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Review

Towards Passive Building Thermal Regulation: A State-of-the-Art Review on Recent Progress of PCM-Integrated Building Envelopes

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Abstract: The building envelope serves as a barrier against climatic conditions and as insulation to prevent energy waste within buildings. As global energy shortages become more pressing, the requirements for building envelopes are becoming increasingly stringent. Among the available technologies, phase change materials (PCMs) stand out for their high latent thermal energy storage and temperature stabilization capabilities. This paper reviews the recent advancements in PCM technology for building envelopes, starting with an overview of organic, inorganic, and eutectic PCMs, along with their respective advantages and disadvantages. The paper explores various incorporation methods such as shape stabilization, macroencapsulation, micro/nanoencapsulation, and solid–solid transition techniques. The integration of PCMs enhances thermal inertia, reduces thermal fluctuations, and delays heat peaks, presenting several multifunctional benefits. However, challenges such as fire hazards, potential toxicity, pollution, reduced mechanical performance, and higher initial costs persist. In light of these challenges, criteria for PCM integration in building applications are introduced. Additionally, the paper reviews recent hybrid technologies that combine PCMs with other novel technologies for building envelopes, including radiant temperature regulation systems, thermochromic windows, passive radiative cooling coatings, and others. It is shown that these PCM-integrated hybrid technologies significantly improve energy savings and indoor comfort. PCMs offer substantial potential for modern green building strategies and have further applications in other building contexts. Finally, the paper provides future prospects for studies in this field, aiming towards a green and energy-saving future.

Keywords: phase change material; building envelope; indoor comfort; zero carbon building

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1. Introduction

The evolution of building envelopes has closely paralleled the progression of human civilization, historically functioning as protective barriers against harsh climatic conditions. The energy crisis of 1973 acted as a catalyst, significantly amplifying the focus on research related to building envelopes, which are responsible for approximately 36% of energy consumption in human activities [1]. The concept of the "building envelope" encompasses a diverse range of components, including opaque envelopes, structural materials, insulation, and glazing [2,3]. Numerous studies have investigated various materials suitable for building envelopes across different climatic conditions, extending from traditional materials like wood and earth [4–6] to cutting-edge hybrid polymers that boast enhanced properties such as superior thermal insulation, radiative sky cooling, fire resistance, and radiant cooling capabilities [7–10].

Within this spectrum, phase change materials (PCMs) have been recognized as particularly promising for their passive thermal regulation properties when integrated into building envelopes, owing to their latent thermal energy storage (LTES) capabilities. Unlike conventional sensible heat storage methods, PCMs can maintain a relatively stable temperature range while they absorb and release heat during their phase transitions, typically from solid to liquid, as illustrated in Figure 1. This distinctive capability enables PCMs to act as buffers to mitigate temperature fluctuations or as thermal energy reservoirs that can store surplus heat or cooling energy for subsequent use. Such dynamic processes significantly enhance a building's thermal inertia, thereby reducing the reliance on heating and cooling systems and consequently lowering the building's carbon footprint. Recent literature has extensively discussed these aspects [11–15]. For instance, Rathore et al. [16] provided a comprehensive summary concerning the integration techniques, performance evaluations, and underlying principles of PCMs in building materials. Li et al. [17] explored the thermal and optical performance of PCMs specifically for glazing applications, acknowledging the substantial potential for energy savings but also noting challenges such as diminished heat gain in colder regions, scattering effects caused by the porous structures of solid-state PCMs, and the ongoing need for refined models to simulate dynamic processes. Al-Yasiri and Szabó [18] highlighted a research gap in PCM applications for extreme climates and emphasized the necessity for extended durability testing. They also noted that while the low thermal conductivity of PCMs provides excellent insulation, it simultaneously impedes the efficiency of energy charge–discharge cycles, impacting the overall energy storage capacity.

Despite these challenges, the domain of PCMs in building envelopes is rapidly expanding, with innovative technologies emerging at an unprecedented rate. For example, the transformation of PCMs from solid–liquid to solid–solid states through chemical modifications is being investigated as a viable approach to stabilize their shape and prevent leakage [19]. Moreover, the integration of PCMs with other functional materials such as radiative cooling agents, photothermal, and photocatalytic materials is enhancing the multifunctional capabilities of PCM composites beyond simple thermal energy storage [20–23]. In light of these advancements, it is essential to continually update and disseminate the latest research findings to further promote the application of PCMs in building envelopes, steering toward a zero-carbon future.

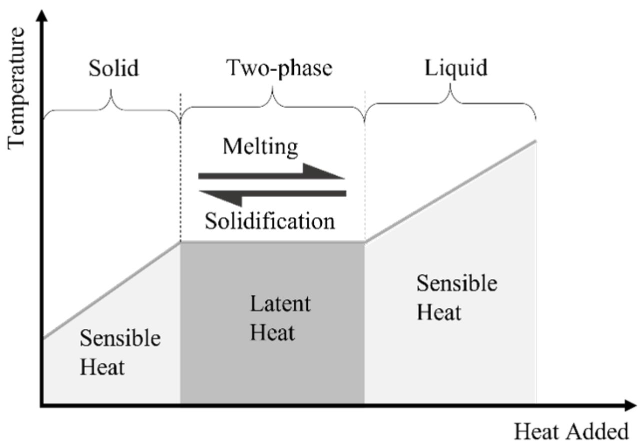

Figure 1. Temperature–enthalpy diagram of a PCM.

This paper begins by introducing different types of PCMs, emphasizing their distinct properties and functionalities. Special attention is given to recent advances in eutectic alloys with room temperature melting points, which are often overlooked in many PCM review articles. Examples of these PCMs are discussed, particularly those with appropriate phase change temperatures for building applications. We also explore PCM incorporation methods and anti-leakage techniques, including solid–solid PCMs (SSPCMs) that enhance the durability and reliability of PCMs in building contexts. Unlike existing review works on traditional building envelopes, this paper focuses on the innovative integration of PCMs with other energy-saving technologies such as radiant temperature control and radiative cooling. It addresses both successes and challenges, offering insights into future research directions. The review aims to present a comprehensive view of the state of the art in PCM technology, underscoring its potential to significantly impact energy conservation strategies in multifunctional building envelopes.

2. Features and Classification of PCMs

PCMs used in building envelopes must satisfy a range of critical criteria, including an appropriate phase-transition range, high latent heat capacity, efficient heat transfer capabilities, stable phase equilibrium, high density, minimal volume change during phase changes, low vapor pressure to circumvent containment issues, resistance to supercooling, a rapid crystallization rate, long-term chemical stability, compatibility with construction materials, non-toxicity, safety from fire hazards, and economic viability. The energy storage capacity of a PCM is determined by a combination of its sensible and latent thermal energy storage capacities. However, despite their potential, PCMs inherently exhibit some limitations such as tendencies toward supercooling, phase separation, leakage, and low thermal conductivity. These challenges necessitate careful selection and engineering to optimize the performance of PCMs in practical applications.

Assuming the heat capacity C_p is constant, the sensible heat Q_s of an ideal PCM with mass m is given by

$$Q_s = mC_p(T_2 - T_1) \tag{1}$$

where T_1 and T_2 are the start and end temperatures during the heat storage process. In contrast, when a phase change is completed, the total stored thermal energy by the PCM is calculated by

$$Q = mC_p(T_2 - T_1) + H \tag{2}$$

where H signifies the latent heat of the PCM. It is important to note that most commercialized PCMs do not exhibit a fixed melting point as one might assume. Instead, due to material impurities, they typically display a melting range as indicated in Figure 1 [24–26]. Figure 2 illustrates different types of differential scanning calorimetry (DSC) results, which reveal various melting patterns. For instance, paraffin wax is a mixture of n-alkanes, and the presence of different types of alkanes and variations in the lengths of molecular chains not only results in a non-fixed melting temperature but also contributes to solid–solid phase changes due to alterations in crystalline structures [27,28].

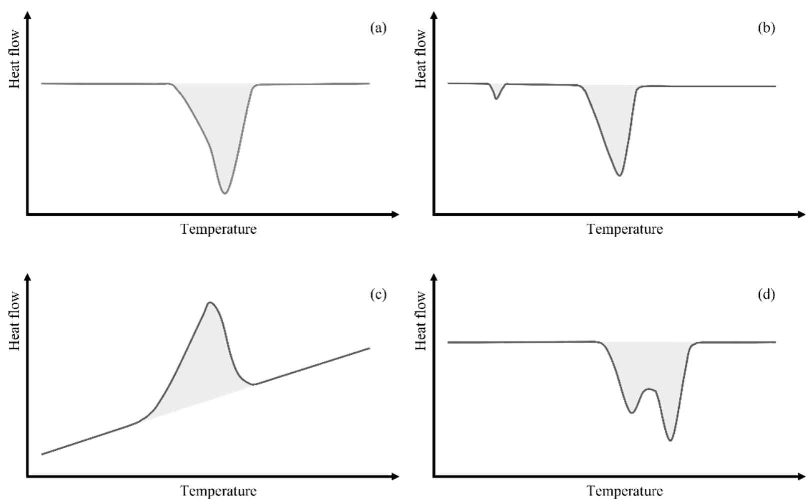

Figure 2. DSC patterns of different PCMs with (**a**) single-phase change process; (**b**) more than one phase change process; (**c**) temperature-dependent heat capacity; (**d**) merged phase change processes.

PCMs can be categorized based on their chemical composition into three types, organic, inorganic, and eutectic, each demonstrating unique properties that make them suitable for integration into building envelopes. Each type possesses advantages over others in different aspects as shown in Figure 3. Organic PCMs are particularly valued for their congruent melting behavior, minimal supercooling, excellent compatibility with construction materials, and stability, making them a preferred choice for many applications. In contrast, inorganic PCMs are chosen for their high latent heat capacity and higher thermal conductivity, although they pose challenges such as phase separation and potential corrosion, which can limit their usability. Eutectic PCMs, which are combinations of different types of PCMs, are engineered to combine the advantageous properties of the composed materials. This hybrid approach allows for the customization of melting points and latent heat capacities to meet specific requirements, thus broadening their applicability in diverse scenarios [15,29].

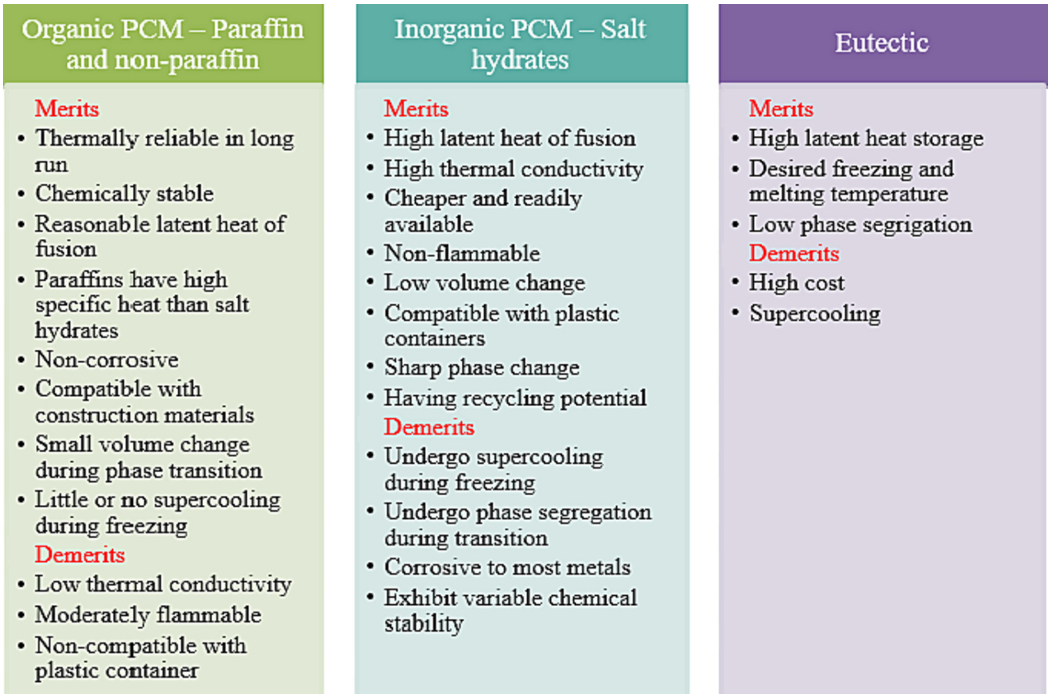

Figure 3. Merits and demerits of different types of PCMs. Figures reprinted from [30].

2.1. Organic PCMs

Organic PCMs are generally divided into two main categories: paraffins and non-paraffins. Paraffins, which are mixtures of n-alkanes, exhibit a range of melting points that increase with the length of the molecule's chain, making them highly versatile for use in building envelopes [31]. They are characterized by multiple allotropic forms, which vary in physical characteristics and crystal structures [32]. These allotropes can transition between states in response to temperature changes, with the conversion being entirely reversible. The advantages of using paraffins for heat storage are manifold: they offer a high latent heat of fusion, minimal supercooling, low vapor pressure in their liquid state, chemical inertness, long-term stability, self-nucleating properties, and an absence of phase segregation [33,34]. Additionally, as byproducts of the oil industry, paraffins are readily available at reasonable costs, enhancing their economic viability [35,36].

Non-paraffins encompass a diverse group that includes bio-based PCMs (BPCMs) such as fatty acids and alcohols, and polymer PCMs represented by polyethylene glycol (PEG). BPCMs are typically derived from bioproducts like plant and animal fats [37,38]. They are characterized by their recyclability, degradability, and lower melting points, making them more eco-friendly and suitable for low-temperature applications [39,40]. Furthermore, BPCMs exhibit high surface tension in their liquid state, which helps confine the material within the host matrix, thereby addressing leakage concerns [41]. PEG, on the other hand, offers benefits including ease of synthesis, non-toxicity, biocompatibility, low cost, flexibility, compatibility with various additives, and the potential for environmentally friendly fabrication processes [42].

Despite their numerous advantages, organic PCMs commonly suffer from low thermal conductivity, necessitating the use of conductivity-enhancing techniques for effective application. Additionally, the potential fire hazards associated with organic PCMs should not be underestimated. Recent studies, such as those by Weng et al. [43], have explored the integration of fire retardants to mitigate the flammability risks associated with these materials. The ongoing development and refinement of organic PCMs for use in building envelopes continue to promise further optimizations in energy efficiency and sustainability within the construction sector. Table 1 provides the thermophysical properties (melting point/range T_m, average thermal conductivity k, and latent heat H) of some representative organic PCMs applicable to building envelopes.

Table 1. Thermophysical properties of some organic PCM candidates for building envelopes.

PCM	T_m (°C)	H (kJ/kg)	k (W/(m·K))
n-Octadecane [44]	24.90	204.91	0.192
Tetradecane [45]	5.8	227	-
Pentadecane [45]	9.9	206	-
Hexadecane [45]	18.1	236	-
n-Eicosane [46]	36.58	248.5	0.25
Paraffin [47]	21.7–22.7	161.6	0.21
Paraffin [25]	27–29	245	-
Paraffin [48]	27–33	165	0.13
Paraffin [49]	44	174.12	-
Paraffin [50]	70	173.03	0.197
Lauric acid [51]	43.93	178.11	-
Myristic acid [51]	54.28	191.27	-
Palmitic acid [51]	62.73	206.16	-
Stearic acid [51]	69.62	217.62	-
PEG [52]	21.3–31.5	187.03	-
PEG [53]	18.51	118.22	-
Lauryl alcohol [54]	24	217	0.221
Oleic acid [55]	5–7	140	-
Butyl stearate [55]	21	88	-
Isopropyl palmitate [55]	11	117	-

2.2. Inorganic PCMs

Inorganic PCMs include salt hydrates, molten salts, and metallic PCMs (encompassing metals and eutectic alloys). These inorganic PCMs generally exhibit higher energy storage capacities and superior thermal conductivities compared to their organic counterparts [56]. Notably, the melting points of some inorganic PCMs, particularly molten salts, often exceed 200 °C, which makes them less suitable for building envelope applications due to the high operational temperatures required. Table 2 provides the thermophysical properties of some inorganic PCM candidates. Decades ago, metallic PCMs were often excluded from building applications due to their excessively high melting temperatures [57]. However, advancements in materials science have facilitated the discovery of low-temperature metals and alloys, sparking renewed interest in these materials for their significantly higher thermal conductivities compared to other PCM types.

Salt hydrates, composed of ionic compounds incorporating water molecules within their crystal lattice, offer high energy storage density at a relatively low cost [58]. They are often preferred over organic PCMs due to their non-flammable and odorless properties, which enhance safety and comfort in inhabited spaces. Nevertheless, salt hydrates face several challenges that limit their broader application. One major issue is incongruent melting, where the solid phase, typically a lower hydrate of the same salt, separates and settles at the bottom of the container, leading to chemical instability and irreversible loss of thermal storage capability [32]. Additionally, supercooling in salt hydrates can delay heat release, which is a disadvantage in many building applications despite its potential benefits for long-term energy storage [59,60]. To address these issues, the addition of nucleating and thickening agents is a common practice [61–63]. The corrosive nature of salt hydrates also poses significant challenges as they can degrade metals, especially when encapsulated in metal containers. Although the thermal conductivity of salt hydrates is higher than that of organic PCMs—for example, the thermal conductivity of solid $CaCl_2 \cdot 6H_2O$ is 1.08 W/(m·K), which is four times higher than that of OP42E paraffin [64]—the overall thermal energy storage efficiency remains low, necessitating further heat transfer enhancement techniques.

Metallic PCMs for building envelopes, including low melting point metals and metal eutectics, are increasingly considered for efficient thermal energy storage due to their excellent thermal conductivity. This intrinsic property eliminates the need for additional heat transfer enhancement, making metallic PCMs highly efficient. They also tend to have higher overall energy densities and offer stability advantages compared to salt hydrates [65]. However, metallic PCMs face challenges such as containment issues and high corrosivity in their liquid state, which can compromise safety and reduce system longevity [66]. Despite these challenges, ongoing developments in metallic PCMs hold promise for advancing high-temperature energy storage solutions, which are crucial for the next generation of energy-efficient buildings.

Table 2. Thermophysical properties of some inorganic PCM candidates for building envelopes.

PCM	Classification	T_m (°C)	H (kJ/kg)	k (W/(m·K))
$Na_2SO_4 \cdot 10H_2O$ [67]	Salt hydrate	32.24	139.9	0.34
$CaCl_2 \cdot 6H_2O$ [68]	Salt hydrate	29.6	212	0.82
$Na_2HPO_4 \cdot 12H_2O$ [69]	Salt hydrate	35.1	209.5	1.25
$CH_3COONa \cdot 3H_2O$ [70]	Salt hydrate	58.3	286.3	-
$Na_2CO_3 \cdot 10H_2O$ [71]	Salt hydrate	33	247	0.6
$FeCl_3 \cdot 6H_2O$ [71]	Salt hydrate	37	223	-
$Mg(NO_3)_2 \cdot 6H_2O$ [72]	Salt hydrate	91.5	146	0.4
$Zn(NO_3)_2 \cdot 6H_2O$ [73]	Salt hydrate	34.6	140	-
Gallium [74]	Metal	29.78	80.16	32
Bi-Sn-In [75]	Alloy	60.9	29.18	16.4
Bi-21In-18Pb-12Sn [76]	Alloy	56.83	28.98	32.2∼10.6
Ga-13.5Sn [76]	Alloy	20	78.29	30
Bi–Cd–Sn–Pb [77]	Alloy	70	32.9	18
$In_{51}Bi_{32.5}Sn_{16.5}$ [78]	Alloy	61.53	28.98	-
In-Sn-Bi [79]	Alloy	54.9	25	16.85
50Bi/25Pb/13Sn/12Cd [80]	Alloy	73	30.6	23

2.3. Eutectic PCMs

Eutectic PCMs are homogeneous mixtures composed of two or more different PCMs, which can be combinations of organic–organic, inorganic–inorganic, or organic–inorganic materials. The primary objective in synthesizing eutectic PCMs is to moderate their melting temperatures, typically achieving a melting point that is lower than that of each individual component, thereby aligning with desired operational temperatures [81]. The melting point of eutectic PCMs can be determined using the Schroeder equation by analyzing the phase diagram of the binary eutectic system [82]. As illustrated in Figure 4a, the phase diagram features two solubility lines, labeled "a" and "a′", which converge at an equilibrium state known as the eutectic point, denoted as $X_{1,e}$. This point marks the highest degree of melting point depression achievable in the system, allowing for the precise quantification of the melting points of eutectic PCMs by understanding the thermal behavior of the constituent PCMs.

However, one issue with eutectic PCMs is the presence of impurities, which can introduce thermal instability, often leading to latent heat loss after multiple cycles of charging and discharging [83]. Despite this challenge, recent advancements in eutectic PCM technology have significantly minimized these issues [84–86]. Another concern with eutectic PCMs, particularly those containing an inorganic component, is the problem of supercooling as shown in Figure 4b [87]. Ideally, a eutectic PCM should not suffer from phase separation if the composition is maintained at the equilibrium point indicated on the phase diagram. However, if one of the components undergoes supercooling, it disrupts this phase equilibrium, leading to phase separation and a corresponding loss in latent heat [88]. Table 3 displays the thermophysical properties of some recently developed eutectic PCMs with phase change temperatures suitable for building envelope applications.

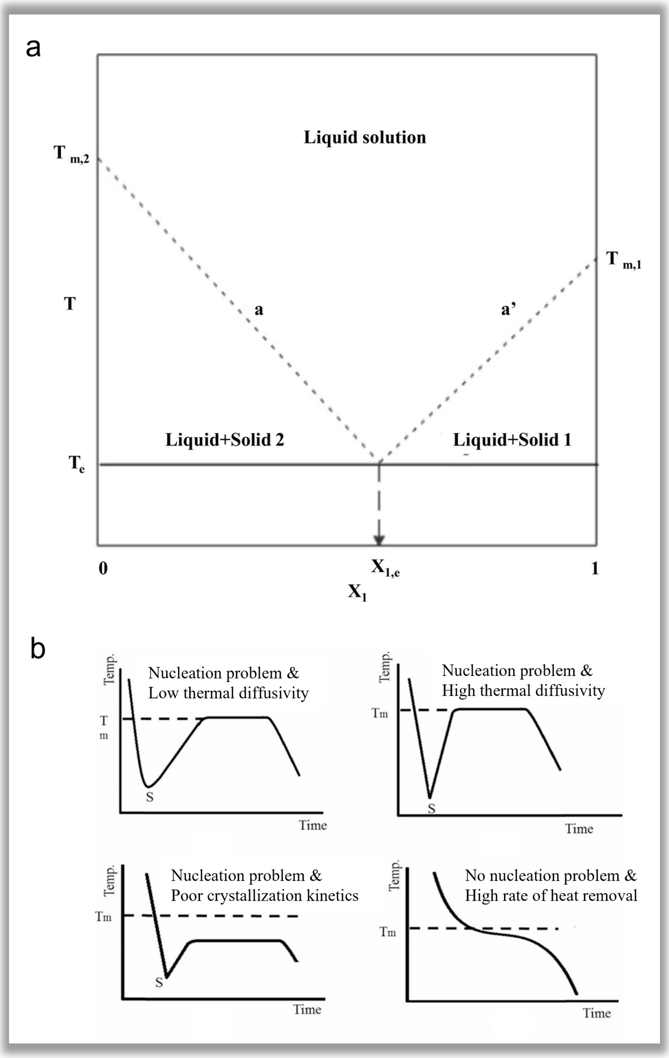

Figure 4. (**a**) Phase diagram of a simple binary eutectic system, reprinted from [89]. (**b**) Different thermal behaviors of PCMs suffering from supercooling, reprinted from [90].

Table 3. Thermophysical properties of some recently developed eutectic PCMs.

Classification	Composition (in wt%)	T_m(°C)	H (kJ/kg)	k (W/(m·K))
Inorganic–organic [91]	$CH_3COONa{\cdot}3H_2O$, CH_4N_2O, 6:4	31.4	205.3	-
Binary organic [92]	Lauryl alcohol, stearyl alcohol, 9:1	22.93	205.79	0.18
Binary organic [93]	Lauric acid, stearyl alcohol, 7:3	39.87	186.94	-
Binary inorganic [94]	$CaCl_2{\cdot}6H_2O$, $Na_2HPO_4{\cdot}12H_2O$, 78.3:21.7	22.6	143.6	-
Ternary inorganic [94]	$Na_2SO_4{\cdot}10H_2O$, $Na_2CO_3{\cdot}10H_2O$, $Na_2HPO_4{\cdot}12H_2O$, 34.8:46.2:19	20.2	207.65	-
Binary organic [95]	Palmitic acid, stearic acid, 61:39	54.8	223.6	0.8602
Binary inorganic [96]	$Na_2SO_4{\cdot}10H_2O$, $Na_2HPO_4{\cdot}12H_2O$, 62:38	27.1	202.4	0.464
Ternary organic [97]	Adipic acid, sebacic acid, stearic acid, -	61.7	193.3	-
Binary organic [98]	Paraffin, stearic acid, 45:35	56.2	192.5	0.368
Binary organic [98]	Palmitic acid, stearic acid, 32:68	55.8	213.3	0.323
Binary organic [98]	Palmitic acid, myristic acid, 14:86	51.3	225.8	0.285
Binary organic [99]	Decanoic acid, PEG, 1:1	22.9	173.9	0.2025

3. Incorporation Methods

As PCMs undergo state transitions between solid and liquid during phase change processes, several methods of incorporation are required to prevent the leakage of liquid PCMs in applications. Generally, there are four types of incorporation methods: the first involves using highly porous materials to contain the liquid PCM, which is commonly referred to as shape stabilization or form stabilization [100,101]. The second method involves encapsulating PCMs within a macroscale container [102,103], while the third method focuses on constructing core–shell structures to create micro/nanoencapsulated PCMs [104]. Finally, the fourth method converts solid–liquid PCMs into SSPCMs through chemical linking [105]. Each of these methods aims to enhance the application feasibility of PCMs by addressing the challenges associated with the liquid phase of the material.

3.1. Shape-Stabilized PCMs

PCMs can be incorporated into porous materials such as graphene [106], a matrix of carbon nanotubes [107], and expanded graphite [54]. These materials provide space for the volume change of PCMs, and the liquid PCMs are held within the porous structure due to the combined effects of capillary force, surface tension, and van der Waals forces [46,108]. Not only do these porous materials serve as supporting matrices for PCMs, but they also modulate the thermal conductivities of the PCMs to either enhance heat storage efficiency or improve thermal insulation capabilities [109,110]. The fabrication process for these composites is generally straightforward [111], involving the mixing of the substrate foam material and PCM at a temperature above the PCM melting point, followed by cooling and shaping in molds; vacuum impregnation may be employed to achieve a more intimate combination, allowing the PCM to thoroughly impregnate the porous structure and form a shape-stabilized composite.

Yang et al. [112] prepared a shape-stabilizing PCM by incorporating lauryl alcohol/stearic acid eutectic PCM and Al_2O_3 nanoparticles as thermal conductivity enhancers into ceramsite, creating a ceramsite-based shape-stabilized PCM as shown in Figure 5a. It was found that this shape-stabilized PCM effectively prevents leakage with a melting point of 22.5 °C, and the enthalpy of the PCM composite is 133.4 kJ/kg. By integrating the PCM composite into concrete blocks, satisfying mechanical performance was achieved, and temperatures on both the hot side and cold side of the PCM-integrated building envelope were reduced as shown in Figure 5b,c. Kumar et al. [113] experimentally studied the effectiveness of incorporating a lauric acid/zeolite/graphite PCM composite into gypsum plaster, observing maximum temperature reductions of 13.86% and 7.78% in peak indoor surface temperatures at the roof and south wall, respectively. Atinafu et al. [114] studied the performance of four different carbon-based materials—biochar, activated carbon, carbon nanotubes, and expanded graphite—on n-heptadecane. It was found that expanded graphite has the highest PCM loading ratio of 94.5%, a result attributed to the intermolecular interactions between the PCM and the carbon materials, including hydrogen bonding, pore characteristics, and surface functionality.

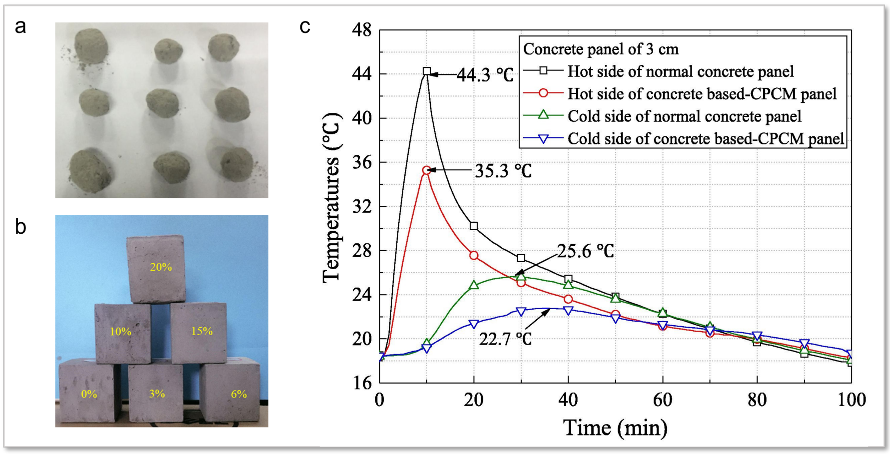

Figure 5. (**a**) The ceramsite-based shape-stabilized PCM. (**b**) Concrete incorporated with different mass fractions of shape-stabilized PCM. (**c**) Temperature variation on the hot and cold sides of a 10 cm × 10 cm × 3 cm thick concrete panel integrated with 15 wt% PCM compared to a normal concrete panel. Figures reprinted from [112].

3.2. Macroencapsulated PCMs

PCMs can be encapsulated within macroscale containers, allowing these macroencapsulated PCMs to be further integrated with building materials such as bricks and concrete as illustrated in Figure 6. Compared to other types of PCM incorporation methods, macroencapsulation offers superior mechanical strength and a higher PCM loading ratio. Moreover, because the encapsulation isolates the PCM from the environment, it also enhances the stability of the PCM itself. This method not only ensures structural integrity but also optimizes the thermal performance of the building materials by incorporating the thermal management capabilities of PCMs [115,116].

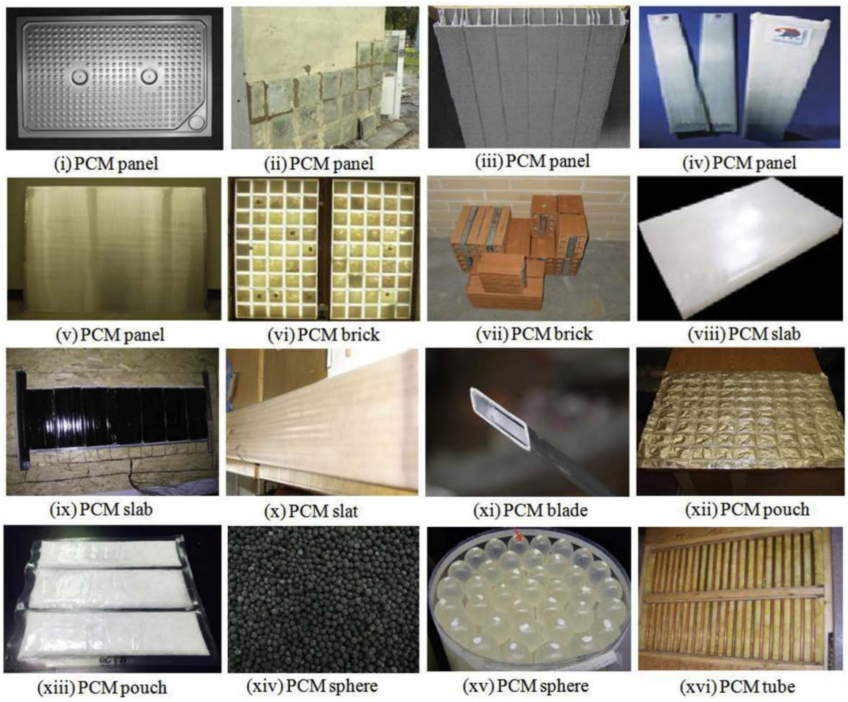

Figure 6. PCM macroencapsulation methods for building envelopes. Figure reprinted from [117].

Abass and Muthulingam [118] developed a reinforced concrete roof integrated with macroencapsulated PCMs to enhance passive cooling in buildings. Their findings indicate that the PCM-integrated roof slab significantly improves thermal performance by reducing interior temperatures by up to 7.2 °C during sunny hours, decreasing heat transfer into the building by up to 60.6%, and reducing the thermal load by up to 54%. This demonstrates the effectiveness of macroencapsulation in mitigating heat ingress, particularly during peak solar radiation periods. Rida and Hoffmann [119] investigated the impact of the exposed surface area of a macroencapsulated PCM (coconut oil) panel when applied to ceilings. They discovered that increasing the exposed surface area by 50% reduced the time needed for the PCM to melt completely by 20%, highlighting the importance of surface area in the thermal performance of PCM applications. Hu et al. [120] developed a casing pipe wall system with macroencapsulated PCM, characterized by enhanced anti-leakage properties, mechanical strength, and cost effectiveness. This innovative design involves filling the inner and outer pipes with PCMs of different melting points, allowing the wall to provide both passive heating and cooling. This dual functionality is particularly beneficial in regions of China that experience both hot summers and cold winters. Under optimal operating conditions, the wall surface temperatures were observed to be approximately 20.5 °C in summer and 26.8 °C in winter, demonstrating substantial improvements in maintaining comfortable indoor temperatures throughout the year.

3.3. Micro/Nanoencapsulated PCMs

Compared to macroencapsulation, PCMs can also be encapsulated at the microscale (diameter above 1 mm) or nanoscale (diameter less than 1 mm) by constructing a core–shell structure. The smaller size of micro/nanoencapsulated PCMs facilitates their integration into various building materials. These micro/nanoencapsulated PCMs offer a high surface area for heat transfer, which is advantageous for thermal management. However, their thermal conductivity is not particularly remarkable due to limitations in enhancing heat transfer at such small scales [104].

The encapsulation also provides insulation from the surrounding environment, enabling high thermal stability. Al-Absi et al. [121] compared the thermal performance of microencapsulated PCM-integrated cement render (CR) and foamed concrete (FC) on building walls with conventional CR and FC as shown in Figure 7a. The study demonstrated that PCM panels can significantly reduce temperature fluctuations over three heating and cooling cycles. The integration of PCMs results in a lower temperature profile for PCM-integrated walls during the heating period and higher profiles during the cooling period, attributed to the phase change processes of PCMs. During the heating period, the use of PCM panels can lead to a maximum temperature reduction of 4.8 °C for the external surface and 7.35 °C for the internal surface. Additionally, the peaks of internal surface temperature can be reduced by up to 3.95 °C. The micro/nanoencapsulation of PCMs also provides a protective layer that enhances the stability of PCMs. Maleki et al. [122] developed a plaster wallboard integrated with nanoencapsulated PCM as shown in Figure 7b. It was observed that the thermal and mechanical performance of the nanoencapsulated PCM remained stable even after 500 thermal cycles. Cabeza et al. [123] studied the long-term performance of a concrete wall integrated with microencapsulated PCMs. Their findings revealed that after 10 years of operation, the PCM-integrated wall continued to effectively reduce temperature fluctuations, with no significant degradation of the PCMs noted. Although there was a slight reduction in the mechanical performance of the wall, it still functioned comparably to its original performance, underscoring the potential of microencapsulated PCMs in sustainable building practices that require long-term thermal management solutions.

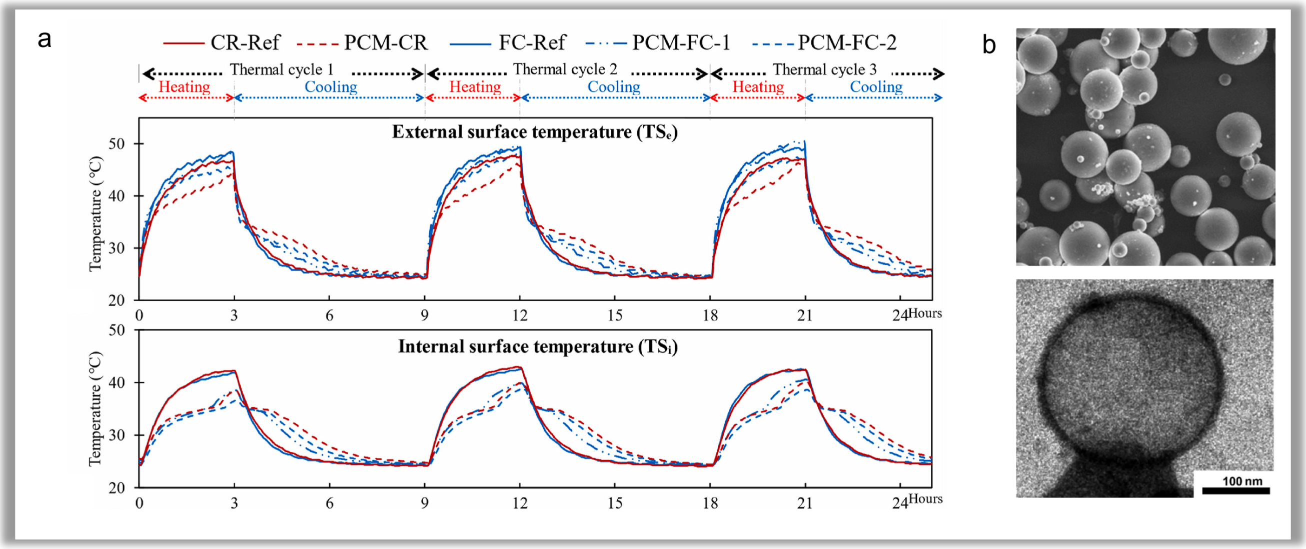

Figure 7. (**a**) Exterior surface temperature and interior surface temperature of a building wall integrated with/without PCM panels in three heating and cooling cycles. Figure reprinted from [121]. (**b**) SEM image (**top**) and TEM image (**bottom**) of the nanoencapsulated PCM. Figure reprinted from [122].

3.4. SSPCMs

SSPCMs remain in the solid state during their phase change processes. There are two types of SSPCMs. The first type consists of natural SSPCMs, which undergo a phase change by altering their crystalline structure, such as certain salt hydrates and paraffin [64,124–126]. The second type comprises chemically modified SSPCMs derived from conventional solid–liquid PCMs to promote a solid–solid phase transition. Unlike some PCMs that transition between crystalline structures, such as paraffin [127], chemically modified SSPCMs typically transition from a crystalline structure to an amorphous phase [19]. This transformation is primarily observed in polymer-based PCMs with hydroxyl-terminated structures.

PEG is a commonly studied base material for SSPCMs. A distinctive feature of PEG is its repeating ethyl–ether segments, which facilitate grafting or crosslinking with other polymers, thereby enhancing its structural integrity and functional adaptability [128]. Despite these benefits, the chemical stabilization process can reduce the latent heat capacity and alter the melting point [129]. Additionally, the absence of natural convection in SSPCMs necessitates the use of heat transfer enhancement techniques such as fins and metal foams [130–133]. Nevertheless, SSPCMs substantially mitigate leakage issues, presenting a significant advantage, particularly in applications where the containment of the PCM is critical.

Gao et al. [134] explored the application of PEG-based SSPCMs in building windows. They developed a novel, translucent PCM window that maintained consistent optical properties. Implementing a 3 mm thick layer of this PCM enabled energy savings of up to 9.4% for heating, 6.7% for ventilation, and 3.2% for air conditioning across the entire building. This demonstrates the potential of SSPCMs in reducing energy consumption in building applications. Harlé [135] investigated the use of SSPCM integrated with plaster to create a composite material for building applications. The study found that while the addition of PCM reduced the mechanical performance of the plaster, a concentration of 20 wt% PCM achieved an optimal balance between mechanical strength and thermal performance. This composite material exhibited satisfactory thermal regulation capabilities and stability, indicating its viability for enhancing building energy efficiency while maintaining structural integrity.

4. Criteria for PCM Integration in Building Applications

For the incorporation of PCMs in buildings, various issues need to be considered during the design process. For instance, the cost of the building increases when using such materials to replace conventional insulation materials. Moreover, integrating PCMs into building materials in any form can reduce their mechanical strength. This section discusses the criteria for PCM incorporation in buildings, providing a thorough evaluation of the main considerations for PCM selection and design.

4.1. Thermophysical Properties

The thermophysical properties that need to be considered for PCM selection in building applications mainly include latent heat, thermal conductivity, and melting point (or range). For each of these properties, there is no single criterion in the design principles that definitively states whether higher values are better. For example, some studies suggest that an ideal PCM for buildings should have high latent heat (or high energy storage density for metallic PCMs). While this can be true for applications requiring high energy storage capacity, it is not universally applicable. Chen et al. [136] showed that for PCM-integrated building envelopes in summer, using a PCM with higher latent heat can save more energy under high cooling energy consumption. However, for low cooling energy use, a higher latent heat PCM makes the stored heat more difficult to dissipate, leading to more significant energy waste.

Another factor to consider is thermal conductivity. In most cases, the application of PCMs in buildings requires some heat transfer enhancement techniques to ensure that the PCM can quickly respond to temperature changes, thereby increasing its energy storage efficiency [137,138]. However, the low thermal conductivity of PCMs (such as organic PCMs and salt hydrates) can be beneficial as a thermal insulation material [139].

The melting point of PCMs should be selected according to their applications. Generally, for heat supply applications, the melting point of PCM should lie between 29 and 60 °C; for building envelope applications, it should be 22–28 °C; and for refrigeration applications, it should be below 21 °C [140]. Overall, the selection of PCMs in terms of their thermophysical properties, amount of use, and incorporation position should be optimized based on the local climate conditions and the design of the buildings [141–143].

4.2. Chemical and Thermal Stability

Buildings are long-term investments that stand for decades, requiring PCMs with good stability. This means that PCMs should maintain their thermal performance after a large amount of cycles of charging and discharging. As a result, the PCM should retain its chemical composition and not react by itself during heating and cooling. Additionally, PCMs should not react with encapsulating materials and other surrounding building materials. Such issues are usually observed in inorganic salt hydrates and metallic PCMs. Studies have reported that inorganic PCM-integrated concrete can lead to corrosion problems with steel rebars [144,145]. This issue is typically solved by building a barrier between the corrosive PCM and the materials prone to corrosion, either through encapsulation or coating [146]. Furthermore, PCMs should exhibit minimal supercooling effects, which are usually observed in micro/nanoencapsulated PCMs and inorganic PCMs as discussed in Section 2. The degree of supercooling can be mitigated by increasing the roughness of the encapsulation or adding additives as nucleation sites for solidification [147].

To date, many PCMs with great stability and reliability have been prepared in recent studies. Emeema et al. [148] prepared paraffin/carbon quantum dot (CQD) composites. Thermogravimetric analysis (TGA) results indicated that adding CQD to paraffin raised the onset degradation temperature of the composites to as high as 297 °C from 269 °C, implying a longer lifespan of the composite. In a year-long test with 300 charging and discharging cycles, it was shown that the latent heat of the paraffin/QOD composite decreased slightly by 0.6%, demonstrating great potential for long-term operations.

4.3. Safety Issues

Despite their non-corrosive, low-cost, chemically stable, and non-supercooling advantages, fire safety is a crucial concern for organic PCMs in building envelopes, which must be considered in the design of buildings. Mclaggan et al. [149] showed that different applications of PCMs in buildings exhibit different levels of fire risks. When integrating PCMs in wall linings, fire risks can be quantified and mitigated by designers through proper fire risk assessment. However, using PCMs as insulation material at very high loadings results in extremely high heat release rates, even if the burning duration is short. Present methods to reduce the flammability of organic PCMs include the incorporation of flame retardants, chemical transformations, and surface coatings [150].

Toxicity of PCMs is another safety concern. Many studies indicate that low toxicity to humans can be found in many salt hydrates, with different salt hydrates exhibiting different toxicity levels [151–153]. Although this does not cause considerable issues if they are carefully encapsulated, the disposal of these salt hydrate wastes can cause significant environmental problems. For organic PCMs, although they are non-toxic, they still release toxic gases if they catch fire [43,154], highlighting the need for anti-flammability techniques in applications.

4.4. Economic Considerations

The decision to integrate PCMs in buildings is influenced by the economic benefits relative to the cost. The cost consists of the initial investment and annual cost for the PCM-integrated system. The initial investment cost is determined by the pricing of the PCMs and the PCM incorporation technique [155]. PCM pricing varies significantly across different regions, irrespective of the PCM category. Moreover, macroencapsulation is considered the most cost-friendly PCM incorporation technique, while micro/nanoencapsulations are the most expensive [156,157]. In calculating the payback time, the benefits of using PCM can be directly evaluated based on the saved energy, as the energy and price have a clear relation. Another consideration is the degradation in PCM performance, which can be evaluated by exergy [158].

4.5. Recyclability and Environmental Impact

The recycling of PCMs in building material waste presents both challenges and opportunities from environmental and economic perspectives. The recyclability of PCMs is primarily determined by their incorporation methods. For instance, it is almost impossible to recycle PCMs in concrete waste containing microencapsulated PCMs. Conversely, it is much easier to collect macroencapsulated PCMs. Specifically, great recyclability has been observed in many SSPCMs through simple shredding, heating, and remoulding processes. Yang et al. [159] prepared a PEG-based SSPCM exhibiting excellent recyclability, with almost no difference between the original and the recycled PCM. Similar achievements have been reported by Yang et al. [160], Bai et al. [161], and Yang et al. [162].

The environmental impact of a PCM-integrated building envelope should be evaluated from two aspects: first, how much greenhouse gas emission is reduced by the integrated PCM, and second, the pollution and greenhouse emissions caused from manufacturing to installation of the PCM-integrated building envelope [163]. A well-accepted method for analyzing the environmental impact of PCMs in buildings is to conduct a life cycle assessment (LCA) or life cycle cost analysis (LCCA). By conducting an LCA in Puigverd de Lleida (Spain), Gracia et al. [164] showed that the benefits of PCMs increase in locations where the weather conditions are consistent throughout the year. It is better to use salt hydrates than paraffins to reduce the manufacturing/disposal impact. Zhang et al. [165] conducted an LCCA of residential building walls enhanced with PCMs and showed that in Xi'an, China, for PCM Brick exterior walls, the thicker the phase change layer, the better the economic and environmental benefits. The payback period in the Xi'an area is between 10.13 and 13.41 years, the carbon payback period is between 3.3 and 4.3 years, and the carbon reduction is between 244.69 and 82.60 kg CO_2/m^2.

5. Novel Applications of PCMs for Building Envelopes

PCMs and their composites can be integrated into various building materials and components. Traditional applications involve PCM-integrated building materials such as bricks [13,166], panels [167,168], slabs [118,169], and more, which are then incorporated into roofs, floors, and walls to serve as thermal dampers. These materials help reduce and delay thermal fluctuations, thereby acting as a passive thermal regulation technique to achieve a comfortable indoor temperature [170,171] based on their energy charge and discharge cycles.

There are also hybrid applications of PCMs with other building envelopes as shown in Table 4. A notable example is the integration of PCMs with building-integrated photovoltaics (BIPVs). In this application, PCMs function as a heat sink with large heat capacity to cool down the PV panels and simultaneously reduce the heat load to the building introduced by the PV panels [172–174]. Moreover, the heat stored in the PCM can be utilized by auxiliary devices like heat pumps and thermoelectric generators, which further improves the energy efficiency of the building [175,176]. Another well-known integration is the combination of PCMs with Trombe walls [177]. The marriage of these two passive temperature regulation techniques can provide more stable temperature stabilization performance, thanks to the improved energy density, stabilized temperature variations, and high thermal insulation performance introduced by the PCM [178–180].

Moreover, new energy-saving techniques in buildings, such as radiant cooling, radiative sky cooling, and thermochromic coatings have emerged in recent years. This section introduces the novel integration techniques of PCMs with these hybrid technologies.

Table 4. Some hybrid PCM applications in building envelopes with different incorporation methods.

PCM	Incorporation	Integrated Application
Poly (Octadecyl Methacrylate) (PSMA) [181]	SSPCM	Thermo-optical coating for windows
Paraffin [182]	Macroencapsulated PCM	BIPV facade
Binary eutectic PCM [183]	Macroencapsulated PCM	Trombe wall
$CaCl_2{\cdot}6H_2O$ [184]	Shape-stablized PCM	Radiant cooling panel system
n-dodecane [185]	Microencapsulated PCM	Radiative cooling coating
PEG [186]	Shape-stablized PCM	Photothermal functional concrete
n-octadecane [187]	Shape-stablized PCM	Electromagnetic interference shielding wall
Binary eutectic PCM [188]	Microencapsulated PCM	Icephobic coating
OM32 (salt hydrate) [189]	Macroencapsulated PCM	Solar photocatalytic ventilation wall

5.1. PCM-Integrated Radiant Cooling/Heating Systems

Radiant cooling (RC) and radiant heating (RH) systems are increasingly recognized for their ability to provide high thermal comfort due to the significant role of radiative heat transfer between humans and indoor building envelopes [190]. Moreover, RC systems are instrumental in advancing low-carbon buildings, with reports indicating energy savings of up to 41% compared to traditional air conditioners and 34% compared to Variable Air Volume (VAV) systems [191–193]. The integration of PCMs into these systems enhances their energy storage capability, providing more stable surface temperatures and improved energy efficiency [194].

Bogatu et al. [195] analyzed the performance of a macroencapsulated PCM panel embedded with water pipes, designed for use as an RC ceiling (as shown in Figure 8a). The system, actively cooled by the discharge of water, successfully maintained the indoor thermal environment. Findings indicated that the average specific cooling power of the system was 11.3 W/m^2, surpassing that of commercial microencapsulated PCM gypsum panels but falling below the performance of traditional RC panels. González and Prieto [196] conducted a numerical study on the thermal performance of an RH floor integrated with PCM bands. They discovered that incorporating PCM into the concrete core somewhat reduced the heat transfer efficiency. However, during the discharge phase when the heating was turned off, the PCM RH floor maintained a stable heat flux ranging from 31.4 W/m^2 to 44.6 W/m^2 for more than 24 h, aligning closely with the time-average value.

Liu et al. [197] studied a PCM-integrated RH Trombe wall (as illustrated in Figure 8b). Their research revealed that this integration lowered the peak inner surface temperature of the south wall by 3 °C compared to a traditional Trombe wall and also reduced indoor heat gain by 55.2%, indicating superior energy efficiency. Cesari et al. [198] explored the integration of two types of PCMs with different melting points (17 °C and 27 °C) in a radiant floor system, designed to offer both cooling and heating capabilities (as depicted in Figure 8c). During summer, the system could be turned off, allowing the PCM to absorb excess heat and shift energy use to off-peak hours. In winter, the system maintained an indoor temperature of approximately 20 °C for 9 h without heating, achieving a 13% energy saving compared to an air handling unit (AHU) alone.

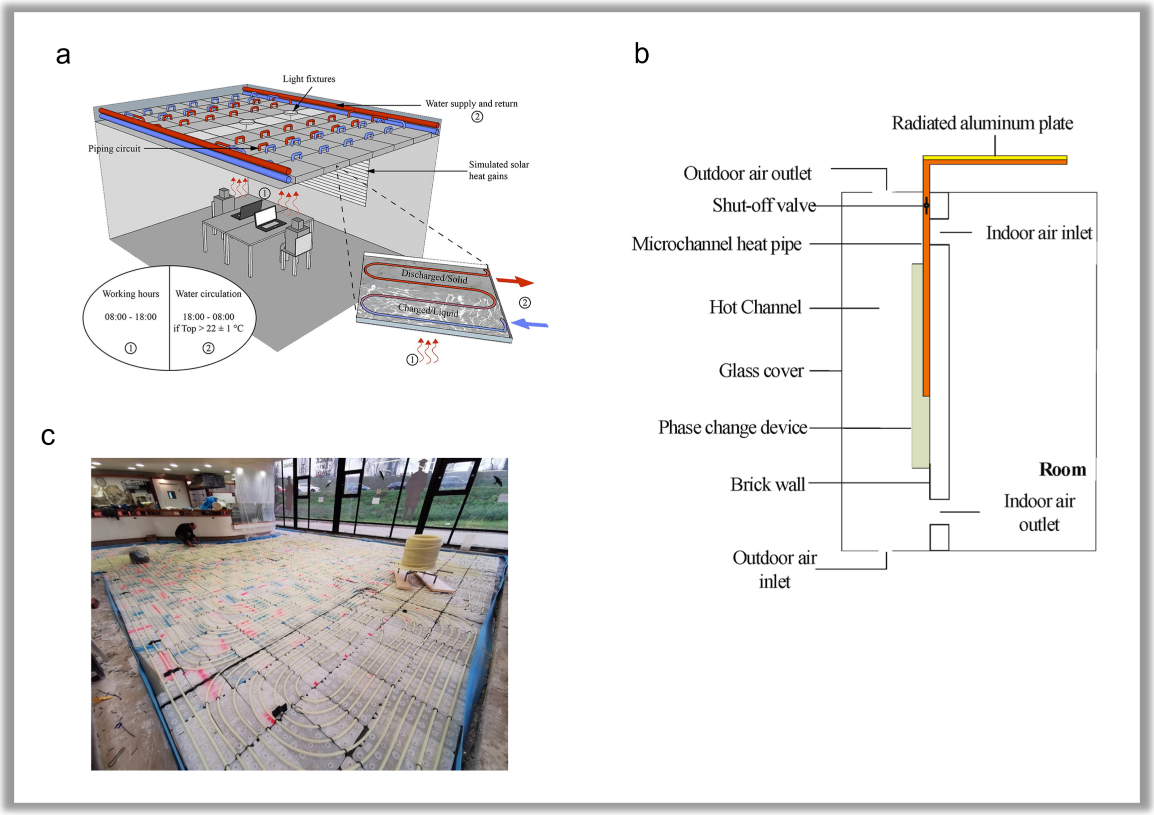

Figure 8. (**a**) Schematic of an RC ceiling with PCM. Figure reprinted from [195]. (**b**) Schematic of a PCM-integrated RH Trombe wall. Figure reprinted from [197]. (**c**) Radiant floor integrated with macroencapsulated PCM. Figure reprinted from [198].

5.2. PCM Assisted Passive Radiative Cooling

Passive radiative cooling (PRC) has emerged as a promising technology for reducing cooling loads and mitigating the urban heat island effect. Advances in material science over the past decade have significantly contributed to the development of daytime PRC materials characterized by their emissivity in the mid-infrared region, specifically within the atmospheric window (mainly between 8–13 µm), which enhances their cooling capabilities. The integration of PCMs with PRC materials not only improves thermal stability but also enhances the ability to save and shift cooling capacity [199].

Atiganyanun et al. [200] explored a method for incorporating microencapsulated PCMs into PRC paint (specifically $BaSO_4$) to boost its cooling performance. Their findings indicated that the addition of microencapsulated PCM had little impact on the emissivity of the paint. Additionally, the PCM was able to absorb excess heat from the interior, thereby maintaining the paint's cooling effectiveness. Yang et al. [199] developed a bi-layer phase change material-enhanced radiative cooler (PCMRC) as shown in Figure 9. The PCMRC demonstrated adaptive temperature regulation capabilities: during the day, the PCM layer absorbs excess heat from the RC layer, which is above the melting temperature of the PCM. At night, the PCM releases this stored heat to the surroundings. This cycle effectively provided an average ambient temperature reduction of 6.3 °C during the day and an average temperature increase of 2.1 °C at night, showcasing its dual cooling and warming functions. Su et al. [201] introduced a dynamic radiative cooler incorporating a top layer of paraffin. In this innovative design, the paraffin not only serves as a PCM for energy storage but also acts as a self-switchable cover. This transition occurs as the paraffin changes from solid to liquid; the spectral transmittance of solid paraffin remains below 5%, whereas it exceeds 90% when the paraffin is in its liquid state. This property allows for an adaptive response to varying thermal conditions, enhancing the overall functionality of the radiative cooler.

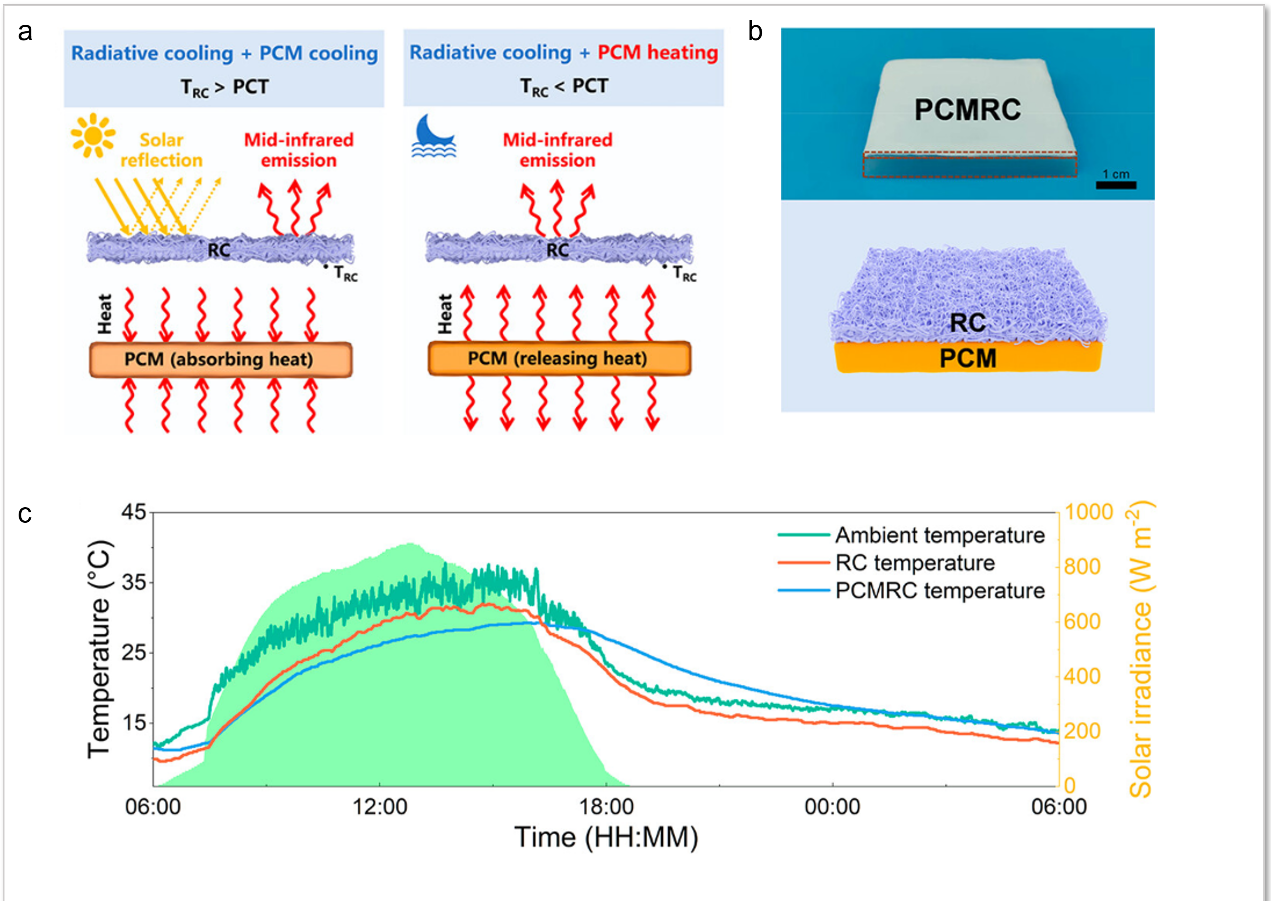

Figure 9. A bi-layer phase change material-enhanced radiative cooler (PCMRC). (**a**) Working principle of the PCMRC. (**b**) The structure of the PCMR. (**c**) Cooling performance comparison using RC and the PCMRC. The data were measured from 4 to 5 April 2022, in Shenzhen, China. Figures reprinted from [199].

5.3. PCM-Integrated Thermochromic Coatings

Thermochromic coatings are a novel energy-saving solution that regulate solar irradiation penetration to minimize radiative heat exchange between buildings and the environment [202]. These coatings respond dynamically to changes in temperature, adjusting their properties to either block or allow solar heat, thus helping to maintain indoor thermal comfort more efficiently. Hydrogels, perovskite, and vanadium dioxide (VO_2) are predominant materials for thermochromic coatings [203]. VO_2, as a type of PCM, is particularly noted for its ability to shift from a monoclinic to a rutile phase at a transition temperature of 341 K, changing its transparency in the NIR region and thereby enabling smart thermal regulation [204]. However, the high phase change temperature of VO_2

limits its practical applications in cooler climates or during milder weather conditions. To address this, researchers have explored doping strategies to modify the transition temperature. For example, Shen et al. [26] successfully reduced the phase change temperature of VO_2 by 21.6 °C through tungsten doping, making it more suitable for a broader range of climatic conditions.

Further advancements in thermochromic technologies include the development of multifunctional coatings. Pi et al. [205] prepared a smart window coating consisting of core–shell VO_2 nanoparticles that are both thermochromic and hydrophobic, providing antifouling properties. This superhydrophobic surface is resistant to a broad range of liquids and exhibits robust mechanical strength, making it ideal for long-term applications. Geng et al. [206] developed a self-templated method to produce ultrahigh transparent VO_2 nanoparticles. By controlling the grain size, they achieved a luminous transmittance of up to 82.9% for a single-sided VO_2 coating, enhancing both the aesthetic and functional properties of the material. The integration of thermochromic coatings with other types of PCMs can further enhance thermal performance. Jin et al. [207] numerically analyzed the thermal performance of window structures with various glazings. They found that triple glazing windows integrated with PCM, VO_2 coating, and low-E coating were the most energy efficient, reducing heat gain by up to 32% on sunny days and 40% on cloudy days during summer compared to standard double glazing. Ji and Li [208] explored a combined thermochromic–PCM system aimed at improving thermal performance in extreme environmental conditions as shown in Figure 10. Their simulations indicated that this system could reduce annual energy demand by 42.9 kWh/m^2, achieving an energy saving rate of up to 39%. Moreover, Imghoure et al. [209] assessed the thermal performance of a smart wall with five different configurations, incorporating W-doped VO_2 and two layers of PCMs with distinct melting temperatures as shown in Figure 10. This configuration demonstrated optimal performance, achieving comfortable indoor temperatures in both summer and winter seasons.

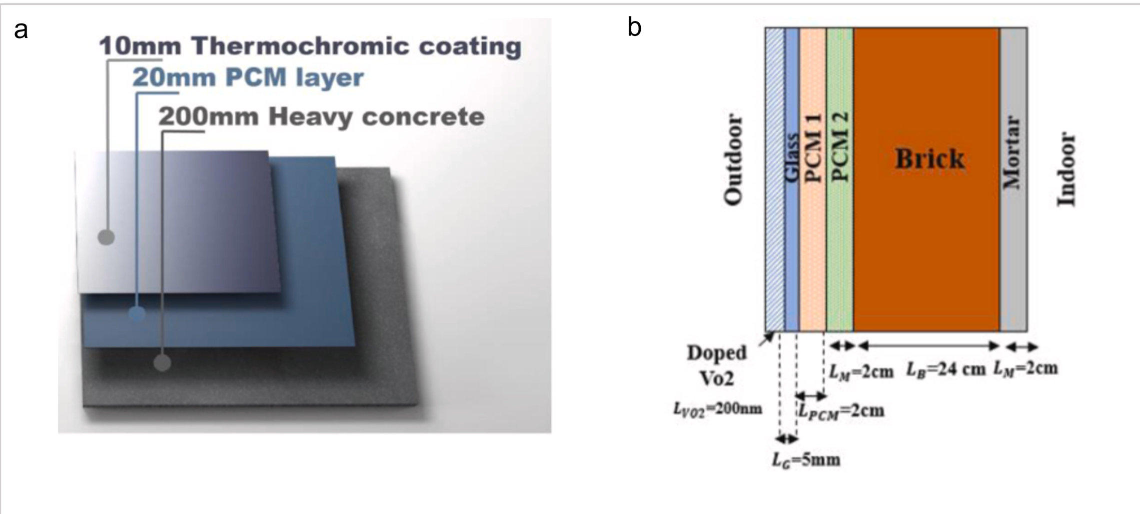

Figure 10. (**a**) A combined thermochromic–PCM system for extreme weather conditions. Figure reprinted from [208]. (**b**) Configuration of a PCM thermochromic smart wall towards indoor comfort for both summer and winter seasons. Figures reprinted from [209].

5.4. Other Applications

PCMs offer significant benefits in thermal regulation and energy storage, making them ideal for integration with various building envelope systems. Čurpek et al. [182] investigated the dynamic thermal response of a PCM-integrated BIPV system as illustrated in Figure 11a. Their study revealed that by incorporating PCMs, the BIPV/PCM system could reduce the peak operating temperature of photovoltaic panels by approximately

3 °C. This temperature reduction is crucial, as it enhances the electrical efficiency of the PV panels, which typically decrease in performance as temperature increases. Additionally, the integration of PCMs also resulted in reduced temperature fluctuations on the wall side, contributing positively to maintaining a more consistent and comfortable indoor environment. Izadpanah et al. [210] assessed the thermal efficiency of a double skin facade (DSF) integrated with PCMs and a green roof. Their findings indicated that this combination significantly reduced the cooling load in three different cities in Iran as depicted in Figure 11b. The synergy between the DSF, which provides an additional layer of thermal insulation and solar shading, and the PCM, which modulates the heat gains and losses, coupled with the natural cooling effect of a green roof, creates an effective barrier against heat penetration, thereby enhancing the overall energy efficiency of the building. Németh et al. [211] advanced the functionality of PCMs by developing an antimicrobial microencapsulated PCM, which involves encapsulating coconut oil in a calcium alginate shell embedded with silver nanoparticles. This novel PCM demonstrated significant antimicrobial properties, effectively eliminating both bacteria and fungi by the antimicrobial effect introduced by the Ag nanoparticles as shown in Figure 11c. The experimental results indicated that the highest loading of Ag nanoparticles (1.3%wt related to the total capsule) dispersed on the shell was particularly effective. This development holds promise for applications in office and home buildings, where it can provide both thermal regulation and antimicrobial functions, ensuring a healthier indoor environment. These applications indicate that PCMs not only contribute to thermal management but also broaden the scope of their utility in creating more adaptive and health-conscious building environments.

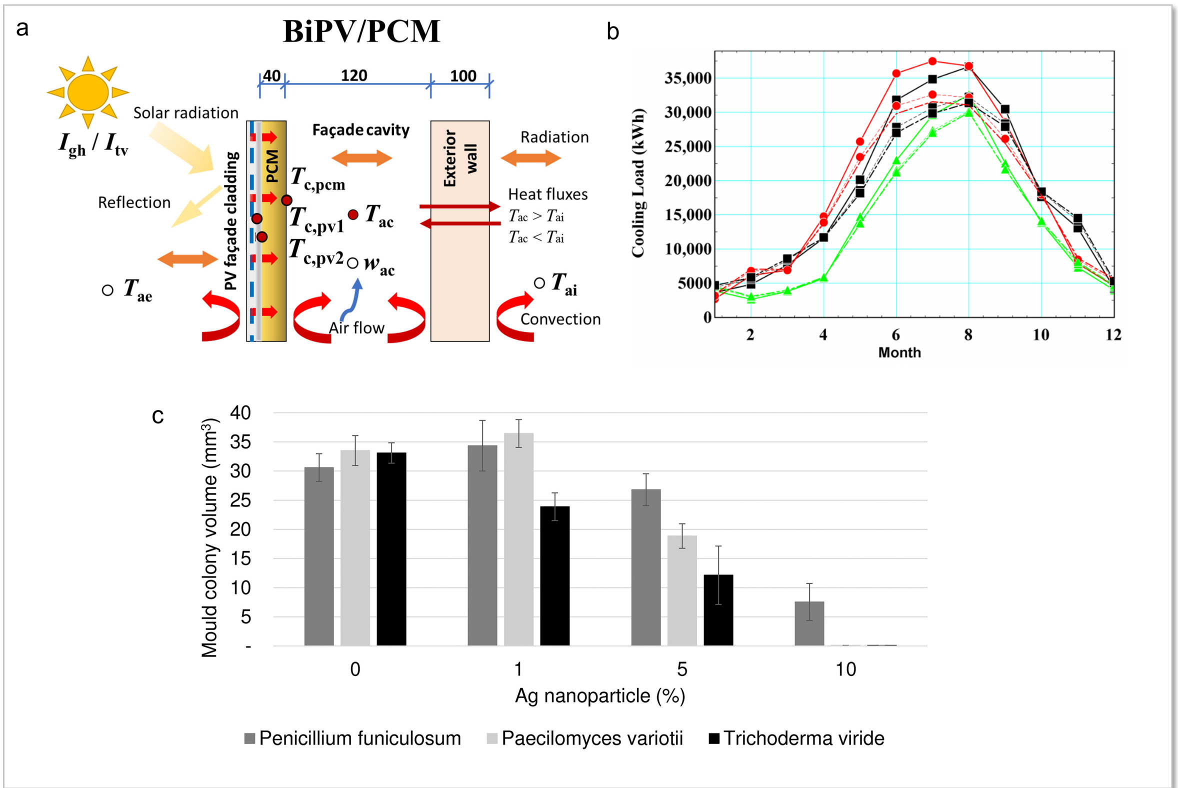

Figure 11. (**a**) Schematic of a BIPV/PCM facade. Figure reprinted from [182]. (**b**) Cooling load of a building with different envelope configurations in three Iranian cities, Amol (green curves), Tehran (black curves), and Yazd (red curves). The bold solid line, dashed line, and bold dashed line represent the cooling load by the DSF, DSF with PCM, and DSF with PCM and a green roof, respectively. Figure reprinted from [210]. (**c**) Antifungal effect with varying Ag nanoparticle concentration. Figure reprinted from [211].

6. Conclusions and Future Prospects

This paper provides a comprehensive review of the state-of-the-art PCM technology for building envelope applications. Various types of PCMs, including organic, inorganic, and eutectic candidates, are surveyed, and their advantages and disadvantages are analyzed. Different PCM incorporation methods such as shape stabilization, macroencapsulation, micro/nanoencapsulation, and solid–solid transition techniques are also discussed. These methods are crucial in addressing challenges like leakage and phase separation, thereby enhancing the practical viability of PCMs for construction uses. Furthermore, this paper conducts a review of the criteria for integrating PCMs into buildings and explores the novel applications of PCMs. The integration of PCMs into various building envelopes demonstrates their potential to meet specific environmental and functional requirements, making them a versatile and essential component of modern green building strategies. The main findings of this review are summarized below:

- In building envelopes, PCMs can increase the thermal inertia of a building, reduce thermal fluctuations, and delay heat peaks. Although some materials, such as SSPCMs and eutectic alloys, show great potential, they currently have limited studies in building envelopes due to their underdevelopment.
- The novel applications of PCMs in buildings leverage their temperature-stabilizing and energy storage capabilities, providing multifunctional benefits and significant potential for use in various building applications.
- Despite their advantages, integrating PCMs can introduce several issues, including fire hazards, potential toxicity, pollution, reduced mechanical performance, and higher initial costs. These issues should be considered during the building design process and are often overlooked in novel applications discussed in this paper.
- It is shown that integrating PCMs in buildings can reduce the energy consumption of HVAC systems. However, in some regions, traditional insulation materials may suffice, and the payback time for PCM integration may exceed the building's lifespan. Therefore, conducting a LCA or LCCA is necessary for PCM-integrated buildings.
- There are numerous choices for PCMs in building envelope design, each with distinct advantages in different aspects. Selection should be optimized based on integration circumstances, building design, sustainability considerations, and local climate.

These are some promising areas for future study to further advance PCM applications in building envelopes, summarized below:

- Currently, there are few studies on the applications of eutectic alloy PCMs in building envelopes. Although these PCMs are more costly than organic PCMs and salt hydrates, their high thermal conductivity and volumetric energy density warrant further investigation.
- Research on SSPCMs has primarily focused on material preparation rather than applications. Techniques for enhancing heat transfer in SSPCMs require further development.
- The long-term performance of PCMs currently relies on thermal stability and reliability analysis, yet there is a lack of experimental data over extended periods.
- Further investigations are needed to integrate PCMs with other functional materials, such as photothermal materials for building envelopes in cold regions, noise-canceling materials, or electromagnetic wave insulation materials for buildings with specialized uses.
- Studies should be conducted on the large-scale impacts of PCM-integrated envelopes on the urban heat island effect.

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References

1. Jia, L.; Lu, L.; Chen, J. Exploring the cooling potential maps of a radiative sky cooling radiator-assisted ground source heat pump system in China. *Appl. Energy* **2023**, *349*, 121678. [CrossRef]
2. Kumar, D.; Alam, M.; Memon, R.A.; Bhayo, B.A. A critical review for formulation and conceptualization of an ideal building envelope and novel sustainability framework for building applications. *Clean. Eng. Technol.* **2022**, *11*, 100555. [CrossRef]
3. Cristino, T.M.; Neto, A.F.; Wurtz, F.; Delinchant, B. The evolution of knowledge and trends within the building energy efficiency field of knowledge. *Energies* **2022**, *15*, 691. [CrossRef]
4. Pihelo, P.; Kalamees, T. The effect of thermal transmittance of building envelope and material selection of wind barrier on moisture safety of timber frame exterior wall. *J. Build. Eng.* **2016**, *6*, 29–38. [CrossRef]
5. Stazi, F.; Tomassoni, E.; Bonfigli, C.; Di Perna, C. Energy, comfort and environmental assessment of different building envelope techniques in a Mediterranean climate with a hot dry summer. *Appl. Energy* **2014**, *134*, 176–196. [CrossRef]
6. Sitzia, F.; Lisci, C.; Mirao, J. Accelerate ageing on building stone materials by simulating daily, seasonal thermo-hygrometric conditions and solar radiation of Csa Mediterranean climate. *Constr. Build. Mater.* **2021**, *266*, 121009. [CrossRef]
7. Kapoor, G.; Singhal, M. Impact of innovative thermal insulation materials in the building envelope on energy efficiency of residential buildings. *Mater. Today Proc.* **2024**, *in press* . [CrossRef]
8. Ma, Z.; Liu, X.; Xu, X.; Liu, L.; Yu, B.; Maluk, C.; Huang, G.; Wang, H.; Song, P. Bioinspired, highly adhesive, nanostructured polymeric coatings for superhydrophobic fire-extinguishing thermal insulation foam. *ACS Nano* **2021**, *15*, 11667–11680. [CrossRef] [PubMed]
9. Karimi, F.; Soltani, P.; Zarrebini, M.; Hassanpour, A. Acoustic and thermal performance of polypropylene nonwoven fabrics for insulation in buildings. *J. Build. Eng.* **2022**, *50*, 104125. [CrossRef]
10. Guo, Y.; Ruan, K.; Shi, X.; Yang, X.; Gu, J. Factors affecting thermal conductivities of the polymers and polymer composites: A review. *Compos. Sci. Technol.* **2020**, *193*, 108134. [CrossRef]
11. Li, C.; Wen, X.; Cai, W.; Yu, H.; Liu, D. Phase change material for passive cooling in building envelopes: A comprehensive review. *J. Build. Eng.* **2023**, *65*, 105763. [CrossRef]
12. Wang, P.; Liu, Z.; Zhang, X.; Hu, M.; Zhang, L.; Fan, J. Adaptive dynamic building envelope integrated with phase change material to enhance the heat storage and release efficiency: A state-of-the-art review. *Energy Build.* **2023**, *286*, 112928. [CrossRef]
13. Gao, Y.; Meng, X. A comprehensive review of integrating phase change materials in building bricks: Methods, performance and applications. *J. Energy Storage* **2023**, *62*, 106913. [CrossRef]
14. Rathore, P.K.S.; Shukla, S.K.; Gupta, N.K. Potential of microencapsulated PCM for energy savings in buildings: A critical review. *Sustain. Cities Soc.* **2020**, *53*, 101884. [CrossRef]
15. Wang, X.; Li, W.; Luo, Z.; Wang, K.; Shah, S.P. A critical review on phase change materials (PCM) for sustainable and energy efficient building: Design, characteristic, performance and application. *Energy Build.* **2022**, *260*, 111923. [CrossRef]
16. Rathore, P.K.S.; Gupta, N.K.; Yadav, D.; Shukla, S.K.; Kaul, S. Thermal performance of the building envelope integrated with phase change material for thermal energy storage: An updated review. *Sustain. Cities Soc.* **2022**, *79*, 103690. [CrossRef]
17. Li, D.; Wu, Y.; Wang, B.; Liu, C.; Arıcı, M. Optical and thermal performance of glazing units containing PCM in buildings: A review. *Constr. Build. Mater.* **2020**, *233*, 117327. [CrossRef]
18. Al-Yasiri, Q.; Szabó, M. Incorporation of phase change materials into building envelope for thermal comfort and energy saving: A comprehensive analysis. *J. Build. Eng.* **2021**, *36*, 102122. [CrossRef]
19. Raj, C.R.; Suresh, S.; Bhavsar, R.; Singh, V.K. Recent developments in thermo-physical property enhancement and applications of solid solid phase change materials: A review. *J. Therm. Anal. Calorim.* **2020**, *139*, 3023–3049. [CrossRef]
20. Mousavi, S.; Rismanchi, B.; Brey, S.; Aye, L. PCM embedded radiant chilled ceiling: A state-of-the-art review. *Renew. Sustain. Energy Rev.* **2021**, *151*, 111601. [CrossRef]
21. Li, D.; Ma, Y.; Zhang, S.; Yang, R.; Zhang, C.; Liu, C. Photothermal and energy performance of an innovative roof based on silica aerogel-PCM glazing systems. *Energy Convers. Manag.* **2022**, *262*, 115567. [CrossRef]

22. Zhao, A.; Xiao, X.; Hu, Z.T.; Zhu, W.; Yang, J.; Yang, E.H. Multifunctional F-doped TiO_2 PCM microcapsules for visible-light-driven photocatalysis and latent heat storage. *Appl. Energy* **2024**, *359*, 122674. [CrossRef]
23. Wu, Y.; Zhao, H.; Sun, H.; Duan, M.; Lin, B.; Wu, S. A review of the application of radiative sky cooling in buildings: Challenges and optimization. *Energy Convers. Manag.* **2022**, *265*, 115768. [CrossRef]
24. Ushak, S.; Gutierrez, A.; Galleguillos, H.; Fernandez, A.G.; Cabeza, L.F.; Grágeda, M. Thermophysical characterization of a by-product from the non-metallic industry as inorganic PCM. *Sol. Energy Mater. Sol. Cells* **2015**, *132*, 385–391. [CrossRef]
25. Sun, X.; Lee, K.O.; Medina, M.A.; Chu, Y.; Li, C. Melting temperature and enthalpy variations of phase change materials (PCMs): A differential scanning calorimetry (DSC) analysis. *Phase Transitions* **2018**, *91*, 667–680. [CrossRef]
26. Shen, Z.; Kwon, S.; Lee, H.L.; Toivakka, M.; Oh, K. Enhanced thermal energy storage performance of salt hydrate phase change material: Effect of cellulose nanofibril and graphene nanoplatelet. *Sol. Energy Mater. Sol. Cells* **2021**, *225*, 111028. [CrossRef]
27. Louanate, A.; El Otmani, R.; Kandoussi, K.; Boutaous, M. Non-isothermal crystallization kinetics of paraffin wax as a phase changing energy storage material. *Phys. Scr.* **2020**, *95*, 105003. [CrossRef]
28. Nazari Sam, M.; Caggiano, A.; Mankel, C.; Koenders, E. A comparative study on the thermal energy storage performance of bio-based and paraffin-based PCMs using DSC procedures. *Materials* **2020**, *13*, 1705. [CrossRef]
29. Aftab, W.; Usman, A.; Shi, J.; Yuan, K.; Qin, M.; Zou, R. Phase change material-integrated latent heat storage systems for sustainable energy solutions. *Energy Environ. Sci.* **2021**, *14*, 4268–4291. [CrossRef]
30. Tripathi, B.M.; Shukla, S.K. A comprehensive review of the thermal performance in energy efficient building envelope incorporated with phase change materials. *J. Energy Storage* **2024**, *79*, 110128. [CrossRef]
31. Atinafu, D.G.; Yun, B.Y.; Kwon, E.E.; Chang, S.J.; Kim, S. Unveiling the effect of molecular chain length on the thermal energy storage capacity and transition temperature of alkane-based phase change composites. *Chem. Eng. J.* **2023**, *462*, 142303. [CrossRef]
32. Abhat, A. Low temperature latent heat thermal energy storage: Heat storage materials. *Sol. Energy* **1983**, *30*, 313–332. [CrossRef]
33. Chang, Z.; Wang, K.; Wu, X.; Lei, G.; Wang, Q.; Liu, H.; Wang, Y.; Zhang, Q. Review on the preparation and performance of paraffin-based phase change microcapsules for heat storage. *J. Energy Storage* **2022**, *46*, 103840. [CrossRef]
34. Vakhshouri, A.R. Paraffin as phase change material. In *Paraffin Overview*; InTech Open: London, UK, 2020; pp. 1–23.
35. Jia, F.R.; Jing, W.T.; Liu, G.X.; Yue, Q.; Wang, H.M.; Shi, L. Paraffin-based crude oil refining process unit-level energy consumption and CO2 emissions in China. *J. Clean. Prod.* **2020**, *255*, 120347. [CrossRef]
36. Adlan, N.A.; Sabri, S.; Masomian, M.; Ali, M.S.M.; Rahman, R.N.Z.R.A. Microbial biodegradation of paraffin wax in Malaysian crude oil mediated by degradative enzymes. *Front. Microbiol.* **2020**, *11*, 565608. [CrossRef] [PubMed]
37. Nazari, M.; Jebrane, M.; Terziev, N. Bio-based phase change materials incorporated in lignocellulose matrix for energy storage in buildings—A review. *Energies* **2020**, *13*, 3065. [CrossRef]
38. Mishra, R.K.; Verma, K.; Mishra, V.; Chaudhary, B. A review on carbon-based phase change materials for thermal energy storage. *J. Energy Storage* **2022**, *50*, 104166. [CrossRef]
39. Yu, S.; Jeong, S.G.; Chung, O.; Kim, S. Bio-based PCM/carbon nanomaterials composites with enhanced thermal conductivity. *Sol. Energy Mater. Sol. Cells* **2014**, *120*, 549–554. [CrossRef]
40. Mehrizi, A.A.; Karimi-Maleh, H.; Naddafi, M.; Karimi, F. Application of bio-based phase change materials for effective heat management. *J. Energy Storage* **2023**, *61*, 106859. [CrossRef]
41. Sarı, A.; Karaipekli, A. Preparation, thermal properties and thermal reliability of palmitic acid/expanded graphite composite as form-stable PCM for thermal energy storage. *Sol. Energy Mater. Sol. Cells* **2009**, *93*, 571–576. [CrossRef]
42. Kumar, A.; Jain, H.; Tripathi, B.P. Synthesis and nanoencapsulation of poly (ethylene glycol)-distearates phase change materials for latent heat storage and release. *ACS Appl. Energy Mater.* **2020**, *3*, 5965–5976. [CrossRef]
43. Weng, J.; Huang, Q.; Li, X.; Zhang, G.; Ouyang, D.; Chen, M.; Yuen, A.C.Y.; Li, A.; Lee, E.W.M.; Yang, W.; et al. Safety issue on PCM-based battery thermal management: Material thermal stability and system hazard mitigation. *Energy Storage Mater.* **2022**, *53*, 580–612. [CrossRef]
44. Raju, K.; Kumar, G.N.; Ram, V.V.; Parameshwaran, R. Preparation, thermal and structural properties of n-octadecane/melamine formaldehyde nanocapsules embedded cement mortar for energy storage application in buildings. *Mater. Today Proc.* **2022**, *56*, 1424–1431. [CrossRef]
45. Bo, H.; Gustafsson, E.M.; Setterwall, F. Tetradecane and hexadecane binary mixtures as phase change materials (PCMs) for cool storage in district cooling systems. *Energy* **1999**, *24*, 1015–1028. [CrossRef]
46. Li, C.; Zhang, B.; Liu, Q. N-eicosane/expanded graphite as composite phase change materials for electro-driven thermal energy storage. *J. Energy Storage* **2020**, *29*, 101339. [CrossRef]
47. Liu, Y.; Wang, M.; Cui, H.; Yang, L.; Liu, J. Micro-/macro-level optimization of phase change material panel in building envelope. *Energy* **2020**, *195*, 116932. [CrossRef]
48. Hasan, M.I.; Basher, H.O.; Shdhan, A.O. Experimental investigation of phase change materials for insulation of residential buildings. *Sustain. Cities Soc.* **2018**, *36*, 42–58. [CrossRef]
49. de Albuquerque Landi, F.F.; Fabiani, C.; Pisello, A.L. Palm oil for seasonal thermal energy storage applications in buildings: The potential of multiple melting ranges in blends of bio-based fatty acids. *J. Energy Storage* **2020**, *29*, 101431. [CrossRef]
50. Aslfattahi, N.; Saidur, R.; Arifutzzaman, A.; Sadri, R.; Bimbo, N.; Sabri, M.F.M.; Maughan, P.A.; Bouscarrat, L.; Dawson, R.J.; Said, S.M.; et al. Experimental investigation of energy storage properties and thermal conductivity of a novel organic phase change material/MXene as A new class of nanocomposites. *J. Energy Storage* **2020**, *27*, 101115. [CrossRef]

51. Fan, Z.; Zhao, Y.; Liu, X.; Shi, Y.; Jiang, D. Thermal properties and reliabilities of lauric acid-based binary eutectic fatty acid as a phase change material for building energy conservation. *ACS Omega* **2022**, *7*, 16097–16108. [CrossRef]
52. Sun, J.; Zhao, J.; Zhang, W.; Xu, J.; Wang, B.; Wang, X.; Zhou, J.; Guo, H.; Liu, Y. Composites with a novel core–shell structural expanded perlite/polyethylene glycol composite PCM as novel green energy storage composites for building energy conservation. *Appl. Energy* **2023**, *330*, 120363. [CrossRef]
53. Mokhtari, S.; Madhkhan, M. The performance effect of PEG-silica fume as shape-stabilized phase change materials on mechanical and thermal properties of lightweight concrete panels. *Case Stud. Constr. Mater.* **2022**, *17*, e01298. [CrossRef]
54. Wu, M.; Liu, C.; Rao, Z. Experimental study on lauryl alcohol/expanded graphite composite phase change materials for thermal regulation in building. *Constr. Build. Mater.* **2022**, *335*, 127400. [CrossRef]
55. Dinesh, R.; Hussain, S.I.; Roseline, A.A.; Kalaiselvam, S. Experimental investigation on heat transfer behavior of the novel ternary eutectic PCM embedded with MWCNT for thermal energy storage systems. *J. Therm. Anal. Calorim.* **2021**, *145*, 2935–2949. [CrossRef]
56. Mohamed, S.A.; Al-Sulaiman, F.A.; Ibrahim, N.I.; Zahir, M.H.; Al-Ahmed, A.; Saidur, R.; Yılbaş, B.; Sahin, A. A review on current status and challenges of inorganic phase change materials for thermal energy storage systems. *Renew. Sustain. Energy Rev.* **2017**, *70*, 1072–1089. [CrossRef]
57. Soares, N.; Costa, J.J.; Gaspar, A.R.; Santos, P. Review of passive PCM latent heat thermal energy storage systems towards buildings' energy efficiency. *Energy Build.* **2013**, *59*, 82–103. [CrossRef]
58. Onder, E.; Sarier, N. Thermal regulation finishes for textiles. In *Functional Finishes for Textiles: Improving Comfort, Performance and Protection*; Woodhead Publishing: Cambridge, UK, 2015; p. 17.
59. Sandnes, B. *Exergy Efficient Production, Storage and Distribution of Solar Energy*; U.S. Department of Energy Office of Scientific and Technical Information: Oak Ridge, TN, USA, 2003.
60. Sandnes, B.; Rekstad, J. Supercooling salt hydrates: Stored enthalpy as a function of temperature. *Sol. Energy* **2006**, *80*, 616–625. [CrossRef]
61. Beaupere, N.; Soupremanien, U.; Zalewski, L. Nucleation triggering methods in supercooled phase change materials (PCM), a review. *Thermochim. Acta* **2018**, *670*, 184–201. [CrossRef]
62. He, Z.; Ma, H.; Lu, S. Preparation and thermal performance study of a novel hydrated salt composite PCM for space heating. *J. Energy Storage* **2024**, *90*, 111906. [CrossRef]
63. Cabeza, L.F.; Castell, A.; Barreneche, C.d.; De Gracia, A.; Fernández, A. Materials used as PCM in thermal energy storage in buildings: A review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1675–1695. [CrossRef]
64. Jiao, K.; Lu, L.; Wen, T.; Wang, Q. A modified mixture theory for one-dimensional melting of pure PCM and PCM/metal foam composite: Numerical analysis and experiment validation. *Int. J. Heat Mass Transf.* **2022**, *186*, 122461. [CrossRef]
65. Yagi, J.; Akiyama, T. Storage of thermal energy for effective use of waste heat from industries. *J. Mater. Process. Technol.* **1995**, *48*, 793–804. [CrossRef]
66. Copus, M.; Fraser, B.; Reece, R.; Hands, S.; Cuskelly, D.; Sugo, H.; Reed, S.; Bradley, J.; Post, A.; Kisi, E. On-sun testing of Miscibility Gap Alloy thermal storage. *Sol. Energy* **2019**, *177*, 657–664. [CrossRef]
67. Liu, L.; Li, J.; Deng, Y.; Yang, Z.; Huang, K.; Zhao, S. Optimal design of multi-layer structure composite containing inorganic hydrated salt phase change materials and cement: Lab-scale tests for buildings. *Constr. Build. Mater.* **2021**, *275*, 122125. [CrossRef]
68. Rezvanpour, M.; Borooghani, D.; Torabi, F.; Pazoki, M. Using $CaCl_2 \cdot 6H_2O$ as a phase change material for thermo-regulation and enhancing photovoltaic panels' conversion efficiency: Experimental study and TRNSYS validation. *Renew. Energy* **2020**, *146*, 1907–1921. [CrossRef]
69. Xie, N.; Gao, X.; Zhong, Y.; Ye, R.; Chen, S.; Ding, L.; Zhong, T. Enhanced thermal performance of $Na_2HPO_4 \cdot 12H_2O$ composite phase change material supported by sepiolite fiber for floor radiant heating system. *J. Build. Eng.* **2022**, *56*, 104747. [CrossRef]
70. Xiao, Q.; Fan, J.; Fang, Y.; Li, L.; Xu, T.; Yuan, W. The shape-stabilized light-to-thermal conversion phase change material based on $CH_3COONa \cdot 3H_2O$ as thermal energy storage media. *Appl. Therm. Eng.* **2018**, *136*, 701–707. [CrossRef]
71. Man, X.; Lu, H.; Xu, Q.; Wang, C.; Ling, Z. Review on the thermal property enhancement of inorganic salt hydrate phase change materials. *J. Energy Storage* **2023**, *72*, 108699. [CrossRef]
72. Gupta, N.; Kumar, A.; Dhasmana, H.; Kumar, V.; Kumar, A.; Shukla, P.; Verma, A.; Nutan, G.V.; Dhawan, S.; Jain, V. Enhanced thermophysical properties of Metal oxide nanoparticles embedded magnesium nitrate hexahydrate based nanocomposite for thermal energy storage applications. *J. Energy Storage* **2020**, *32*, 101773. [CrossRef]
73. Dixit, P.; Reddy, V.J.; Dasari, A.; Chattopadhyay, S. Preparation of perlite based-zinc nitrate hexahydrate composite for electric radiant floor heating in model building and numerical analysis. *J. Energy Storage* **2022**, *52*, 104804. [CrossRef]
74. Bouhal, T.; Meghari, Z.; El Rhafiki, T.; Kousksou, T.; Jamil, A.; Ghoulam, E.B. Parametric CFD analysis and impact of PCM intrinsic parameters on melting process inside enclosure integrating fins: Solar building applications. *J. Build. Eng.* **2018**, *20*, 634–646. [CrossRef]
75. Chen, K.; Ding, J.; Wang, W.; Lu, J. Shape-stable Bi-Sn-In alloy/Ag/copper foam composite phase change material for thermal storage and management. *Chem. Eng. J.* **2023**, *454*, 140087. [CrossRef]
76. Pan, A.; Wang, Y.; Cao, Y.; Zhang, H.; Zhao, J.; Hao, Z.; Wu, W. Research on thermal properties of phase change thermal control materials Bi-21In-18Pb-12Sn and Ga-13.5 Sn with low melting point. *J. Mater. Res. Technol.* **2020**, *9*, 3897–3906. [CrossRef]

77. Ding, B.; Zhu, X.; Wang, H.; He, X.Y.; Tan, Y. Experimental study on phase change heat transfer characteristics of alloys. *Int. J. Heat Mass Transf.* **2017**, *105*, 261–269. [CrossRef]
78. Deng, C.; Zhang, X.; Peng, J.; Yang, X.; Shang, B.; Luo, X. In51Bi32. 5Sn16. 5@ SiO2 microcapsules-based composite phase change materials with high thermal conductivity and heat storage density for electronics thermal management. *J. Energy Storage* **2024**, *86*, 111432. [CrossRef]
79. Ding, B.; Feng, W.C.; Fang, J.; Li, S.Z.; Gong, L. How natural convection affect cooling performance of PCM heat sink. *Int. J. Heat Mass Transf.* **2022**, *184*, 122272. [CrossRef]
80. Huang, P.; Wei, G.; Cui, L.; Xu, C.; Du, X. Numerical investigation of a dual-PCM heat sink using low melting point alloy and paraffin. *Appl. Therm. Eng.* **2021**, *189*, 116702. [CrossRef]
81. Singh, P.; Sharma, R.; Ansu, A.; Goyal, R.; Sarı, A.; Tyagi, V. A comprehensive review on development of eutectic organic phase change materials and their composites for low and medium range thermal energy storage applications. *Sol. Energy Mater. Sol. Cells* **2021**, *223*, 110955. [CrossRef]
82. Sun, M.; Liu, T.; Sha, H.; Li, M.; Liu, T.; Wang, X.; Chen, G.; Wang, J.; Jiang, D. A review on thermal energy storage with eutectic phase change materials: Fundamentals and applications. *J. Energy Storage* **2023**, *68*, 107713. [CrossRef]
83. Qiu, W.; Bai, Y.; Fang, Y.; Wang, S. Preparation and thermal properties of novel inorganic-organic eutectic composite material with high latent heat and thermal conductivity based on aluminum sulfate salt. *J. Energy Storage* **2022**, *55*, 105364. [CrossRef]
84. Jacob, J.; Pandey, A.; Abd Rahim, N.; Selvaraj, J.; Paul, J.; Samykano, M.; Saidur, R. Quantifying thermophysical properties, characterization, and thermal cycle testing of nano-enhanced organic eutectic phase change materials for thermal energy storage applications. *Sol. Energy Mater. Sol. Cells* **2022**, *248*, 112008. [CrossRef]
85. Chen, C.; Wang, X.; Ma, F.; Wang, Y.; Jiu, S.; Chen, Y. Preparation and characterization of modified activated carbon-based shape stabilized eutectic phase change materials for gypsum composites application. *Constr. Build. Mater.* **2023**, *369*, 130551. [CrossRef]
86. Sang, G.; Zeng, H.; Guo, Z.; Cui, H.; Zhang, Y.; Cui, X.; Zhang, L.; Han, W. Studies of eutectic hydrated salt/polymer hydrogel composite as form-stable phase change material for building thermal energy storage. *J. Build. Eng.* **2022**, *59*, 105010. [CrossRef]
87. Zahir, M.H.; Mohamed, S.A.; Saidur, R.; Al-Sulaiman, F.A. Supercooling of phase-change materials and the techniques used to mitigate the phenomenon. *Appl. Energy* **2019**, *240*, 793–817. [CrossRef]
88. Gunasekara, S.N.; Martin, V.; Chiu, J.N. Phase equilibrium in the design of phase change materials for thermal energy storage: State-of-the-art. *Renew. Sustain. Energy Rev.* **2017**, *73*, 558–581. [CrossRef]
89. Chakraborty, S.; Chormale, J.H.; Bansal, A.K. Deep eutectic systems: An overview of fundamental aspects, current understanding and drug delivery applications. *Int. J. Pharm.* **2021**, *610*, 121203. [CrossRef]
90. Garg, H.P.; Mullick, S.C.; Bhargava, V.K. *Solar Thermal Energy Storage*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2012.
91. Li, X.; Fu, Z.; Qiao, Y.; Zhang, Z.; Zhou, Y.; Hai, C.; Shen, Y.; Sun, Y.; Zeng, J.; Ren, X. Preparation, characterization, and modification of sodium acetate trihydrate-urea binary eutectic mixtures as phase change material. *Energy Fuels* **2020**, *34*, 6439–6447. [CrossRef]
92. Philip, N.; Veerakumar, C.; Sreekumar, A. Lauryl alcohol and stearyl alcohol eutectic for cold thermal energy storage in buildings: Preparation, thermophysical studies and performance analysis. *J. Energy Storage* **2020**, *31*, 101600. [CrossRef]
93. Liu, J.; Jiang, D.; Fei, H.; Xu, Y.; Zeng, Z.; Ye, W. Preparation and energy storage properties of a lauric acid/octadecanol eutectic mixture. *ACS Omega* **2021**, *6*, 23542–23550. [CrossRef]
94. Kalidasan, B.; Pandey, A.; Saidur, R.; Tyagi, S.; Mishra, Y.K. Experimental evaluation of binary and ternary eutectic phase change material for sustainable thermal energy storage. *J. Energy Storage* **2023**, *68*, 107707.
95. Zhang, D.; Sani, B.M.; Xu, P.; Liu, K.; Gu, F. Preparation and characterization of binary eutectic phase change material laden with thermal conductivity enhancer for cooling steel slag asphalt pavement. *Constr. Build. Mater.* **2023**, *388*, 131688. [CrossRef]
96. Kalidasan, B.; Pandey, A.; Saidur, R.; Kothari, R.; Sharma, K.; Tyagi, V. Eco-friendly coconut shell biochar based nano-inclusion for sustainable energy storage of binary eutectic salt hydrate phase change materials. *Sol. Energy Mater. Sol. Cells* **2023**, *262*, 112534. [CrossRef]
97. Dai, J.; Ma, F.; Sangiorgi, C.; Tarsi, G.; Fu, Z.; Tataranni, P.; Li, C.; Hou, Y. Assessment of high-enthalpy composite eutectic phase change materials efficiency in asphalt binders for cooling pavements. *J. Clean. Prod.* **2024**, *442*, 140999. [CrossRef]
98. Chang, S.; Zhang, L.; Li, X.; Liu, B.; Meng, Y.; Hu, H. Experimental study of novel paraffin-fatty acid eutectic mixtures for thermal management of electronic devices. *J. Energy Storage* **2024**, *84*, 110846. [CrossRef]
99. Yu, K.; Jia, M.; Liu, Y.; Yang, Y. Binary decanoic acid/polyethylene glycol as a novel phase change material for thermal energy storage: Eutectic behaviors and energy conservation evaluation. *J. Energy Storage* **2023**, *68*, 107663. [CrossRef]
100. Gandhi, M.; Kumar, A.; Elangovan, R.; Meena, C.S.; Kulkarni, K.S.; Kumar, A.; Bhanot, G.; Kapoor, N.R. A review on shape-stabilized phase change materials for latent energy storage in buildings. *Sustainability* **2020**, *12*, 9481. [CrossRef]
101. Wu, M.; Wu, S.; Cai, Y.; Wang, R.; Li, T. Form-stable phase change composites: Preparation, performance, and applications for thermal energy conversion, storage and management. *Energy Storage Mater.* **2021**, *42*, 380–417. [CrossRef]
102. Laasri, I.A.; Es-sakali, N.; Charai, M.; Mghazli, M.O.; Outzourhit, A. Recent progress, limitations, and future directions of macro-encapsulated phase change materials for building applications. *Renew. Sustain. Energy Rev.* **2024**, *199*, 114481. [CrossRef]
103. Lachheb, M.; Younsi, Z.; Youssef, N.; Bouadila, S. Enhancing building energy efficiency and thermal performance with PCM-Integrated brick walls: A comprehensive review. *Build. Environ.* **2024**, *256*, 111476. [CrossRef]

104. Ghasemi, K.; Tasnim, S.; Mahmud, S. PCM, nano/microencapsulation and slurries: A review of fundamentals, categories, fabrication, numerical models and applications. *Sustain. Energy Technol. Assessments* **2022**, *52*, 102084. [CrossRef]
105. Usman, A.; Xiong, F.; Aftab, W.; Qin, M.; Zou, R. Emerging solid-to-solid phase-change materials for thermal-energy harvesting, storage, and utilization. *Adv. Mater.* **2022**, *34*, 2202457. [CrossRef] [PubMed]
106. Abu-Hamdeh, N.H.; Khoshaim, A.; Alzahrani, M.A.; Hatamleh, R.I. Study of the flat plate solar collector's efficiency for sustainable and renewable energy management in a building by a phase change material: Containing paraffin-wax/Graphene and Paraffin-wax/graphene oxide carbon-based fluids. *J. Build. Eng.* **2022**, *57*, 104804. [CrossRef]
107. Sarrafha, H.; Kasaeian, A.; Jahangir, M.H.; Taylor, R.A. Transient thermal response of multi-walled carbon nanotube phase change materials in building walls. *Energy* **2021**, *224*, 120120. [CrossRef]
108. Meng, Y.; Zhao, Y.; Zhang, Y.; Tang, B. Induced dipole force driven PEG/PPEGMA form-stable phase change energy storage materials with high latent heat. *Chem. Eng. J.* **2020**, *390*, 124618. [CrossRef]
109. Zhang, M.; Xiao, Q.; Chen, C.; Li, L.; Yuan, W. Developing a heat-insulating composite phase change material with light-to-thermal conversion performance from graphene oxide/silica hybrid aerogel. *Appl. Therm. Eng.* **2020**, *174*, 115303. [CrossRef]
110. Rathore, P.K.S.; kumar Shukla, S. Improvement in thermal properties of PCM/Expanded vermiculite/expanded graphite shape stabilized composite PCM for building energy applications. *Renew. Energy* **2021**, *176*, 295–304. [CrossRef]
111. Mishra, A.K.; Lahiri, B.; Philip, J. Carbon black nano particle loaded lauric acid-based form-stable phase change material with enhanced thermal conductivity and photo-thermal conversion for thermal energy storage. *Energy* **2020**, *191*, 116572. [CrossRef]
112. Yang, Y.; Wu, W.; Fu, S.; Zhang, H. Study of a novel ceramsite-based shape-stabilized composite phase change material (PCM) for energy conservation in buildings. *Constr. Build. Mater.* **2020**, *246*, 118479. [CrossRef]
113. Kumar, N.; Rathore, P.K.S.; Sharma, R.; Gupta, N.K. Integration of lauric acid/zeolite/graphite as shape stabilized composite phase change material in gypsum for enhanced thermal energy storage in buildings. *Appl. Therm. Eng.* **2023**, *224*, 120088. [CrossRef]
114. Atinafu, D.G.; Yun, B.Y.; Wi, S.; Kang, Y.; Kim, S. A comparative analysis of biochar, activated carbon, expanded graphite, and multi-walled carbon nanotubes with respect to PCM loading and energy-storage capacities. *Environ. Res.* **2021**, *195*, 110853. [CrossRef]
115. Alam, T.E.; Dhau, J.S.; Goswami, D.Y.; Stefanakos, E. Macroencapsulation and characterization of phase change materials for latent heat thermal energy storage systems. *Appl. Energy* **2015**, *154*, 92–101. [CrossRef]
116. Rathore, P.K.S.; Shukla, S.K. An experimental evaluation of thermal behavior of the building envelope using macroencapsulated PCM for energy savings. *Renew. Energy* **2020**, *149*, 1300–1313. [CrossRef]
117. Liu, Z.; Yu, Z.J.; Yang, T.; Qin, D.; Li, S.; Zhang, G.; Haghighat, F.; Joybari, M.M. A review on macro-encapsulated phase change material for building envelope applications. *Build. Environ.* **2018**, *144*, 281–294. [CrossRef]
118. Abass, P.J.; Muthulingam, S. Thermal energy storage performance of biaxial voided RCC roof slab integrated with macroencapsulated PCM for passive cooling of buildings. *J. Energy Storage* **2024**, *88*, 111478. [CrossRef]
119. Rida, M.; Hoffmann, S. The influence of macro-encapsulated PCM panel's geometry on heat transfer in a ceiling application. *Adv. Build. Energy Res.* **2022**, *16*, 445–465. [CrossRef]
120. Hu, Z.; Li, W.; Yang, C.; Huang, H.; Guo, Y.; Ge, F.; Zhang, Y. Thermal performance of an active casing pipe macro-encapsulated PCM wall for space cooling and heating of residential building in hot summer and cold winter region in China. *Constr. Build. Mater.* **2024**, *422*, 135831. [CrossRef]
121. Al-Absi, Z.A.; Hafizal, M.I.M.; Ismail, M. Experimental study on the thermal performance of PCM-based panels developed for exterior finishes of building walls. *J. Build. Eng.* **2022**, *52*, 104379. [CrossRef]
122. Maleki, B.; Khadang, A.; Maddah, H.; Alizadeh, M.; Kazemian, A.; Ali, H.M. Development and thermal performance of nanoencapsulated PCM/plaster wallboard for thermal energy storage in buildings. *J. Build. Eng.* **2020**, *32*, 101727. [CrossRef]
123. Cabeza, L.F.; Navarro, L.; Pisello, A.L.; Olivieri, L.; Bartolomé, C.; Sánchez, J.; Álvarez, S.; Tenorio, J.A. Behaviour of a concrete wall containing micro-encapsulated PCM after a decade of its construction. *Sol. Energy* **2020**, *200*, 108–113. [CrossRef]
124. Palacios, A.; Navarro, M.E.; Barreneche, C.; Ding, Y. Hybridization of Salt Hydrates with Solid–Solid Phase Change Materials: A Novel Pathway to Sorption Thermochemical Materials Manufacturing. *Adv. Sustain. Syst.* **2023**, *7*, 2200184. [CrossRef]
125. Gough, R.; Primm, K.; Rivera-Valentín, E.; Martínez, G.; Tolbert, M. Solid-solid hydration and dehydration of Mars-relevant chlorine salts: Implications for Gale Crater and RSL locations. *Icarus* **2019**, *321*, 1–13. [CrossRef]
126. Broadhurst, M.G. An analysis of the solid phase behavior of the normal paraffins. *J. Res. Natl. Bur. Stand. Sect. A Phys. Chem.* **1962**, *66*, 241. [CrossRef]
127. Paneliya, S.; Khanna, S.; Singh, A.P.; Patel, Y.K.; Vanpariya, A.; Makani, N.H.; Banerjee, R.; Mukhopadhyay, I. Core shell paraffin/silica nanocomposite: A promising phase change material for thermal energy storage. *Renew. Energy* **2021**, *167*, 591–599. [CrossRef]
128. Shi, J.; Aftab, W.; Liang, Z.; Yuan, K.; Maqbool, M.; Jiang, H.; Xiong, F.; Qin, M.; Gao, S.; Zou, R. Tuning the flexibility and thermal storage capacity of solid–solid phase change materials towards wearable applications. *J. Mater. Chem. A* **2020**, *8*, 20133–20140. [CrossRef]
129. Wang, R.; Xiao, Y.; Lei, J. A solid-solid phase change material based on dynamic ion cross-linking with reprocessability at room temperature. *Chem. Eng. J.* **2020**, *390*, 124586. [CrossRef]

130. Hariti, Y.; Hader, A.; Faraji, H.; Boughaleb, Y. Scaling Law of Permeability and Porosity for Fluid Transport Phenomena in Porous PCM Media. *J. Appl. Comput. Mech.* **2021**, *7*, 84–92. [CrossRef]
131. Midhun, V.; Maroliya, M.; Saha, S.K. Numerical investigation and optimisation of solid–solid phase change material composite-based plate-fin heat sink for thermal management of electronic package. *Appl. Therm. Eng.* **2024**, *248*, 123183. [CrossRef]
132. Maroliya, M.; Midhun, V.; Saha, S.K. Comparative Study of Solid-Solid and Solid-Liquid Phase Change Materials for a Pin-Finned Heat Sink in Avionics Thermal Management. In Proceedings of the 27th National and 5th International ISHMT-ASTFE Heat and Mass Transfer Conference, Bihar, India, 14–17 December 2023; Begel House Inc.: Danbury, CT, USA, 2024.
133. Zhi, M.; Yue, S.; Zheng, L.; Su, B.; Fu, J.; Sun, Q. Recent developments in solid-solid phase change materials for thermal energy storage applications. *J. Energy Storage* **2024**, *89*, 111570. [CrossRef]
134. Gao, Y.; Zheng, Q.; Jonsson, J.C.; Lubner, S.; Curcija, C.; Fernandes, L.; Kaur, S.; Kohler, C. Parametric study of solid-solid translucent phase change materials in building windows. *Appl. Energy* **2021**, *301*, 117467. [CrossRef]
135. Harlé, T.; Hebert, R.L.; Nguyen, G.T.; Ledésert, B.A. A composite of cross-linked polyurethane as solid–solid phase change material and plaster for building application. *Energy Build.* **2022**, *262*, 111945. [CrossRef]
136. Chen, X.n.; Xu, B.; Xie, X.; Pei, G. Evaluating and optimizing the energy saving benefits of latent heat in phase change materials with new indices. *Appl. Therm. Eng.* **2023**, *228*, 120479. [CrossRef]
137. Liu, L.; Su, D.; Tang, Y.; Fang, G. Thermal conductivity enhancement of phase change materials for thermal energy storage: A review. *Renew. Sustain. Energy Rev.* **2016**, *62*, 305–317. [CrossRef]
138. Wu, M.; Li, T.; He, Q.; Du, R.; Wang, R. Thermally conductive and form-stable phase change composite for building thermal management. *Energy* **2022**, *239*, 121938. [CrossRef]
139. Zakaria, N.M.; Omar, M.A.; Mukhtar, A. Numerical Study on the Thermal Insulation of Smart Windows Embedded with Low Thermal Conductivity Materials to Improve the Energy Efficiency of Buildings. *CFD Lett.* **2023**, *15*, 41–52. [CrossRef]
140. Pasupathy, A.; Velraj, R.; Seeniraj, R. Phase change material-based building architecture for thermal management in residential and commercial establishments. *Renew. Sustain. Energy Rev.* **2008**, *12*, 39–64. [CrossRef]
141. Zahir, M.H.; Irshad, K.; Shafiullah, M.; Ibrahim, N.I.; Islam, A.K.; Mohaisen, K.O.; Sulaiman, F.A.A. Challenges of the application of PCMs to achieve zero energy buildings under hot weather conditions: A review. *J. Energy Storage* **2023**, *64*, 107156. [CrossRef]
142. Nurlybekova, G.; Memon, S.A.; Adilkhanova, I. Quantitative evaluation of the thermal and energy performance of the PCM integrated building in the subtropical climate zone for current and future climate scenario. *Energy* **2021**, *219*, 119587. [CrossRef]
143. Kitagawa, H.; Asawa, T.; Del Rio, M.A.; Kubota, T.; Trihamdani, A.R. Thermal energy simulation of PCM-based radiant floor cooling systems for naturally ventilated buildings in a hot and humid climate. *Build. Environ.* **2023**, *238*, 110351. [CrossRef]
144. Kim, Y.R.; Khil, B.S.; Jang, S.J.; Choi, W.C.; Yun, H.D. Effect of barium-based phase change material (PCM) to control the heat of hydration on the mechanical properties of mass concrete. *Thermochim. Acta* **2015**, *613*, 100–107. [CrossRef]
145. Porisini, F.C. Salt hydrates used for latent heat storage: Corrosion of metals and reliability of thermal performance. *Sol. Energy* **1988**, *41*, 193–197. [CrossRef]
146. Liu, M.; Zhang, X.; Ji, J.; Yan, H. Review of research progress on corrosion and anti-corrosion of phase change materials in thermal energy storage systems. *J. Energy Storage* **2023**, *63*, 107005. [CrossRef]
147. Shamseddine, I.; Pennec, F.; Biwole, P.; Fardoun, F. Supercooling of phase change materials: A review. *Renew. Sustain. Energy Rev.* **2022**, *158*, 112172. [CrossRef]
148. Emeema, J.; Murali, G.; Reddi, B.V.; Mangesh, V. Investigations on paraffin wax/CQD composite phase change material-Improved latent heat and thermal stability. *J. Energy Storage* **2024**, *85*, 111056. [CrossRef]
149. McLaggan, M.S.; Hadden, R.M.; Gillie, M. Flammability assessment of phase change material wall lining and insulation materials with different weight fractions. *Energy Build.* **2017**, *153*, 439–447. [CrossRef]
150. Png, Z.M.; Soo, X.Y.D.; Chua, M.H.; Ong, P.J.; Suwardi, A.; Tan, C.K.I.; Xu, J.; Zhu, Q. Strategies to reduce the flammability of organic phase change Materials: A review. *Sol. Energy* **2022**, *231*, 115–128. [CrossRef]
151. Wong-Pinto, L.S.; Milian, Y.; Ushak, S. Progress on use of nanoparticles in salt hydrates as phase change materials. *Renew. Sustain. Energy Rev.* **2020**, *122*, 109727. [CrossRef]
152. Du, K.; Calautit, J.; Wang, Z.; Wu, Y.; Liu, H. A review of the applications of phase change materials in cooling, heating and power generation in different temperature ranges. *Appl. Energy* **2018**, *220*, 242–273. [CrossRef]
153. Purohit, B.; Sistla, V. Inorganic salt hydrate for thermal energy storage application: A review. *Energy Storage* **2021**, *3*, e212. [CrossRef]
154. Xu, Z.; Chen, W.; Wu, T.; Wang, C.; Liang, Z. Thermal management system study of flame retardant solid–solid phase change material battery. *Surfaces Interfaces* **2023**, *36*, 102558. [CrossRef]
155. Cascone, Y.; Capozzoli, A.; Perino, M. Optimisation analysis of PCM-enhanced opaque building envelope components for the energy retrofitting of office buildings in Mediterranean climates. *Appl. Energy* **2018**, *211*, 929–953. [CrossRef]
156. Cárdenas-Ramírez, C.; Jaramillo, F.; Gómez, M. Systematic review of encapsulation and shape-stabilization of phase change materials. *J. Energy Storage* **2020**, *30*, 101495. [CrossRef]
157. Raj, A.; Srinivas, M.; Jayaraj, S. A cost-effective method to improve the performance of solar air heaters using discrete macro-encapsulated PCM capsules for drying applications. *Appl. Therm. Eng.* **2019**, *146*, 910–920. [CrossRef]
158. Rezaei, M.; Anisur, M.; Mahfuz, M.; Kibria, M.; Saidur, R.; Metselaar, I. Performance and cost analysis of phase change materials with different melting temperatures in heating systems. *Energy* **2013**, *53*, 173–178. [CrossRef]

159. Yang, S.; Du, X.; Deng, S.; Qiu, J.; Du, Z.; Cheng, X.; Wang, H. Recyclable and self-healing polyurethane composites based on Diels-Alder reaction for efficient solar-to-thermal energy storage. *Chem. Eng. J.* **2020**, *398*, 125654. [CrossRef]
160. Yang, Y.; Cai, X.; Kong, W. A novel intrinsic photothermal and flexible solid–solid phase change materials with super mechanical toughness and multi-recyclability. *Appl. Energy* **2023**, *332*, 120564. [CrossRef]
161. Bai, S.; Zhang, K.; Zhang, Q.; Zhu, Y.; Wang, W.; Zhang, J.; Li, X.; Zhang, X.; Wang, R. Intrinsic Flame Retardancy and Flexible Solid–Solid Phase Change Materials with Self-Healing and Recyclability. *ACS Appl. Mater. Interfaces* **2023**, *15*, 48613–48622. [CrossRef] [PubMed]
162. Yang, B.; Zhang, X.; Ji, J.; Hua, W.; Jiang, M. Multifunctional phase change film with high recyclability, adjustable thermal responsiveness, and intrinsic self-healing ability for thermal energy storage. *J. Energy Chem.* **2024**, *97*, 216–227. [CrossRef]
163. Anika, U.A.; Kibria, M.G.; Kanka, S.D.; Mohtasim, M.S.; Paul, U.K.; Das, B.K. Exergy, exergo-economic, environmental and sustainability analysis of pyramid solar still integrated hybrid nano-PCM, black sand, and sponge. *Sol. Energy* **2024**, *274*, 112559. [CrossRef]
164. De Gracia, A.; Rincón, L.; Castell, A.; Jiménez, M.; Boer, D.; Medrano, M.; Cabeza, L.F. Life Cycle Assessment of the inclusion of phase change materials (PCM) in experimental buildings. *Energy Build.* **2010**, *42*, 1517–1523. [CrossRef]
165. Zhang, L.; Zhang, Q.; Jin, L.; Cui, X.; Yang, X. Energy, economic and environmental (3E) analysis of residential building walls enhanced with phase change materials. *J. Build. Eng.* **2024**, *84*, 108503. [CrossRef]
166. Gupta, M.K.; Rathore, P.K.S.; Kumar, R.; Gupta, N.K. Experimental analysis of clay bricks incorporated with phase change material for enhanced thermal energy storage in buildings. *J. Energy Storage* **2023**, *64*, 107248. [CrossRef]
167. Yang, S.; Zhang, Y.; Zhao, Y.; Torres, J.F.; Wang, X. PCM-based ceiling panels for passive cooling in buildings: A CFD modelling. *Energy Build.* **2023**, *285*, 112898. [CrossRef]
168. Kumar, D.; Alam, M.; Doshi, A.J. Investigating the influence of thermal conductivity and thermal storage of lightweight concrete panels on the energy and thermal comfort in residential buildings. *Buildings* **2023**, *13*, 720. [CrossRef]
169. Rahi, M.F.; Arıcı, M.; Abdulateef, A.M.; Niyas, H. Numerical investigation and optimization of macro-encapsulated phase change material capsules in building roof slab. *J. Energy Storage* **2023**, *68*, 107806. [CrossRef]
170. Babaharra, O.; Choukairy, K.; Faraji, H.; Hamdaoui, S. Improved heating floor thermal performance by adding PCM microcapsules enhanced by single and hybrid nanoparticles. *Heat Transf.* **2023**, *52*, 3817–3838. [CrossRef]
171. Zhang, Q.; Liu, Y.; Zhang, Q.; Wang, G.; Lü, X. Research on the indoor temperature regulation characteristics of a nearly zero energy building with the nonlinear heat capacity building components: A simple model. *J. Build. Eng.* **2023**, *76*, 106850. [CrossRef]
172. El-Nagar, D.H.; Emam, M.; El-Betar, A.; Nada, S.A. Performance improvement of building-integrated photovoltaic panels using a composite phase change material-carbon foam heat sink: An experimental study. *J. Build. Eng.* **2024**, *91*, 109623. [CrossRef]
173. Gao, L.; Zhang, X.; Hua, W. Recent progress in photovoltaic thermal phase change material technology: A review. *J. Energy Storage* **2023**, *65*, 107317. [CrossRef]
174. Maghrabie, H.M.; Mohamed, A.; Fahmy, A.M.; Samee, A.A.A. Performance enhancement of PV panels using phase change material (PCM): An experimental implementation. *Case Stud. Therm. Eng.* **2023**, *42*, 102741. [CrossRef]
175. Kang, Y.K.; Joung, J.; Kim, M.; Jeong, J.W. Energy impact of heat pipe-assisted microencapsulated phase change material heat sink for photovoltaic and thermoelectric generator hybrid panel. *Renew. Energy* **2023**, *207*, 298–308. [CrossRef]
176. Gallero, F.J.G.; Siles, G.G.; Maestre, I.R.; Blázquez, J.L.F.; Bottarelli, M. Performance analysis of a novel façade-based building integrated photovoltaic-thermal system with phase change material for domestic hot water. *Appl. Therm. Eng.* **2024**, *240*, 122321. [CrossRef]
177. Elsaid, A.M.; Hashem, F.A.; Mohamed, H.A.; Ahmed, M.S. The energy savings achieved by various Trombe solar wall enhancement techniques for heating and cooling applications: A detailed review. *Sol. Energy Mater. Sol. Cells* **2023**, *254*, 112228. [CrossRef]
178. Li, J.; Zhang, Y.; Zhu, Z.; Zhu, J.; Luo, J.; Peng, F.; Sun, X. Thermal comfort in a building with Trombe wall integrated with phase change materials in hot summer and cold winter region without air conditioning. *Energy Built Environ.* **2024**, *5*, 58–69. [CrossRef]
179. Shen, J.; Lassue, S.; Zalewski, L.; Huang, D. Numerical study on thermal behavior of classical or composite Trombe solar walls. *Energy Build.* **2007**, *39*, 962–974. [CrossRef]
180. Chan, H.Y.; Riffat, S.B.; Zhu, J. Review of passive solar heating and cooling technologies. *Renew. Sustain. Energy Rev.* **2010**, *14*, 781–789. [CrossRef]
181. Xiao, Z.; Mishra, P.; Nejad, A.M.; Tao, M.; Granados-Focil, S.; Van Dessel, S. Thermal optimization of a novel thermo-optically responsive SS-PCM coatings for building enclosures. *Energy Build.* **2021**, *247*, 111129. [CrossRef]
182. Čurpek, J.; Čekon, M.; Šikula, O.; Slávik, R. Thermodynamic responses of adaptive mechanisms in BiPV façade systems coupled with latent thermal energy storage. *Energy Build.* **2023**, *279*, 112665. [CrossRef]
183. Duan, S.; Wang, L.; Zhao, Z.; Zhang, C. Experimental study on thermal performance of an integrated PCM Trombe wall. *Renew. Energy* **2021**, *163*, 1932–1941. [CrossRef]
184. Zhang, J.; Li, H.; Du, Y.; Xu, T.; Zou, T.; Wei, S.; Zhang, D. Development of $CaCl_2\cdot 6H_2O$-mannitol/SiO_2 shape-stabilized composite phase change material for the radiant cooling panel system. *Energy Build.* **2024**, *313*, 114224. [CrossRef]
185. Long, H.; Lei, S.; Wang, F.; Yang, S.; Ju, H.; Ou, J. Superhydrophobic daytime radiative cooling coating incorporated with phase change microcapsules for building thermal regulation. *J. Mater. Sci.* **2024**, *59*, 6459–6475. [CrossRef]

186. Zheng, C.; Huang, Z.; Wang, D.; Ju, Z.; Zhang, Z.; Zhang, H.; Zhu, Y.; Jiang, Z. Synthesis and properties of biomass derived carbon/PEG composite as photothermal conversion effective phase change material for functional concrete. *Cem. Concr. Compos.* **2024**, *149*, 105495. [CrossRef]
187. Yue, H.; Ou, Y.; Wang, J.; Wang, H.; Du, Z.; Du, X.; Cheng, X. Ti_3C_2Tx MXene/delignified wood supported flame-retardant phase-change composites with superior solar-thermal conversion efficiency and highly electromagnetic interference shielding for efficient thermal management. *Energy* **2024**, *286*, 129441. [CrossRef]
188. Shamshiri, M.; Jafari, R.; Momen, G. An intelligent icephobic coating based on encapsulated phase change materials (PCM). *Colloids Surfaces A Physicochem. Eng. Asp.* **2022**, *655*, 130157. [CrossRef]
189. He, J.W.; Huang, X.Y.; Shu, Z.Y.; Huang, R.N.; Cai, Y.; Lv, Y.; Zhao, F.Y. Preliminary study of a dual channel solar photocatalytic ventilation wall system for year-round air purification and building energy savings. *J. Build. Eng.* **2024**, *82*, 108261. [CrossRef]
190. Hu, R.; Niu, J. A review of the application of radiant cooling & heating systems in Mainland China. *Energy Build.* **2012**, *52*, 11–19.
191. Sastry, G. VAV vs. radiant: Side-by-side comparison. *ASHRAE J.* **2014**, *56*, 16.
192. Taweekun, J. An experimental and simulated study on thermal comfort. *Int. J. Eng. Technol.* **2013**, *5*, 177.
193. Zhang, F.; Guo, H.A.; Liu, Z.; Zhang, G. A critical review of the research about radiant cooling systems in China. *Energy Build.* **2021**, *235*, 110756. [CrossRef]
194. Rebelo, F.; Figueiredo, A.; Vicente, R.; Almeida, R.; Ferreira, V. Innovation and progress in the incorporation of phase change materials into radiant floor systems. *J. Energy Storage* **2023**, *74*, 109495. [CrossRef]
195. Bogatu, D.I.; Kazanci, O.B.; Olesen, B.W. An experimental study of the active cooling performance of a novel radiant ceiling panel containing phase change material (PCM). *Energy Build.* **2021**, *243*, 110981. [CrossRef]
196. González, B.; Prieto, M. Radiant heating floors with PCM bands for thermal energy storage: A numerical analysis. *Int. J. Therm. Sci.* **2021**, *162*, 106803. [CrossRef]
197. Liu, H.; Tan, Q.; Shi, Y.; Yu, B.; Zhang, M. Enhancing Indoor Thermal Comfort and Energy Efficiency: A Comparative Study of RC-PCM Trombe Wall Performance. *Renew. Energy* **2024**, *227*, 120542. [CrossRef]
198. Cesari, S.; Baccega, E.; Emmi, G.; Bottarelli, M. Enhancement of a radiant floor with a checkerboard pattern of two PCMs for heating and cooling: Results of a real-scale monitoring campaign. *Appl. Therm. Eng.* **2024**, *246*, 122887. [CrossRef]
199. Yang, M.; Zhong, H.; Li, T.; Wu, B.; Wang, Z.; Sun, D. Phase change material enhanced radiative cooler for temperature-adaptive thermal regulation. *ACS Nano* **2023**, *17*, 1693–1700. [CrossRef] [PubMed]
200. Atiganyanun, S.; Hasuchon, C.; Prithan, K.; Wongwan, K.; Kumnorkaew, P. Inclusion of microencapsulated phase change materials in waterborne paints to enhance radiative cooling performance. *Mater. Today Proc.* **2023**. [CrossRef]
201. Su, W.; Kang, R.; Cai, P.; Hu, M.; Kokogiannakis, G.; Darkwa, J.; Chen, J.; Xu, S.; Wang, L. Development of spectrally self-switchable cover with phase change material for dynamic radiative cooling. *Sol. Energy Mater. Sol. Cells* **2023**, *251*, 112125. [CrossRef]
202. Aburas, M.; Ebendorff-Heidepriem, H.; Lei, L.; Li, M.; Zhao, J.; Williamson, T.; Wu, Y.; Soebarto, V. Smart windows–Transmittance tuned thermochromic coatings for dynamic control of building performance. *Energy Build.* **2021**, *235*, 110717. [CrossRef]
203. Zhang, Z.; Zhang, L.; Zhou, Y.; Cui, Y.; Chen, Z.; Liu, Y.; Li, J.; Long, Y.; Gao, Y. Thermochromic energy efficient windows: Fundamentals, recent advances, and perspectives. *Chem. Rev.* **2023**, *123*, 7025–7080. [CrossRef] [PubMed]
204. Alsaadi, M.; Lerttraikul, K.; Chatraphorn, S.; Kittiwatanakul, S. Strategies for Enhanced Optical Performance and Durability of VO_2-based Thermochromic Windows. *Adv. Eng. Mater.* **2024**, *26*, 2302224. [CrossRef]
205. Pi, J.; Li, C.B.; Sun, R.Y.; Li, L.Y.; Wang, F.; Song, F.; Wu, J.M.; Wang, X.L.; Wang, Y.Z. Superhydrophobic and thermochromic VO2-Based composite coatings for energy-saving smart windows. *Compos. Commun.* **2022**, *32*, 101167. [CrossRef]
206. Geng, C.; Dou, S.; Zhao, J.; Ren, F.; Gu, J.; Wei, H.; Guan, H.; Liang, S.; Li, L.; Li, Y.; et al. Self-templated method to fabricate VO2 nanoparticles with ultrahigh luminous transmittance for energy-efficient thermochromic windows. *Appl. Surf. Sci.* **2022**, *592*, 153267. [CrossRef]
207. Jin, Q.; Long, X.; Liang, R. Numerical analysis on the thermal performance of PCM-integrated thermochromic glazing systems. *Energy Build.* **2022**, *257*, 111734. [CrossRef]
208. Ji, R.; Li, X. Numerical analysis on the energy performance of the PCMs-integrated thermochromic coating building envelopes. *Build. Environ.* **2023**, *233*, 110113. [CrossRef]
209. Imghoure, O.; Belouaggadia, N.; Ezzine, M.; Lbibb, R.; Younsi, Z. Evaluation of phase change material and thermochromic layers in a "smart wall" in different climates for improving thermal comfort in a building. *J. Build. Eng.* **2022**, *56*, 104755. [CrossRef]
210. Izadpanah, S.; Fazelpour, F.; Eftekhari Yazdi, M. Comparative study of simultaneous use of a double or a triple skin facade with phase change materials, green roof, and photovoltaics in residential buildings of Iran. *Environ. Prog. Sustain. Energy* **2023**, *42*, e13935. [CrossRef]
211. Németh, B.; Németh, Á.S.; Ujhidy, A.; Tóth, J.; Trif, L.; Jankovics, H.; Kriszt, B.; Dobolyi, C.; May, Z.; Gyenis, J.; et al. Antimicrobial functionalization of Ca alginate-coconut oil latent heat storing microcapsules by Ag nanoparticles. *Int. J. Energy Res.* **2020**, *44*, 11998–12014. [CrossRef]