recycling processes	Simple treatment and recycling
Environmental Performance	Environmentally friendly thermal properties	Non-toxic and environmentally safe	Good environmental performance based on life cycle assessment

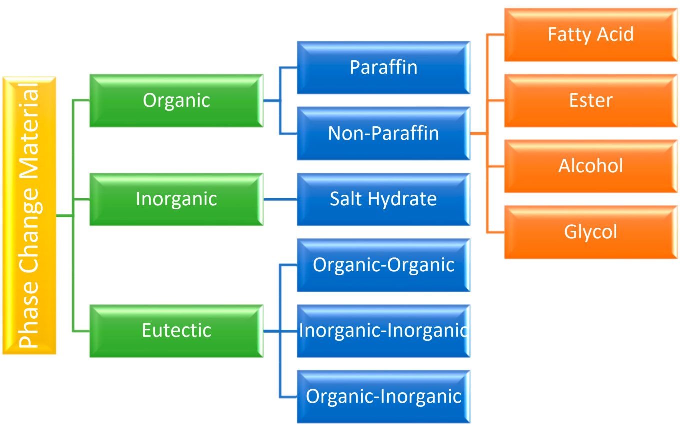

Figure 6. Flow chart of different types of phase change materials.

Eutectics and compounds are additional categories for inorganic materials. When two or more components melt and freeze at the same time and form crystals during the crystallization process, the result is a substance known as a eutectic. There is not much room for the individual components to separate because a eutectic almost always melts and freezes without segregation. At almost constant temperature, a eutectic mixture melts. Salts, salt hydrates, aqueous solutions, and water are the primary inorganic components [19]. There are three species of PCMs.

4.2.1. Organic PCMs

Organic PCMs are natural materials. They are divided into two categories, paraffin and non-paraffin [51]. Organic materials also have compatible melting where they melt and freeze more than once in isolation. Self-nucleation causes organic materials to solidify with almost or negative supercooling and also with less corrosiveness [17].

Paraffins

The majority of the straight chain n-alkanes (CH_3-(CH_2)-CH_3) make up paraffin wax. A significant amount of latent heat is released during the crystallization of the (CH_3)- chain. With chain length both the melting point and latent heat of fusion rise.

Due to their accessibility over a wide temperature range, paraffins are suitable as a heat of fusion storage material. However, only technical-grade paraffins may be used as PCMs in latent heat storage systems due to cost considerations. Paraffins are non-corrosive, safe, dependable, and less expensive. They exhibit minimal volume changes during melting and have low vapor pressure in the melt state because they are chemically inert and stable below 500 degrees Celsius [17]. The freeze–melt cycle of system-using paraffins is typically very long due to these characteristics of the paraffins. With more carbon atoms present, alkane has a higher melting point. Along with other beneficial traits like consistent melting and good nucleating qualities, paraffins have a number of other advantages. They exhibit a few unfavorable characteristics including low thermal conductivity, incompatibility with plastic containers, and moderate flammability.

Due to its important properties including its high heat of fusion, fluctuating stage change temperature, zero supercooling characteristics, lower vapor pressure, chemical inertness, and constant conductivity, paraffin has been used for energy storage [40]. TES materials are less expensive than PCMs because of their higher storage density and lower operating temperatures [52]. Only technical-grade paraffin is used in latent heat storage systems because it is more affordable, safe for biological systems, and non-toxic [53]. Paraffin is sufficiently available from many manufacturers. The CnH2n+2 family of alkanes (paraffins) would make the most promising candidates [54]. Due to the characteristics that make the paraffin type of organic phase change better suited for such applications as well as numerous other factors, many researchers have been developing new experiments to observe and analyze the phenomenon.

Non-paraffins

Fatty acids

The two critical parameters that have been examined and analyzed in PCMs are known as the phase change parameters such as temperature and latent heat. According to earlier research, scientists have tested these two properties using a variety of organic materials, primarily fatty acids, as PCMs [55]. Fatty acid is a component of the non-paraffin subgroup of organic phase change materials, which also includes paraffin. Due to the classification and production of fatty acids by both plants and animals, they are known in a small group of renewable PCMs [56]. These are categorized as being both animal- and plant-based and hydrolyzed to produce a mixture of fatty acids that have been purified and separated from one another to create fats and oils. Fatty acids are one of the few renewable feed stocks that have the same properties as paraffin waxes in PCM applications. Some of the properties of fatty acids as PCMs have been discovered and studied, including density, specific heat, latent heat, and thermal conductivity. In comparison to other phase change materials that have been discussed and tested, fatty acids have higher-ranking parameters and production in chemical and thermal properties, zero toxicity, melting compatibility, which has been suitable for a melting temperature range for a few heat storage applications, and are biodegradable. They are capable of achieving melting and freezing cycles without thermal degradation which can accumulate a variety of substances. A PCM with promising energy-storing composites has recently been identified as a eutectic mixture of fatty acids. Fatty acids are used in a select few areas including solar energy systems and construction. They are chosen because they have great thermal and physical characteristics and are simple to incorporate into compound structures [50].

Additionally, since a few industries have already begun to produce fatty acids in greater quantities for use in products like plastics, textiles, and cosmetics, all fatty acids have been widely commercialized for a variety of applications.

Due to their remarkable qualities such as being non-corrosive, reusable, having low initial cost, having little to no super cooling, having a large amount of latent heat, and consistently softening, organic PCMs are used widely in a variety of applications and are more effective than inorganic PCMs. Organic PCMs have a higher installation cost than inorganic PCMs which is one of their disadvantages [57]. Organic PCMs have been the focus of numerous investigations [58]. Based on their favorable circumstances, their improved thermal stability, freezing without supercooling characteristics, capacity to consistently melt, non-segregation, and lack of toxicity, better significant measures have been provided. Due to their high latent heat, paraffin and fatty acids are used more frequently than other types of organic PCMs. Additionally, organic PCMs can be divided into a few different types. For instance, polyalcohol and polyethylene have been hailed as advantageous PCMs because they undergo solid–solid phase transformation by absorbing and releasing significant amounts of latent heat at a constant temperature [58].

4.2.2. Inorganic PCMs

Metals and hydrated salts are the two types of inorganic chemicals that can be employed as PCMs. For usage as PCMs, hydrated salts have been the subject of extensive research. Their usual formula is $AB{\cdot}nH_2O$, and the hydrated salt dehydration reaction is what causes the phase change. Eutectics or low melting metals are included in the metal category; nonetheless, these materials have not yet received much attention in PCM research [17]. The highest thermal conductivity and excellent energy efficiency (high enthalpy) of inorganic PCMs are their best qualities. Their inflammability and minimal volume change during phase transition are other benefits. The primary disadvantage of inorganic phase change materials (PCMs) is their incongruent melting which causes phase segregation, and as a result, lower performance after each charge–discharge cycle. The weak nucleating capabilities, which cause the liquid phase to supercool before crystallization, are another drawback. Furthermore, inorganic PCMs that have restricted compatibility with building materials are very corrosive and occasionally poisonous, and come at a high cost [59].

4.2.3. Eutectic PCMs

The combination of two or more organic, inorganic, or both PCM substances results in the eutectic mixture. One can create an infinite number of eutectic mixes in this method. This provides the chance to create a material with the desired thermal characteristics like latent heat and phase transition temperature. Thus, the capacity to produce a material with the appropriate phase transition temperature for an application is the primary benefit of eutectic mixtures. When comparing the organic eutectic mixes to inorganic or inorganic/organic combinations, there are a few additional benefits. These include high surface tension and chemical compatibility, long-term stability, and the ability to impregnate into porous support materials due to their high phase change enthalpy. Their primary drawback is their expensive price [60].

4.3. Applications of PCMs

Phase change materials (PCMs) are highly valued in various industries due to their exceptional ability to absorb, store, and release large amounts of latent heat during phase transitions typically from solid to liquid and vice versa. This unique property makes PCMs particularly useful for thermal energy storage and management leading to their widespread application in multiple fields as shown in Figure 7.

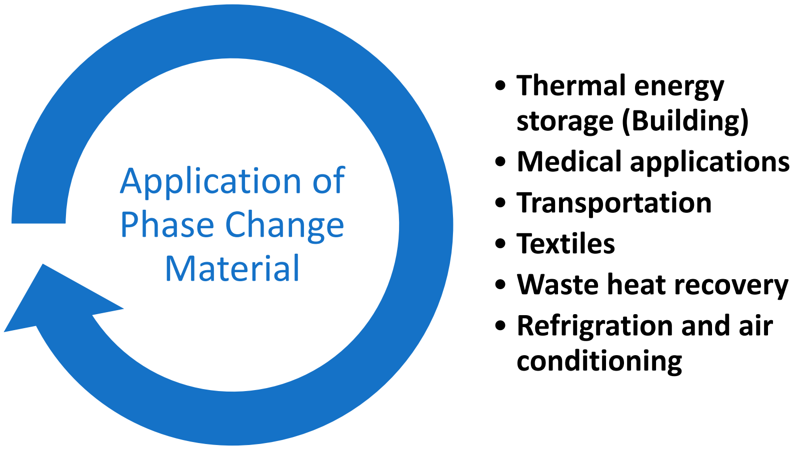

Figure 7. Application of phase change materials.

In the construction industry, PCMs are integrated into building materials to enhance thermal regulation. By embedding PCMs into walls, ceilings, and floors, buildings can achieve more stable indoor temperatures, reducing the reliance on external heating and cooling systems. This integration leads to significant energy savings and improved comfort for occupants. For example, during the day, PCMs absorb excess heat, preventing indoor spaces from becoming too warm. At night, the stored heat is gradually released, maintaining a comfortable temperature even when external temperatures drop [61].

In the renewable energy sector, PCMs play a critical role in solar power systems. Solar energy is inherently intermittent with availability fluctuating based on weather conditions and time of day. PCMs help address this issue by storing excess thermal energy generated during peak sunlight hours [62]. This stored energy can then be used during periods of low solar activity such as nighttime or cloudy days thus ensuring a more reliable and continuous energy supply. This capability not only improves the efficiency of solar power systems but also makes renewable energy a more viable option for widespread use [63].

Temperature-sensitive product transportation is another significant application of PCMs. Products like pharmaceuticals, vaccines, and perishable foods require strict temperature control during transit to maintain their efficacy and safety [64]. PCM-based packaging solutions provide a consistent thermal environment, protecting these products from temperature fluctuations and ensuring they remain within safe temperature ranges. This application is crucial for maintaining the integrity of medical supplies and food safety in global supply chains [65].

In the electronics industry, PCMs are employed to manage the heat generated by high-performance components. Electronic devices, especially those with high processing power, generate significant amounts of heat during operation [66]. PCMs can absorb this excess heat, preventing overheating and improving the reliability and lifespan of electronic components. This application is particularly important in devices like laptops, smartphones, and data centers where effective thermal management is essential for optimal performance and longevity [67].

The textile industry also benefits from PCM technology, particularly in the development of outdoor and athletic wear. Garments incorporating PCMs can regulate body temperature by absorbing excess heat from the body and releasing it when temperatures drop [68]. This thermal regulation enhances comfort and performance for users making PCM-infused clothing ideal for athletes, outdoor enthusiasts, and military personnel who often face varying environmental conditions [69].

In the medical field, PCMs are used in thermal therapy products, such as heating and cooling pads [70]. These pads provide controlled and consistent temperatures for therapeutic purposes, aiding in pain relief, muscle relaxation, and injury recovery. The ability of PCMs to maintain specific temperatures for extended periods makes them ideal for these applications, improving the efficacy of thermal therapies [71].

Furthermore, PCMs are utilized in smart textiles and wearable technology, enhancing the functionality of these products. For instance, smart textiles with embedded PCMs can respond to changes in body temperature, providing dynamic thermal regulation that adapts to the wearer's needs [72]. This innovation is particularly beneficial for health monitoring and comfort in various environmental conditions. This methodology was designed considering the insights from reviewed articles on large-scale applications of PCMs. Challenges like heat transfer efficiency and material compatibility with existing energy-saving systems were prioritized, with a particular focus on real-world implementation scenarios

In summary, the versatile nature of phase change materials makes them indispensable across a wide range of applications. Apart from building walls, PCMs can be effectively used in ceilings, floors, and roofs to enhance thermal regulation. They are also being explored for use in HVAC systems, windows, and as part of thermal storage units in smart building technologies.

From enhancing energy efficiency in buildings and solar power systems to ensuring temperature control in product transportation and improving thermal management in electronics and textiles, PCMs offer significant benefits. Their ability to store and release heat efficiently makes them a key component in advancing technology and improving comfort, safety, and performance in numerous industries. The durability of phase change materials (PCMs) in buildings can be predicted through long-term accelerated aging tests and simulation models that replicate the environmental conditions (e.g., temperature cycles, humidity, UV exposure) to which the PCMs will be subjected over time. Based on existing literature, the durability of PCMs can range from 10 to 30 years depending on the type of PCM used, encapsulation method, and environmental conditions.

Further research should focus on optimizing PCM formulations to enhance their thermal performance, improve their compatibility with building materials, and reduce costs. Additionally, studies should explore the integration of PCMs with other energy-saving technologies, such as smart HVAC systems and renewable energy sources, to maximize their benefits in building applications. Environmental impact assessments and life-cycle analyses will also be important to understand the long-term sustainability of PCM use in buildings.

5. PCM-Incorporated Building Envelope

Phase change material (PCM) applications for thermal energy storage are a thriving field of study these days, with several applications involving temperature control and heat storage. These construction materials have demonstrated great potential for creating an efficient and sustainable constructed environment; using phase change material in the building envelope can provide human comfort and an efficient way to utilize heat [73]. The building envelope is the barrier that envelops the structure and keeps its external walls, windows, floors, and roof separate from the inside environment [74]. As a result, it controls thermal loads, influences the requirement for heating and cooling, and oversees human comfort. The use of PCMs is a ground-breaking method for improving the building's performance by increasing the thermal mass of the structure [75]. In order to maximize the building envelope's heat storage capacity as shown in Figure 8, PCMs are applied in a variety of ways and configurations as part of the building components. There are many intricate factors to take into account in this field of study because of the characteristics of PCMs and the inclusion process [76].

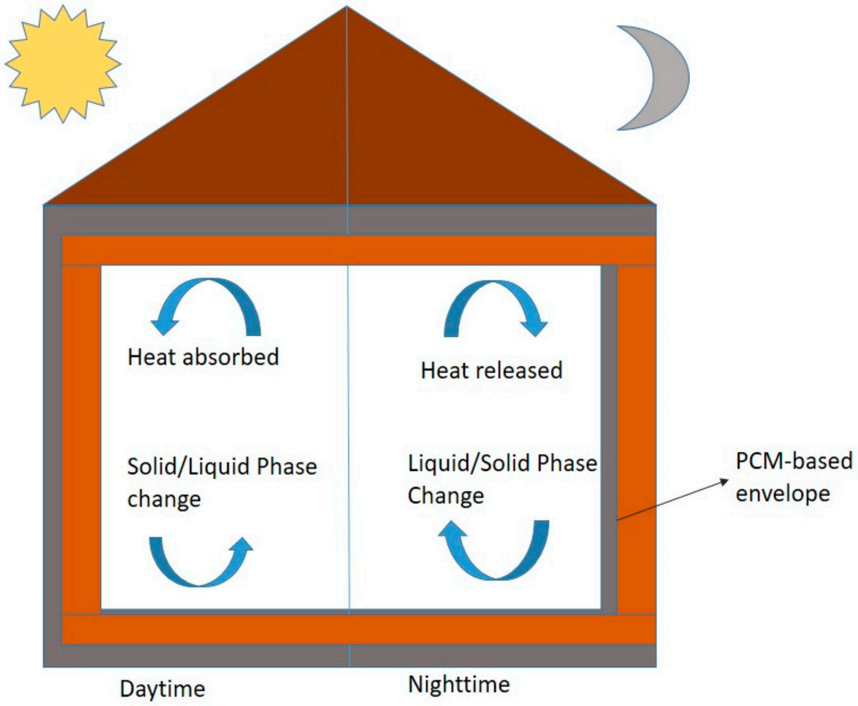

Figure 8. PCM-incorporated building envelope.

Adding PCMs to building envelopes has the following advantages:

- Lower peak temperatures: PCMs have the ability to lower peak temperatures by as much as 4 °C, which can support summertime thermal comfort.
- Enhanced thermal inertia: PCMs have the ability to enhance a building envelope's thermal inertia, hence enhancing comfort and thermal performance.
- Less energy wastage: PCM installation inside walls can cut down on energy wastage [77].

5.1. Selection Criteria of PCMs

As heat storage materials in buildings, PCMs must have acceptable thermo physical, kinetic, chemical, technological, and economic properties. However, it is important to remember that there are very few PCMs that can match all required characteristics as shown in Figure 9. In a practical application, thermo physical parameters such as melting temperature, latent heat of fusion, thermal conductivity, and solid and liquid density are taken into account first. Additional measures will then be taken to compensate for the comparatively poor qualities of the chosen materials such as introducing a nucleating agent to prevent supercooling and employing fin designs or graphite to boost the thermal conductivity of PCMs. When selecting PCMs for integration into buildings, the melting temperature should be matched to the intended operating temperature such as the indoor design temperature and human comfort temperature range. The latent heat of fusion per unit mass should be as high as feasible, allowing for less material to hold the required amount of energy and the utilization of a smaller material container [78]. Heat transfer during fusion or solidification is determined by the thermal conductivity of the solid and liquid PCMs; consequently, high thermal conductivity is advantageous and increases the rate of heat charge and discharge. High specific heat is also required to provide additional sensible heat as PCMs vary in temperature during operation. The density of PCMs is significant, and high density is preferred so that materials occupy less volume. Congruent melting of PCMs is necessary. The ingredients should melt completely resulting in uniform liquid and solid phases. Furthermore, minimal volume variations during phase transition and low vapor pressure at operational temperature are important selection factors for avoiding confinement issues [79].

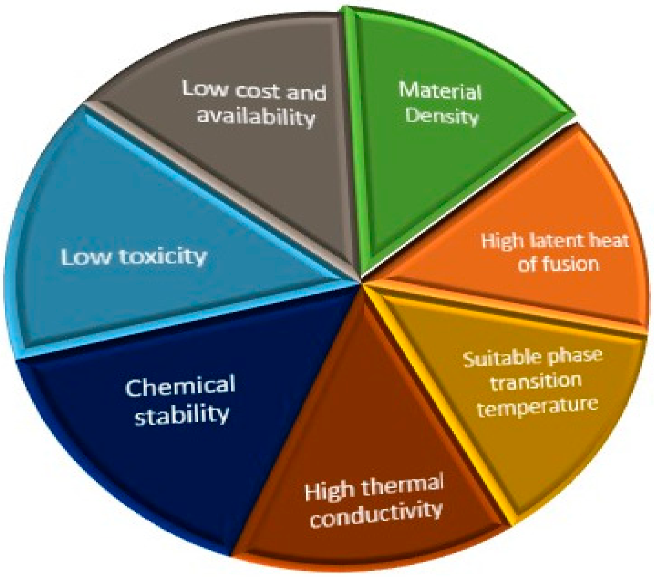

Figure 9. Criteria of PCM selection.

5.2. Various Incorporation Methods of PCMs in Buildings

Phase change materials (PCMs) are utilized in buildings to enhance thermal energy storage, thus improving energy efficiency and indoor thermal comfort [80]. The incorporation of PCMs in building materials can be achieved through several methods as mentioned in Figure 10, each offering distinct advantages and challenges. In summary, the selection of PCMs for building applications must balance thermal performance, material compatibility, and cost-effectiveness. These factors are crucial in determining the viability of PCMs for improving energy efficiency and indoor thermal comfort in real-world scenarios, highlighting the importance of practical considerations in PCM integration.

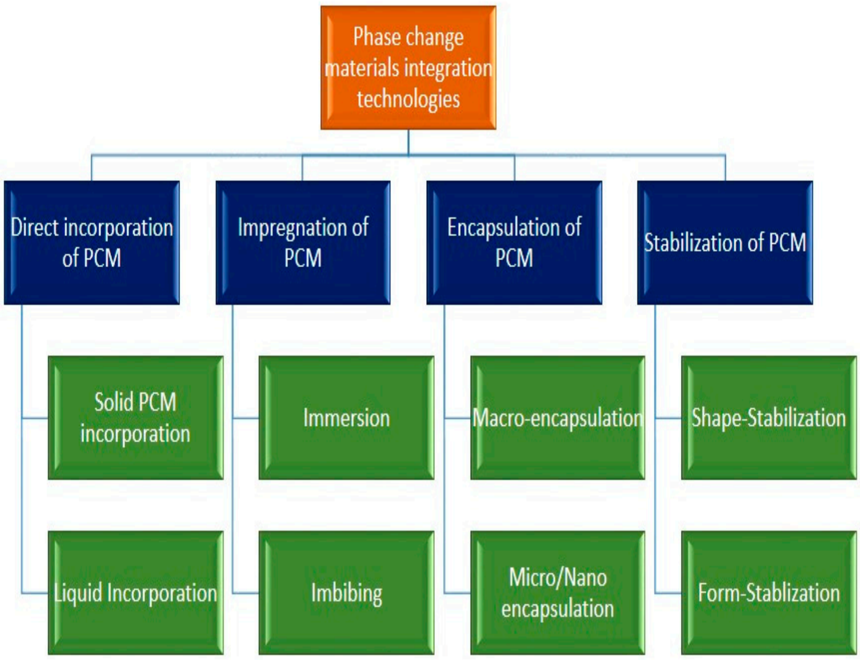

Figure 10. PCMs' integration technologies into building materials.

Below are the primary incorporation methods used in the building sectors:

Direct incorporation:

In this method, a PCM in powder or liquid form is added directly to construction materials such as gypsum mortar, cement mortar, and concrete mixture. This strategy is the simplest and most cost-effective because it requires no prior experience and is simple to implement. On the contrary, the main disadvantage of this approach is the leaking of the PCM during the melting process. This leakage causes incompatibility between materials and increases the risk of fire (for flammable PCMs). Furthermore, this approach affects the mechanical properties of produced materials during high temperatures because the PCM is added to the mixture in a liquid condition thus decreasing the water content ratio [19]. Thus, the incorporation of PCMs offers significant potential for reducing energy consumption in buildings, particularly in climates with high temperature variations. The challenges associated with material stability and cost, however, require careful consideration to ensure long-term feasibility.

Encapsulation (Micro and Macro):

Encapsulation involves enclosing PCMs within a protective shell. This can be achieved at different scales:

- **Microencapsulation:** Encases PCMs in microscopic polymer shells, allowing them to be mixed with building materials without leakage.
- **Macroencapsulation:** Involves larger containers or shells that can be integrated into walls, floors, or ceilings [81].

Advantages:

- Prevents leakage and chemical interaction with the building material.
- Can be easily incorporated into existing structures.

Challenges:

- Increased cost due to encapsulation materials and processes.
- Potential for reduced thermal conductivity due to encapsulating shell.

Shape-stabilized PCMs:

Shape-stabilized PCMs are composed of PCMs dispersed in a supporting matrix (often a polymer or porous material) that prevents the PCM from leaking out even in the liquid phase. The matrix helps retain the PCMs' shape during phase transitions [82].

Advantages:

- Eliminates the risk of leakage.
- Maintains structural integrity during phase transitions.

Challenges:

Complex manufacturing processes. For example, complex procedures in the fabrication of shape-stabilized PCMs require sophisticated procedures, such as encapsulation of PCMs within polymeric matrices or impregnation into porous materials to achieve intricate steps [83].

Potential for reduced thermal storage capacity compared to pure PCMs.

Form-stable PCMs composite:

Form-stable composites involve blending PCMs with supporting materials that provide mechanical strength and prevent leakage. These composites can be shaped into panels, bricks, or other construction elements [17].

Advantages:

- Good mechanical strength and stability. For example, the enhancement of PCM stability and mechanical properties for different applications is a subject of interest to many researchers, such as the polyethylene glycol/graphene oxide composite, in order to ensure reliable performance during repeated thermal cycles [84].
- Versatile application in different construction elements.

Challenges:

- Potential for reduced PCM content, impacting overall thermal storage capacity.
- Complex manufacturing and higher costs.

Immersion:

Immersion involves submerging building materials in liquid PCMs, allowing the PCM to penetrate and fill the porous structure of the material. This method is particularly useful for materials like gypsum board or porous concrete [85].

Advantages:

- Simple method for impregnating porous materials.
- Enhances thermal storage capacity of the material.

Challenges:

- Limited to porous materials.
- Potential for uneven distribution of PCMs within the material.

The incorporation of PCMs in building materials significantly enhances thermal energy storage, contributing to energy-efficient buildings. Each method of incorporation, direct incorporation, encapsulation, shape-stabilization, form-stable composites, and immersion, offers unique benefits and challenges. The selection of an appropriate method depends on factors such as the type of building material, desired thermal properties, and cost considerations [86]. Phase change materials (PCMs) can be effectively combined with materials like concrete, plasterboard, insulation, bricks, composite panels, and fibrous materials in building walls to enhance thermal performance. PCMs help regulate indoor temperatures by absorbing and releasing heat, which reduces the need for heating and cooling. For example, PCM-embedded concrete or bricks increase thermal mass, while PCMs in drywall or insulation enhance energy efficiency by storing heat during the day and releasing it at night. This integration improves comfort and energy savings in buildings by maintaining more stable temperatures.

5.3. Parameters for PCMs' Performance in Buildings

The performance of phase change materials (PCMs) in buildings is influenced by several key parameters. Understanding these parameters is crucial for optimizing the use of PCMs for thermal energy storage and enhancing energy efficiency in building applications. The primary parameters include the melting temperature of PCMs, the thickness of PCM layers, and the location of PCMs within the building structure [87].

(a) Melting Temperature of PCMs

The melting temperature of PCMs is one of the most critical parameters determining their suitability for specific applications. The ideal melting temperature should be within the range of the desired indoor thermal comfort levels, typically between 20 °C and 26 °C, for residential and commercial buildings. This ensures that the PCM can absorb and release heat efficiently during daily temperature fluctuations. The **melting temperature** refers to the point at which a phase change material (PCM) transitions from a solid to a liquid state, a critical factor that influences the material's ability to store and release thermal energy. The **operating temperature** indicates the range in which the PCM remains effective, ensuring that it operates efficiently within the typical temperature conditions of the building environment. The **indoor design temperature** represents the target temperature that buildings aim to maintain for energy efficiency and occupant comfort, which is determined based on the building's use and the climate. Finally, the **temperature range for human comfort,** generally between 20 °C and 24 °C (68 °F and 75 °F), is a key factor when selecting PCMs, as maintaining indoor temperatures within this range can reduce the need for active heating or cooling systems. These temperatures play a significant role in determining the suitability and effectiveness of PCMs in building applications, directly influencing energy efficiency and thermal comfort.

Factors to consider:
Climate and seasonal variations: The melting temperature must align with the local climate conditions to maximize the efficiency of thermal energy storage.
Building usage: Different types of buildings (e.g., residential, commercial, industrial) have varying thermal comfort requirements influencing the choice of PCM with an appropriate melting temperature [88].

(b) Thickness of PCMs

The thickness of the PCM layer is crucial for determining the thermal storage capacity and the rate of heat transfer. Thicker PCM layers can store more energy but they may also slow down the rate of heat absorption and release due to increased thermal resistance [89].

Factors to consider:
Thermal conductivity: The material in which the PCM is encapsulated or incorporated can affect the optimal thickness. Materials with higher thermal conductivity allow for better heat transfer.
Space constraints: Building designs often have space limitations that can restrict the thickness of PCM layers that can be practically applied.
Cost-effectiveness: Thicker layers of PCM can be more expensive so a balance between performance and cost must be achieved.

The location of PCMs within the building structure significantly impacts their effectiveness in regulating indoor temperatures. PCMs can be incorporated in walls, ceilings, floors, or as part of the building's HVAC systems [90].

(c) Location of PCMs

The location of PCMs within the building structure significantly impacts their effectiveness in regulating indoor temperatures. PCMs can be incorporated in walls, ceilings, floors, or as part of the building's HVAC systems [91].

Factors to consider:
Thermal loads: Placing PCMs in areas with high thermal loads (external walls, roofs) can enhance their efficiency in absorbing excess heat during the day and releasing it at night.
Integration with building systems: PCMs can be integrated with radiant heating systems, passive solar designs, or HVAC systems to maximize energy savings.
Occupant comfort: The placement should ensure that the thermal regulation provided by PCMs contributes to the comfort of building occupants without causing unwanted thermal variations.

Optimizing the performance of PCMs in buildings requires careful consideration of their melting temperature, thickness, and location within the building. By tailoring these parameters to the specific conditions and requirements of the building, PCMs can significantly contribute to improved energy efficiency and enhanced thermal comfort. Further research and practical applications will continue to refine these parameters, ensuring that PCMs become a standard component of sustainable building design [92].

5.4. Modeling of PCM Incorporated Building Envelope

Phase change materials (PCMs) are increasingly being integrated into building envelopes to enhance thermal performance and energy efficiency. PCMs leverage their ability to absorb, store, and release significant amounts of thermal energy during phase transitions (e.g., from solid to liquid and vice versa), which occurs at nearly constant temperatures. This property makes PCMs particularly useful in maintaining indoor thermal comfort and reducing the energy demand for heating and cooling systems in buildings [93].

Key Concepts in PCM Modeling for Building Envelopes

(a) Thermal Properties and Phase Change Behavior

- **Latent Heat Storage:** PCMs can store large amounts of heat during the phase change process. When the ambient temperature rises above the PCM's melting point, the material absorbs heat and melts. Conversely, when the temperature drops, the PCM solidifies and releases the stored heat [94].

- **Thermal Conductivity:** The efficiency of heat transfer through PCMs is a critical factor in their performance. Higher thermal conductivity facilitates quicker energy absorption and release which can be advantageous in dynamic thermal environments [95].
- **Specific Heat Capacity:** This property measures the amount of heat required to change the temperature of the PCM. A higher specific heat capacity increases the thermal inertia of the building envelope, stabilizing indoor temperatures against external fluctuations [96].

(b) Numerical Modeling Approaches

- **Finite Difference Method (FDM):** FDM is used to discretize the heat transfer equations governing PCM behavior. By breaking down the building envelope into a grid, FDM can simulate the transient heat flow and phase transitions within PCMs [97].
- **Finite Element Method (FEM):** FEM divides the building envelope into smaller, finite elements and solves the heat transfer equations iteratively. This method is particularly useful for complex geometries and heterogeneous material properties [98].
- **Computational Fluid Dynamics (CFD):** CFD simulations provide detailed analysis of airflow and thermal distribution in spaces where PCMs are used. CFD models can capture the interaction between the PCM and the surrounding air, offering insights into thermal comfort levels and energy savings [99].

(c) Simulation Tools

- **Energy Plus:** Developed by the U.S. Department of Energy, Energy Plus is a robust building energy simulation tool that incorporates PCM models. It can simulate the thermal performance of buildings with PCM-enhanced envelopes, predicting energy consumption and thermal comfort under various climatic conditions [100].
- **TRNSYS:** A transient systems simulation program widely used for modeling energy systems in buildings. TRNSYS includes components for PCM modeling, enabling detailed analysis of their impact on building energy performance and indoor climate [101].

5.5. Practical Implementation and Case Studies

In recent years, the integration of phase change materials (PCMs) into building envelopes has garnered significant interest for its potential to enhance thermal comfort and reduce energy consumption [3,102]. Several case studies illustrate the effectiveness of this approach across various climates and building types as shown in Table 3.

A study conducted by Ahangari and Maerefat (2019) explored an innovative PCM system that significantly improved thermal comfort and reduced energy demand in buildings under different climate conditions. Their findings indicated that PCM integration in building envelopes could effectively manage indoor temperatures, reducing reliance on HVAC systems, and thereby lower energy consumption and associated costs [103]. In another comprehensive analysis, Al-Rashed et al. (2022) evaluated the thermal performance of different PCM types (RT-31, RT-35, and RT-42) integrated into building envelopes in Kuwait's climate. Their numerical study demonstrated that higher PCM melting temperatures correlated with better thermal performance, highlighting the importance of selecting appropriate PCM types based on regional climatic conditions. Further research emphasized the importance of optimizing PCM layer thickness and placement within building envelopes. They found that varying the thickness and position of PCM layers could substantially affect the thermal inertia and overall energy efficiency of buildings, providing a roadmap for more effective PCM applications [104]. Incorporating PCMs into building envelopes has also proven beneficial in retrofitting projects. Cascone et al. (2018) optimized PCM-enhanced opaque building envelope components for office buildings in Mediterranean climates. Their optimization analysis revealed that PCM integration could significantly enhance the energy efficiency of retrofitted buildings, making them more sustainable and cost-effective [105].

A notable study published by Liu et al. (2021) focused on the dynamic modeling and performance evaluation of PCM-enhanced building envelopes in Danish office buildings. Their research identified an optimal PCM with a melting temperature of 24 °C and latent heat of 219 kJ/kg, which was shown to effectively reduce energy consumption for heating and cooling across different seasons [87]. Rathore and Shukla (2020) conducted experiments using macroencapsulated PCM in building walls. They observed that PCM integration significantly reduces indoor temperature fluctuations and enhances energy savings, particularly during peak load periods [106]. Halimov et al. (2019) explored the integration of latent heat storage models specifically within building envelopes. By incorporating phase change materials (PCMs) into the envelope structures, they aimed to improve thermal management and energy efficiency in buildings. The research highlighted that PCM-enhanced envelopes effectively mitigate temperature fluctuations by storing and releasing thermal energy during phase transitions, thereby reducing the overall demand for heating and cooling energy. This enhancement not only lowers primary energy consumption but also translates into reduced operational costs and diminished CO_2 emissions, aligning with sustainable building principles. The findings underscored PCMs' role in optimizing building envelope performance, making significant strides towards environmentally friendly and economically viable construction practices [107]. Souayfane et al. (2016) reviewed the applications of PCM for passive cooling in building envelopes, noting that PCMs can help maintain indoor thermal comfort without the need for active cooling systems, thereby saving energy and enhancing sustainability [108]. The authors propose to perform experimental studies focusing on the thermal conductivity, phase transition temperatures, latent heat capacity, and long-term stability of PCMs when incorporated into building materials. These studies will involve testing different encapsulation techniques, analyzing the thermal performance of PCM-enhanced building components, and conducting accelerated aging tests to evaluate the durability of PCMs under various environmental conditions.

Table 3. Highlighting the PCM types used, key findings.

Study	PCM Types/Incorporation	Key Findings
Ahangari and Maerefat (2019) [103]	Innovative PCM system	Improved thermal comfort, reduced energy demand, effective indoor temperature management, lowered HVAC reliance
Al-Rashed et al. (2022) [109]	RT-31, RT-35, RT-42	Higher melting temperatures correlated with better thermal performance, importance of PCM type selection based on climate
Cascone et al. (2018) [105]	PCM-enhanced opaque building envelope components	Significant enhancement of energy efficiency in retrofitted buildings
Liu et al. (2021) [87]	PCM with melting temperature of 24 °C and latent heat of 219 kJ/kg	Reduced energy consumption for heating and cooling across seasons
Rathore and Shukla (2020) [106]	Macroencapsulated PCM	Significant reduction in indoor temperature fluctuations, enhanced energy savings during peak load periods
Halimov et al. (2019) [107]	Latent heat storage model	Reduced primary energy consumption, operational costs, and CO_2 emissions, contributing to sustainable practices
Souayfane et al. (2016) [108]	PCM for passive cooling	Helped maintain indoor thermal comfort without active cooling systems, saving energy and enhancing sustainability
Tyagi et al. (2020) [110]	Bio-based PCMs	Improved energy efficiency, reduced environmental impact, biodegradable, cost-effective for sustainable building solutions

Table 3. *Cont.*

Study	PCM Types/Incorporation	Key Findings
Zhu et al. (2021) [111]	Microencapsulated PCM in concrete	Enhanced thermal mass and energy savings in buildings, improved durability of building materials
Zhang et al. (2022) [112]	Paraffin-based PCM in roof insulation	Reduced indoor temperature peaks, contributing to significant energy savings in hot climates
Sari and Karaipekli (2017) [113]	Nanoparticle-enhanced PCMs	Enhanced heat transfer, improved thermal energy storage capacity, reduced material degradation over multiple cycles
Huang et al. (2021) [114]	Organic PCMs incorporated into gypsum boards	Improved thermal regulation, better indoor air quality, and significant reduction in heating/cooling loads
Fan et al. (2017) [115]	Composite PCM with graphite	Improved thermal conductivity, faster energy storage and release, better temperature regulation in buildings

These case studies collectively underscore the potential of PCM-enhanced building envelopes in promoting energy efficiency and thermal comfort across various building types and climatic conditions. They provide valuable insights into the selection, optimization, and implementation of PCMs, contributing significantly to the field of sustainable building design.

In conclusion, the modeling of PCM-incorporated building envelopes is a sophisticated process that leverages advanced simulation tools and numerical methods to predict and optimize the thermal performance of buildings. By integrating PCMs, buildings can achieve enhanced energy efficiency, improved indoor comfort, and reduced environmental impact, making them a valuable component in sustainable construction practices.

5.6. Assessment of PCM-Incorporated Buildings

Assessing buildings that incorporate phase change materials (PCMs) involves a comprehensive evaluation of their thermal performance, energy efficiency, cost-effectiveness, and overall sustainability. The sustainability of PCM-incorporated buildings has been extensively studied, demonstrating their potential to reduce energy consumption and CO_2 emissions while promoting thermal comfort. Numerous studies highlight the role of PCMs in achieving long-term energy savings by reducing reliance on active heating and cooling systems The following is a detailed exploration based on available literature:

5.6.1. Thermal Performance Assessment

The thermal performance of PCM-incorporated buildings is typically evaluated through experimental measurements and computer simulations. These assessments involve monitoring indoor temperatures, energy consumption, and thermal comfort parameters over an extended period [116]. Studies often employ tools like building energy simulation software (e.g., EnergyPlus 24.2.0, TRNSYS version 18) to model the dynamic behavior of PCM-integrated building systems under varying climatic conditions. Thermal conductivity, heat capacity, and melting/freezing characteristics of the PCM are crucial factors influencing the thermal performance and effectiveness of the building envelope [117].

5.6.2. Energy Efficiency Analysis

Assessing the energy efficiency of PCM-incorporated buildings involves comparing their energy consumption profiles with conventional buildings without PCM integration [118]. Energy modeling techniques help quantify the reduction in heating and cooling loads attributed to PCM usage thus estimating potential energy savings [119]. Life-cycle cost analysis considers upfront costs of PCM materials, installation, and maintenance against long-term energy savings to determine economic viability [16].

5.6.3. Indoor Comfort Evaluation

PCM integration aims to improve indoor comfort by reducing temperature fluctuations and maintaining stable indoor conditions. Assessments involve subjective evaluations through occupant surveys, as well as objective measurements of thermal comfort indices such as the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) [119]. PCM-incorporated buildings often exhibit enhanced thermal inertia, buffering external temperature changes and enhancing occupant comfort [120].

5.6.4. Sustainability Assessment

Sustainability assessments encompass environmental impacts, resource efficiency, and resilience of PCM-incorporated buildings. Life-cycle assessment (LCA) methodologies evaluate the environmental footprint of PCMs by considering their production, use, and end-of-life disposal [121]. Sustainable building certification systems like LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method) recognize PCM integration as a strategy for achieving energy efficiency and environmental sustainability [122].

These insights serve as a solid foundation for further research and practical implementation, fostering the adoption of PCM technologies to enhance building performance and sustainability in diverse climatic contexts.

6. Conclusions

The conclusion of this study highlights the significant potential of phase change materials (PCMs) in enhancing the energy efficiency and thermal comfort of buildings. The potential of phase change materials (PCMs) in building insulation is significant in terms of energy efficiency and thermal comfort. This study demonstrates that PCMs effectively regulate indoor temperatures through the absorption and re-release of heat during their phase change, leading to substantial reductions in heating and cooling loads, which in turn decrease energy use and operational costs for buildings. Furthermore, the use of PCMs aligns with sustainability goals by minimizing the environmental impacts typically associated with conventional heating and cooling systems. This paper specifically examined the incorporation of PCMs into building insulation systems to enhance thermal performance, analyzing various types of PCMs, their properties, and integration methods to validate their effectiveness in maintaining indoor temperatures. Through experimental and simulation studies conducted under diverse climatic conditions, the thermal behavior of PCM-enhanced building envelopes was assessed, complemented by a cost–benefit analysis and environmental assessment to evaluate the economic viability and sustainability implications of using PCMs in buildings.

Despite these promising findings, several areas require further investigation to optimize the formulation variables, integration methods, and cost factors that currently hinder the widespread adoption of PCM technology in the construction sector. Future research should focus on optimizing PCM formulations by investigating ideal compositions and properties to enhance performance under varying environmental conditions. Additionally, innovative methods for integrating PCMs into different building materials and construction processes should be developed to maximize effectiveness. Long-term field studies are also needed to assess the real-world performance of PCM-enhanced buildings over time, including durability and maintenance considerations. Exploring funding and incentive programs could promote the adoption of PCMs in building projects, particularly in regions with extreme climates. Lastly, expanding environmental assessments to include life-cycle analyses that account for the entire lifespan of PCM products, from production to disposal, would provide a comprehensive understanding of their impact. By addressing these recommendations, future studies can contribute to the broader acceptance and application of phase change materials in the building sector, ultimately fostering energy-efficient and sustainable construction practices.

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