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Advancing sustainable building through passive cooling with phase change materials, a comprehensive literature review

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ABSTRACT

Phase Change Materials (PCMs) present cutting-edge technology with substantial promise for advancing sustainable and energy-efficient cooling in buildings. These materials can absorb and release latent heat during phase transitions, facilitating thermal energy storage and temperature regulation. This comprehensive literature review explores various strategies and methods for implementing passive cooling with PCMs in buildings. The integration of PCMs enhances multiple passive cooling approaches, including solar control, ground cooling, ventilation-based heat dissipation, radiative cooling, and thermal mass-based heat modulation. The analysis delves into PCM classifications, encapsulation techniques, melting enthalpies, integration into diverse building envelopes, and performance across different climates. The findings from this comprehensive review indicated that PCM walls introduce a 2-hour delay in heat transfer and mitigate external temperature fluctuations. Windows equipped with PCM panels reduce heat transfer by 66 %. Combining PCMs with nocturnal radiative cooling leads to interior surface temperature reductions exceeding 13 °C. Natural ventilation with PCMs results in notable energy savings of up to 90 % in hot climates. The combination of free cooling and PCM thermal storage reduces charging times by 35 % while enhancing heat transfer. Simulations performed in the open literature suggested that strategic placement of PCMs in lightweight building walls reduces heat flux and overall energy consumption. Despite facing challenges related to scalability, compatibility, reliability, and recycling, PCM solutions demonstrate robust potential. When integrated thoughtfully into building design, PCMs significantly improve thermal performance and energy efficiency. Experimental validations confirm energy reductions ranging from 14 % to 90 %, underscoring the adaptability of passive cooling techniques leveraging PCM thermal storage and heat transfer capabilities across various climates.

1. Introduction

Over the past three decades, the escalation of energy consumption for space cooling has become an alarming global trend, more than tripling since 1990 [1]. This surge bears substantial ramifications, reaching beyond the strain on electricity grids to impact greenhouse gas (GHG) emissions and the emergence of urban heat islands. The world has witnessed new records of temperature rise in the last few years, underlining the urgency of addressing this trajectory [1]. The repercussions of inadequate access to indoor cooling reverberate across the globe, placing a significant portion of the population at elevated risk of heat stress. This not only adversely affects thermal comfort but also poses threats to labor productivity and human health [2].

As our planet undergoes a warming trend, addressing cooling needs equitably and sustainably assumes paramount significance. Our Net Zero Emissions by 2050 initiative lays out a comprehensive strategy with three key goals for 2030 [3]. First and foremost is the imperative to “build better” through policy support, targeting 20 % of the total existing building floor area globally and ensuring that 100 % of new building constructions are zero-carbon-ready by 2030, with a particular

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emphasis on prioritizing passive solutions for cooling. The second goal involves a necessary shift in behavior, advocating for the moderation of air-conditioning temperature set points within the range of 24–25 °C. The third goal focuses on improving efficiency, with a commitment to achieving the highest available efficiency rating for new air-conditioning equipment by 2035 [3].

In the realm of global buildings, heating and cooling constitute a substantial portion of energy consumption, posing formidable challenges to sustainability and environmental conservation [4]. The 2022 International Energy Agency (IEA) report paints a stark picture, revealing that energy demand in buildings soared to a staggering 133 exajoules (EJ) in 2022. Fig. 1 depicts energy consumption in buildings by fuel in the Net Zero Scenario from 2010 to 2030, illustrating a crucial transition period in the pursuit of sustainable energy practices [4]. The evolving dynamics of fuel usage within buildings are highlighted, offering valuable insights into the progress toward achieving net-zero emissions by 2030.

To counteract the trajectory of increasing energy usage and its environmental consequences, the implementation of tighter building codes retrofits for existing structures, and investments in passive solutions and energy-efficient technologies are deemed indispensable [5]. These actions aim to address the growing need for thermal comfort while mitigating environmental impacts. Passive cooling methods emerge as promising alternatives to traditional energy-intensive cooling systems, leveraging natural elements and strategic design principles to regulate indoor temperatures effectively. Fig. 2 categorizes diverse passive ideas for heating and cooling, documenting various techniques [6]. By disseminating data on these passive cooling methods, their potential to transform building energy use is underscored, fostering a shift towards more sustainable and resilient built environments.

2. Passive cooling concepts

Passive cooling principles are integral to sustainable building design, utilizing natural mechanisms to uphold thermal comfort while minimizing energy consumption. In convective cooling, the air functions as the cooling medium, and diverse forms of natural ventilation are utilized to remove surplus heat from structures [7]. This process harnesses the buoyancy effect or natural wind speed as a driving force, exemplified in techniques such as solar walls, solar chimneys, and cross ventilation [8]. Adequate indoor air quality is crucial for occupant well-being, and ventilation becomes paramount in removing pollutants like CO_2 [9]. Nevertheless, the difficulty lies in finding equilibrium, as conventional ventilation methods have the potential to undermine thermal comfort by depleting heat and escalating the requirement for heating [10]. While mechanical ventilation with heat recovery can function independently as a ventilator for a singular room, in instances involving conventional centralized ventilation systems, integration with the pre-existing air-handling unit (AHU) is necessary [11].

Natural ventilation stands out as a key passive cooling strategy, allowing the movement of air through building openings to enhance indoor air quality and decrease reliance on mechanical cooling systems [12]. Another approach, night ventilation (NV), optimizes cooler nighttime temperatures to dissipate accumulated heat efficiently, aligning with energy-efficient practices [13]. Complementary strategies involve shading techniques, such as overhangs and vegetation, which mitigate solar heat gain and contribute to internal temperature control [14,15]. Similarly, the use of thermal mass materials, like concrete or stone, aids in absorbing and gradually releasing heat, promoting a stable indoor environment [16].

2.1. Passive cooling classification

The categorization of diverse passive ideas for heating and cooling

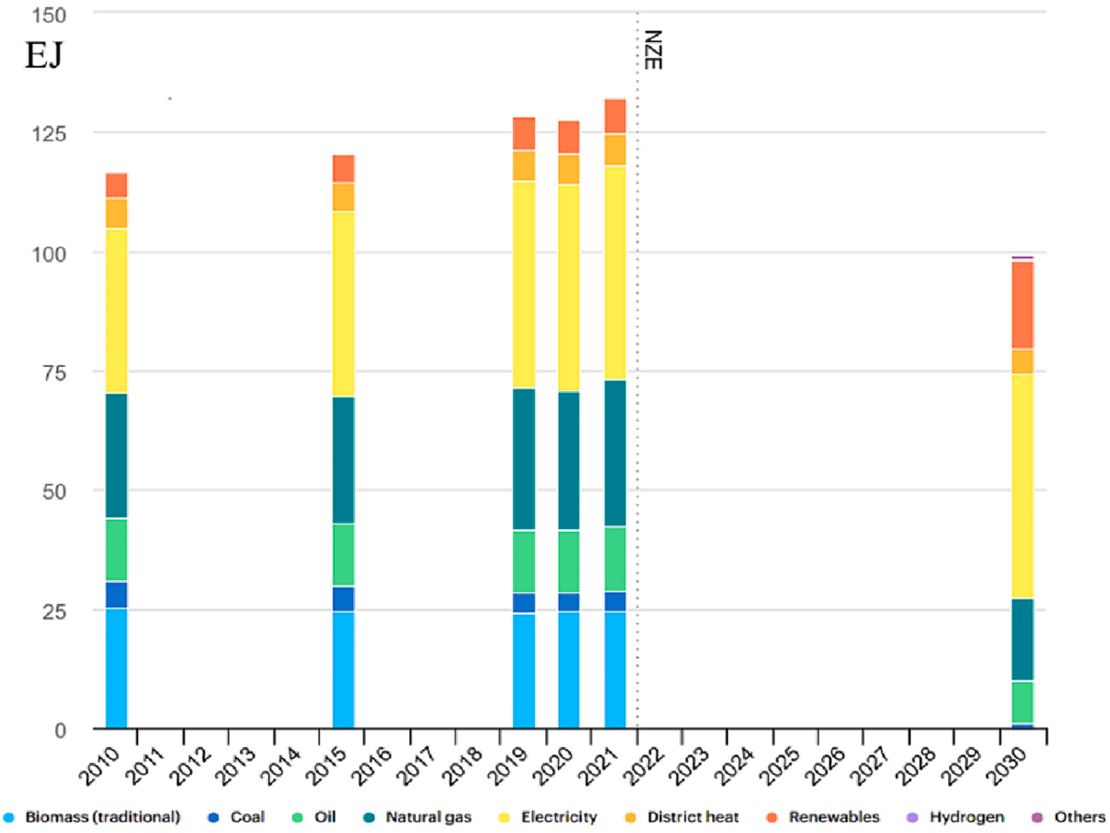

Fig. 1. Net Zero Scenario: Building Energy Consumption by Fuel (2010–2030) [4].

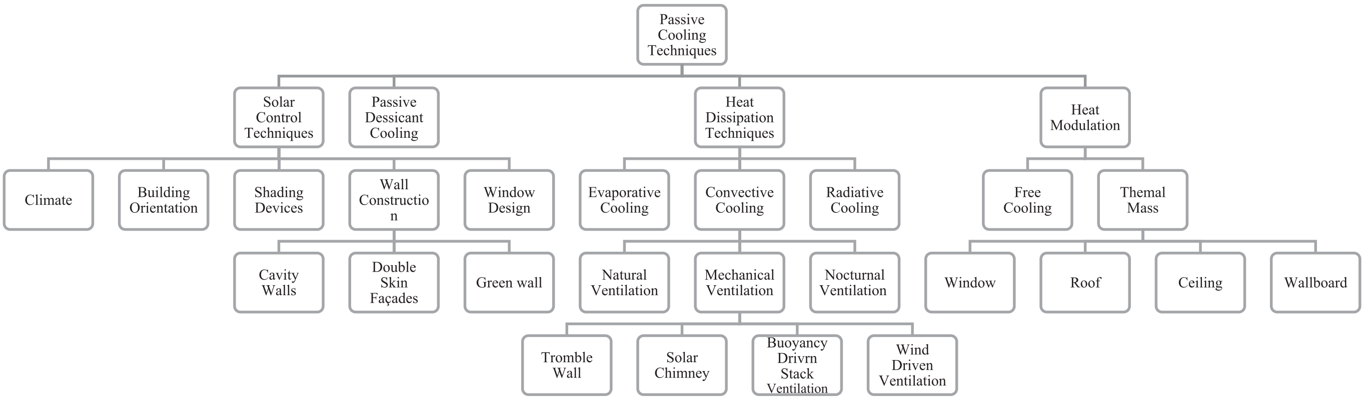

Fig. 2. The categorization of diverse Passive Cooling Techniques [6,17].

has been carried out and documented in Fig. 2. In the pursuit for sustainable and energy-efficient approaches to heating and cooling, a variety of passive strategies has surfaced. These strategies can be broadly categorized into five classes, each with distinct approaches to optimize indoor climate control [6,17].

Solar control strategies focus on managing solar radiation impact by techniques like building orientation, shading devices, wall/window design, and climate [18]. Passive desiccant systems use desiccant materials to naturally control humidity levels, enhancing comfort without relying on energy-intensive systems [19]. Heat dissipation is crucial for creating comfortable indoor environments while reducing energy consumption [20]. Passive ventilation systems, evaporative cooling, and convective cooling facilitate heat removal naturally [21,22]. Mechanical ventilation systems, nocturnal ventilation, and radiative cooling complement these methods [23].

Heat modulation encompasses free cooling and thermal mass techniques [24]. Free cooling utilizes natural processes like cross-ventilation, while thermal mass focuses on storing and releasing heat using PCMs in windows, roofs, ceilings, and wallboards [25].

2.2. Pcms classification

PCMs showcase a variety of features, and their classification can be considered from four primary viewpoints: chemical composition, temperature range, microstructure, and application, as depicted in Fig. 3 [26]. PCMs are broadly classified according to their chemical composition into two main groups: organic and inorganic [27]. Derived from carbon-based compounds, organic PCMs, including paraffins, fatty acids, esters, and bio-based materials, are recognized for their notable latent heat storage capacity. [28]. These materials find widespread application in building materials and textiles [29]. Inorganic PCMs, on the other hand, are composed of non-carbon-based substances like salts and metals [30]. Inorganic PCMs, characterized by high thermal conductivity, find frequent applications in areas such as electronics cooling and solar energy storage [31]. This chemical composition-based classification serves as a foundational framework for understanding and leveraging the diverse thermal properties of PCMs in various industries.

Another significant classification is based on the temperature at which PCMs undergo phase transitions [32]. This includes low-temperature PCMs, which operate below room temperature, medium-temperature PCMs suitable for typical room conditions, and high-temperature PCMs designed for applications above room temperature. This categorization enables the selection of PCMs tailored to specific thermal requirements [33–35]. PCMs can be classified based on their microstructure, distinguishing between microencapsulated and macro-encapsulated PCMs [36]. Microencapsulated PCMs are encapsulated in tiny particles, providing enhanced dispersibility and integration into various materials [37]. Macro-encapsulated PCMs involve larger containers, offering controlled release properties for specific applications requiring a more controlled heat exchange [38].

PCMs exhibit a versatile range of applications across multiple sectors, playing a pivotal role in enhancing thermal management. While finding utility in electronics for cooling applications [39] and textiles to improve comfort [40], PCMs have a pronounced focus on revolutionizing building and construction practices [41]. In this sector, PCMs are seamlessly integrated into diverse applications, including building materials, insulation, windows, wall and roofing systems [42]. Building materials enhanced with PCMs play a role in passive temperature control, optimizing indoor comfort and decreasing the dependence on active heating and cooling systems [43]. This emphasis on the building and construction sector aligns with the broader goals of achieving energy efficiency, sustainability, and enhanced thermal performance in structures, thereby establishing PCMs as integral components in the quest for innovative and environmentally conscious building solutions [44].

In Fig. 4, the relationship between PCM melting enthalpy and temperature is visually represented for distinct groups of PCM [45]. This graphical depiction serves as a valuable tool for the classification of PCMs based on their thermal properties. Each group—organic, inorganic, and eutectic mixtures—exhibits a characteristic melting enthalpy-

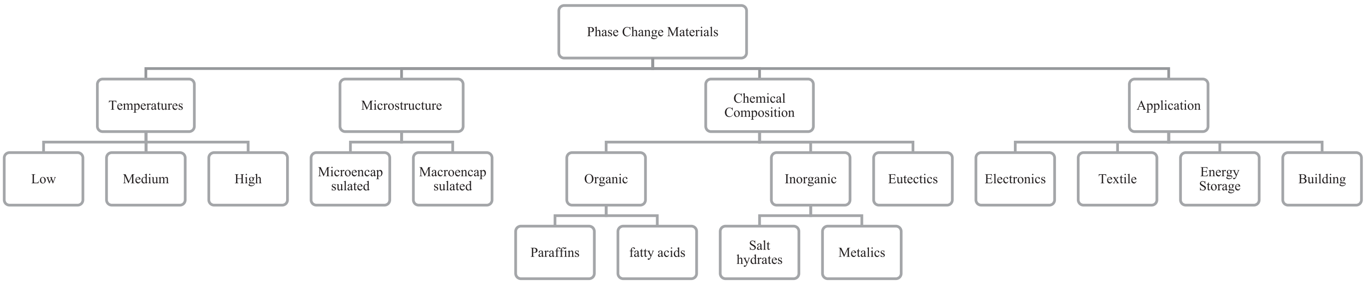

Fig. 3. The categorization of PCM [26].

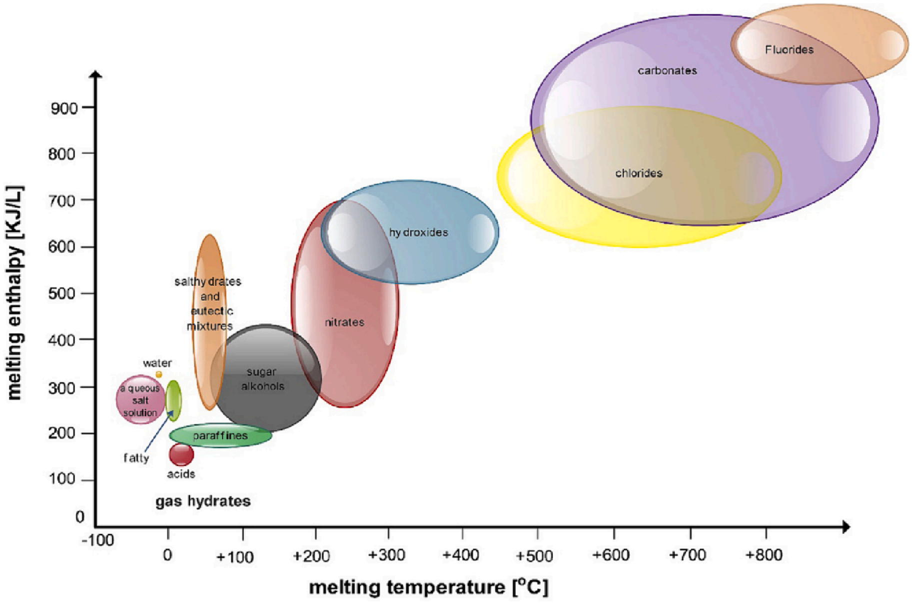

Fig. 4. PCM Melting Enthalpy-Temperature Relationship Across PCM Groups [45].

temperature profile. Organic PCMs, such as paraffin waxes, tend to showcase lower melting enthalpies at moderate temperatures, suggesting a propensity for efficient energy absorption and release within this range [46]. Inorganic PCMs, such as salt hydrates, are likely to display higher melting enthalpies at elevated temperatures, indicating their suitability for applications requiring substantial heat storage capabilities [47]. Eutectic mixtures, combining elements from both organic and inorganic categories, manifest a balanced relationship between melting enthalpy and temperature, underscoring their versatility across a broader spectrum of thermal conditions [48]. This classification, derived from the data presented in Fig. 4, facilitates a nuanced understanding of how different PCMs respond to temperature variations.

2.2.1. *Temperatures*

PCMs can be classified into four temperature ranges based on their melting points, with consideration given to working temperature ranges. This review focuses on four distinct working temperature intervals: (1) the low temperature range from −35 °C to + 5 °C, typically employed for domestic and commercial refrigeration; (2) the medium low temperature range from + 5 °C to + 40 °C, commonly applied in heating and cooling applications within buildings; (3) the medium temperature range from + 40 °C to + 80 °C, utilized for solar-based heating, hot water, and electronic applications; and (4) the high temperature range from + 80 °C to + 300 °C, suitable for absorption cooling, waste heat recovery, and electricity generation [49].

Within the medium low temperature range, often falling between + 5 °C and + 40 °C, PCMs play a crucial role in buildings, effectively moderating indoor temperatures through the storage and release of heat during phase transitions.

2.2.2. *Microstructure*

An effective PCM thermal storage system relies heavily on the encapsulation process, which entails confining PCMs within a suitable container [50]. Two primary encapsulation methodologies, macro-encapsulation, and microencapsulation have undergone extensive exploration for their applications in energy-efficient building systems. Macro-encapsulation involves enclosing a significant amount of PCM within distinct units, typically exceeding 1 cm in diameter [45]. The encapsulating shells can take various forms such as tubes, cylinders, pouches, and cubes [51]. Known for its adaptability, this approach easily conforms to diverse shapes and sizes, making it suitable for various energy storage requirements [52]. In contrast to microencapsulation, the macro process offers flexibility by not requiring a predefined approach [50]. Macro-capsules are typically integrated into exterior walls and precast slabs, optimizing exposure to weather conditions and solar radiation [53].

Microencapsulation involves techniques where small PCM particles or droplets are enclosed within a sealed, continuous shell, typically crafted from thin, high molecular weight polymeric or inorganic films [42]. Despite its advantages in preventing PCM leakage and enhancing heat transfer through a generous surface-to-volume ratio, microencapsulation proves to be a costlier method compared to alternatives [54]. Microencapsulated PCM particles can be dispersed in a powdered form or carrier fluid compatible with the encapsulating film [55]. The morphologies of microcapsules are diverse, encompassing irregular shapes, spheres, tubular structures, and matrix particles [56]. Organic PCM cores, particularly paraffin, are favoured due to their suitable melting points within the thermal comfort range of humans [57]. Challenges in this process include the potential breakage of microcapsules in active systems, indicating an area for future refinement [58]. The integration of carbon additives in building materials featuring PCM microcapsules has demonstrated improved efficiency and heat transfer rates [59].

both macro-encapsulation and microencapsulation play pivotal roles in advancing PCM applications within buildings, contributing significantly to sustainability and durability enhancements [60]. The ongoing exploration and innovations in encapsulation processes highlight the potential for heightened energy efficiency across a spectrum of construction materials [61].

2.2.3. *Chemical composition*

In the pursuit of optimizing thermal comfort within building applications, the selection of PCMs is integral, especially for maintaining desirable room temperatures throughout the changing seasons. The ASHRAE-defined thermal comfort parameters, with recommended temperatures ranging from 23.5–25.5 °C in the summer to 21.0–23.0 °C in the winter, underscore the need for effective solutions. PCMs, with their ability to store and release thermal energy during phase transitions, offer a promising avenue to achieve consistent and comfortable indoor environments. Key parameters influencing the efficacy of PCMs include their melting point, latent heat, and thermal conductivity [62,63]. These factors determine the suitability of PCMs for specific applications, ensuring they align with the desired temperature ranges and thermal performance requirements.

Melting point (°C) is a critical parameter that defines the temperature at which a PCM undergoes a phase transition, shifting from a solid to a liquid state. This characteristic is essential for ensuring that the PCM activates and deactivates within the desired temperature range, aligning with the seasonal thermal requirements of a given space. Latent heat (kJ/kg) represents the amount of energy absorbed or released during the phase change process. It signifies the PCM's capacity to store and release thermal energy efficiently. Higher latent heat values indicate a greater energy storage potential, allowing PCMs to better regulate indoor temperatures and contribute to enhanced thermal comfort.

Thermal conductivity (W/m.K) is a measure of a material's ability to conduct heat. In the context of PCMs, high thermal conductivity facilitates the efficient transfer of heat between the PCM and its surroundings,

Table 1
PCM Characteristics.

PCM Model			Melting Point (°C)	Latent Heat (kJ/kg)	Thermal conductivity (W/m.K)	Study
Organic PCMs	**Paraffins**	C 16, n-Hexadecane	18 –19	200–236	0.14–32	[65,66]
		Hexadecane + diatomite	24	120 solid (s), 118 liquid (l)	0.38	[67]
		C 17, n-Heptadecane	18–21	214	0.14 (l), 0.26 (s)	[65,68]
		C 18, n- Octadecane	22–28	244	0.15 (l), 0.18–0.26 (s)	[65,68,69]
		Glycerin	18	199	–	[69]
		RT 20	22	117–172	0.25	[70–72]
		RT 25	25	117–147	0.56(l), 1.02(s)	[70–72]
		RT 26	26	232	0.20	[70,71]
		RT 27	27	179	0.20	[70,71]
		RT 30	28	206	0.20	[70,71]
		STL 27	27	213	–	[70,71]
		Octadecane + diatomite + Graphite nanoplatelets	30	112 (l), 126 (s)	0.35	[67]
		Hexadecane + diatomite + Graphite nanoplatelets	22	120 (l), 121(s)	0.42	[67]
		5913 (n-paraffin)	23	189	0.21	[65]
	Fatty Acids and Esters	CA (Capric acid)	32	152–163	0.15	[73,74]
		Capric– lauric acid + fire retardant/gypsum	17	28	–	[75]
		Capric + Lauric (82: 18)	19–20	147	–	[65]
		Capric + Lauric (61.5: 38.5)	19	240	0.28	[65,76]
		Capric-palmitate 75.2/24.8	22	153	–	[77]
		Capric-myristic / perlite	21	85	–	[78]
		Capric-lauric 45/55	21	143	–	[79]
		Capric-lauric/ gypsum	19	35	–	[80]
		TH 29	29	188	1.09 (s),0.53 (l)	[70,71,81]
		MP (Methyl Palmitate)	29	230	0.19	[82]
		Butyl stearate	19	140	0.15	[79,83–85]
		Butyl stearate/gypsum	18–19	30	–	[70,75,80]
		Vinyl stearate	27–29	122	–	[85]
		Emerest 2325 (butyl stearate + butyl palmitate) (50: 48)	18–22	140	–	[65]
		Emerest 2325 (butyl stearate + butyl palmitate 49/48)	17–21	138–140	–	[86]
		Propyl palmitate/gypsum	19	40	–	[75]
		1-Dodecanol	20	191	0.18	[87]
		Dodecanol/gypsum	20	17	–	[75]
		Polyglycol E600	22	127	0.1897	[69,73,88]
		Propyl palmitate	19	186	0.60	[70,71]
		SP 22 A 17	22	150	0.60	[70,71]
		SP 25 A 8	25	180	0.60	[70,71]
		SP27	27	180–190		[70,71,89]
		SP 29	29	157	0.60	[70,71,90]
		Dimethyl sebacate	21	120–135	–	[69,85,91]
		Dimethyl sulfoxide	16	85	–	[69]
Inorganic/Salt PCMs	**Salt Hydrates**	KF, 4H2O	18	231	–	[87,92–94]
		45 % Ca(NO3)2 6H2O + 55 % Zn(NO3) 2 6H2O	25	130	–	[91]
		66.6 % CaCl2 6H2O + 33.3 % MgCl2 6H2O	25		–	[91]
		47 % Ca(NO3)2·4H2O + 53 % Mg(NO3) 2·6H2O	30	136	–	[92]
		Na2SO4,10H2O	21–32	198–251	0.45	[65,92–94]
		LiNO3 3H2O	30	215–296	–	[93,95]
		Mn(NO3)2,6H2O	26	126	–	[64]
		CaCl2·6 H2O	24–30	171–192	0.45–0.54 (l), 1.09 (s)	[64,90]
		CaCl2 6H2O + Nucleat + MgCl2 6H2O(2:1)	25	127	–	[64,70]
		48 % CaCl2 + 4.3 % NaCl + 0.4 % KCl + 47.3 % H2O	27	188	0.54 (l), 1.09 (s)	[64,70]
		60 % Na(CH3COO). 3H2O + 40 % CO(NH2) 2	30	200	–	[96]
	Eutectic Mixtures	ClimSel C 21	21	127	0.75(l), 0.93 (s)	[97]
		ClimSel C 24	24	126	0.93(l), 0.74 (s)	[97]
		ClimSel C 28	28	154	0.72(l), 0.98 (s)	[97]
		ClimSel C 32	28	145	1.08 (l), 0.76 (s)	[97]

promoting quicker response times and improved overall performance. This parameter is crucial for ensuring that the PCM effectively absorbs and releases thermal energy, contributing to the maintenance of optimal room temperatures.

Table 1 offer a comprehensive compilation of PCMs, with a focus on those exhibiting a phase change temperature between 18 and 30 degrees Celsius. This temperature range is preferred to address the thermal comfort requirements [64]. This temperature range is preferred to address the thermal comfort requirements, as it aligns with recommended operating temperatures for different seasons. Thermal comfort, a crucial aspect in building design, is defined by the ASHRAE and varies according to seasonal changes. The inclusion of PCMs with specific phase change temperatures becomes pivotal in achieving and maintaining optimal indoor conditions.

2.2.4. Application

PCMs are substances with a high heat of fusion which can store and releasing large amounts of energy. This makes them useful across a wide range of applications including electronics, textiles, energy storage, and buildings. The analysis of the application of PCMs in the building industry will be comprehensively reviewed in the following sections.

2.2.4.1. Electronic. Ensuring electronic components operate within specified maximum temperatures is a crucial global consideration [98]. The utilization of PCMs in thermal storage systems has been explored by employing a one-dimensional thermal model. This investigation aims to optimize advanced packages through the implementation of phase change cooling This approach is instrumental in alleviating thermal transient effects on high-power electronic packages [99]. To address the challenge of poor thermal conductivity during PCM melting and solidification, Thermal Conductivity Enhancers (TCEs) are incorporated, including internal fins, metal networks, PCM-based heat sinks and nanoparticles [100–105]. Research on parameters related to heat sink geometry contributes to a more nuanced understanding, identifying optimal volume fractions for enhanced thermal performance [106,107]. The utilization of multiple PCMs in thermal energy storage (TES) systems signifies improved thermal efficiency [39,108]. The incorporation of multiple PCMs is shown to reduce exergy loss and enhance overall thermal performance. Experimental examinations of various PCM arrangements in a heat sink by researchers reveal extended thermal regulation periods and reduced temperatures [109].

2.2.4.2. Textiles. PCMs can enhance thermo-regulation in textiles by absorbing, storing, and releasing heat. As temperature drops, the stored heat is expelled as PCM returns to solid form. This regulates temperature and maintains thermal comfort. PCMs in textiles have potential applications in clothing, technical, and interior textiles. Since the 1980 s, NASA and textile companies have used PCM technology to develop thermo-regulated garments that control abrupt temperature changes in harsh environments [29]. PCMs can minimize excess heat and sweating while doing physical activity or under hot conditions [110]. PCM incorporation techniques include filled hollow fibers [111], adding during spinning [112], and coating/laminating on fabrics [113,114]. Fiber-based approaches allow easy integration but constrain PCM loading whereas coating is flexible yet lacks durability. Trade-offs between thermal performance, weight, and endurance should be considered when choosing the method [115]. Overall, PCM textiles show promise for temperature regulation across diverse industries from protective clothing to bedding and medical products [116,117]. Further research aims to advance encapsulation and heat transfer to leverage their energy storage capabilities more effectively.

2.2.4.3. Energy storage. PCM TES enhances the viability of solar technology, especially in low or no insolation conditions. Key applications of PCM TES include solar water heaters, cookers, air heaters, and greenhouses [118,119]. In solar water heaters, PCM layers beneath tanks play a crucial role by absorbing heat from water during daylight hours through latent heat storage [120]. However, the effectiveness is hindered by poor heat transfer between the PCM and water. Solar cookers utilize PCM TES to capture and store solar energy for evening cooking requirements [121]. Solar agricultural greenhouses leverage encapsulated PCMs for daytime heat storage and nocturnal heat release, regulating temperatures to enhance plant quality [122]. As solar power continues to expand, the integration of PCM TES in collectors, receivers, and storage tanks is on the rise. PCM TES plays a vital role in balancing energy supply and demand fluctuations in solar thermal power plants. Additionally, PCM TES units are increasingly employed in home heating applications to store heat during off-peak hours for daytime space heating needs [123,124]. In summary, PCM TES has the potential to improve the performance, efficiency, and reliability of solar technology. Ongoing efforts focus on optimizing heat transfer rates and cycling stability. To achieve broader adoption, it is essential to address concerns related to durability and the cost-performance ratio [125,126]. Nevertheless, PCM TES holds promise for significant sustainability benefits through more intelligent utilization of solar energy.

3. Incorporation of PCMs into building envelopes

The discussion on integrating PCMs into building applications primarily focuses on evaluating their impact on human thermal comfort and analyzing temperature variations on building envelope surfaces. Aligned with the European Union's ambitious goal of an 80 % reduction in primary resource consumption by 2050, the Holistic Energy and Architectural Retrofit Toolkit (HEART) aims to contribute to the creation of nearly zero-energy buildings. The HEART toolkit envisions smart buildings that integrate electric, thermal, and information flows, necessitating a transition to intelligent management systems and energy-efficient technologies [127]. Interconnected subcomponents within the HEART project encompass a Decision Support System, prefabricated insulation, universal Photovoltaic (PV) tiles, power controllers, heat pumps, storage units, battery packs, and smart fan coils. Given that buildings account for 40 % of the European Union's total energy consumption, effectively harnessing renewable energy is imperative [128]. To address retrofitting challenges in residential buildings, the integration of PCMs into thermal storage aims to enhance energy efficiency and sustainability in building applications.

3.1. Solar control techniques

The integration of PCMs into passive cooling techniques redefines solar control. PCMs, known for their latent heat absorption and release, add dynamism to passive cooling. Incorporated into building elements, like walls and windows, PCMs act as thermal batteries, absorbing excess heat during high solar exposure and releasing it when temperatures drop. This transformative approach enhances overall thermal performance, offering an efficient means of temperature regulation without heavy reliance on active cooling. The incorporation of PCMs stands as a cutting-edge solution for sustainable and innovative solar control in building design.

3.1.1. Climate

The examination of the utilization of passive PCM in diverse climates has been carried out. The Köppen-Geiger climate classification system, which is classified based on temperature, rainfall, and other climatic characteristics, has been employed for this investigation [129]. In Table 2, several studies have been scrutinized in this context. In Equatorial Singapore, exterior PCM reduces annual heat gain by 21–32 % [130]. Warm Temperate Lleida, Spain, sees PCM mitigate temperature swings, leading to a 15 % energy drop and 1–1.5 kg/year/m^2 CO^2 reduction in summer [131]. In snowy Beijing, shape stabilized PCMs cut daily maximum temperatures by 2 °C [132]. Mediterranean Egypt

Table 2
PCM Integration in Climate Control.

Location, Climate Classification (Köppen-Geiger climate classification)	Key Findings*	Ref
Singapore, Equatorial (Af).	• In exterior applications, resulted in substantial annual heat gain reduction by 21–32 % • Thicker PCM layers exhibited diminishing efficiency and cost benefits, highlighting the overall effectiveness of PCM integration in enhancing building envelope thermal management.	[130]
Lleida, Spain, Warm Temperate (Csa).	• Alleviates daily temperature swings, resulting in a considerable 15 % drop in energy usage and a notable decrease of 1–1.5 kg/year/m2 in CO2 emissions during the summer season.	[131]
Beijing, China, Snow (Dwa).	• Optimized shape stabilized PCM (SSPCM) plates, designed with a melting temperature of 26 °C and a thickness of 20 mm, demonstrated a significant reduction of up to 2 °C in daily maximum temperatures. This showcases the potential for these specific SSPCM attributes to contribute to energy-efficient cooling in summer.	[132]
Egypt, Mediterranean (Csa).	• PCM integration in ceiling panels results in a 7 °C indoor temperature decreases and 14 % total cooling energy savings for an office building.	[133]
Rome, Italy, Mediterranean (Csa) Abu Dhabi, UAE, Arid (BWh).	• The study assessed an innovative cool polyurethane-based membrane with PCM for roofing, finding that PCM integration significantly reduced roof surface temperatures, with optimal results in the cool membrane and PCM around 25 °C to 31 °C, demonstrating effective passive cooling potential in peak summer conditions for Rome and Abu Dhabi.	[134]
Vicuña, Chile, Semi-arid (BSh), and Calama, Chile, Arid (BWk).	• Reduces PV temperatures by up to 17.5 °C, leading to a 5.8 % increase in power generation in Vicuña and a 4.5 % increase in Calama. The suggested setup involves a 40 mm layer of CaCl2–6H2O.	[135]

* The percentage savings presented in the table provided in the referenced papers are indicative and should not be used for explicit work. These numbers serve as estimations based on the specific contexts of the studies cited and may not directly apply to all scenarios. Factors such as building design, climate conditions, and PCM properties can significantly influence actual energy savings.

benefits from a 7 °C indoor temperature drop and 14 % cooling energy savings with PCM in ceiling panels [133]. Rome and Abu Dhabi showcase effective passive cooling in roofing with PCM around 25–31 °C [134]. Semi-arid and arid Vicuña and Calama experience enhanced PV power generation (5.8 % and 4.5 %, respectively) with a 40 mm layer of CaCl^2–6H2O [153].

3.1.2. Building orientation

Strategic building orientation plays a pivotal role in maximizing solar gains during winter while mitigating excess heat in summer, a cornerstone of energy-efficient passive design. Integrating PCMs into selectively oriented building envelopes and walls further enhances solar control and thermal regulation capabilities. Ideally, buildings should be oriented to have their longest facades facing south for consistent solar exposure without extensive east or west facing walls, prone to excessive summer sun. Overhangs and shading devices can further minimize high-angle summer sunlight [136]. Enhancing south walls with PCM insulation layers, panels, or modules allows for the absorption of intense solar gains during the day through latent heat storage as the PCM melts [137,138]. The stored heat is then released slowly as ambient temperatures cool, creating a thermal buffering effect that maximizes winter solar gain benefits while curbing overheating risks in summer [139,140]. Strategically placing PCM layers in east, west, or roof assemblies assists in managing solar loads based on orientations. Varying PCM melting points and positioning PCMs internally or externally allow for tuning thermal inertia, leading to improved occupant comfort and energy efficiency [137]. In cooling-dominated climates, an elongated east–west axis is preferred to minimize east and west solar exposure. External shading projections and high-performance glazing should be optimized to meet codes [141]. PCM integration remains beneficial for additional solar control. Table 3 summarizes key findings from various studies focusing on the impact of PCMs on building orientations for ideal solar gain.

3.1.3. Shading devices

Shading devices, like overhangs and louvers, are crucial in diminishing the requirement for artificial lighting and internal heat generation

Table 3
PCM Integration Orientation Strategies.

Focus	Key Findings*	Ref
Innovative Application of PCMs for Energy Savings.	• PCMs in buildings reduce heat loads by up to 75 %, especially effective for variable load intensity. • Limited impact on North-facing walls; solar radiation intensity crucial for PCM's effect on energy consumption.	[137]
Performance of BIPV and BIPV-PCM Modules in Experimental Room.	• BIPV-PCM module with inorganic glauber salt PCM shows a 10 % increase in electrical efficiency. • Reduced surface temperature and a peak temperature drop of 8 °C observed. • East orientation yields optimal results, advocating for BIPV-PCM adoption in hot and humid climates.	[138]
PCM Impact on Building Orientations for Passive Cooling.	• Energy savings of 70–90 % observed in South-facing walls during peak summer. • Limited savings for North and West walls, emphasizing the importance of strategic PCM placement and layer thickness.	[139]
Comparative Simulation of Walls with and without PCMs.	• No clear optimum temperature; range between 5 °C and 35 °C. • PCM helps reduce maximum heat flux, leading to a decrease in power requirements for HVAC systems. • Unexpected fluctuations in total heat attributed to the high thermal inertia of standard walls.	[140]
Optimization of Thermal Management in PV Modules using Multiple PCMs.	• Innovative arrangement of multiple PCMs enhances melting time by up to 18 %. • Extends PV thermal management duration by 33 %. • Effectiveness influenced by PV inclination and the number of PCMs. • Lower inclination angle and more PCMs augment thermal management potential, improving electrical efficiency and energy storage capacity.	[142]

* The percentage savings presented in the table provided in the referenced papers are indicative and should not be used for explicit work. These numbers serve as estimations based on the specific contexts of the studies cited and may not directly apply to all scenarios.

[12,143]. Emphasizing the importance of passive shading instruments in enhancing energy efficiency, highlighting their role in sustainable architectural design through the endorsement of diverse shading methods. This encourages the implementation of various shading strategies (as passive, active and hybrid shading [144]) to maximize energy conservation and support passive cooling in buildings.

Table 4 highlights some of the key studies that have analyzed the energy and comfort improvements from integrating PCMs into different forms of shading systems. Shading devices incorporating PCMs demonstrate substantial benefits, with a 5 % reduction in cooling load and variations in angles and length leading to an 8 % increase in savings [14]. The application of PCMs to shading systems results in a noteworthy 44 % decrease in cooling energy consumption and a remarkable 34 % improvement in comfortable hours [145]. Combined with other strategies, such as insulation and PV panels, these findings underscore the potential of shading devices with PCMs in achieving significant energy savings and enhancing building performance [146–149]. The studies overall verify promising potential for PCM-enhanced shading devices as a passive cooling technique meriting further real-world testing and optimization.

Table 4
PCM Integration with Shading Devices Strategies.

Shading Type	Location	Climate Zone	Key Findings*	Ref
Horizontal Fins with PCM.	Darwin, Australia.	Hot and humid.	• 5 % reduction in cooling load, while variations in angles and length increased savings to 8 %.	[14]
Horizontal louvers with PCM.	South Korea.	Temperate.	• 44 % cooling energy savings. • 34 % more comfortable hours.	[145]
Generic with optimized PCM.	Algeria.	Multiple zones.	• Up to 63 % heating energy savings15% cooling savings in hot/dry climates.	[146]
Envelope shading and exterior wall thermal insulation with PCM.	Chongqing, China.	monsoonal humid subtropical.	• 11.31 % and 11.55 % savings in AC electric consumption. • When combined, 25.92 % reduction in annual AC electric consumption, 21.08 % cooling and 34.77 % heating electric consumption.	[147]
External shading and insulation including PCMs and PV panels.	Madagascar	Coastal Tropical	• Enhance comfort by 3 %, cut cooling energy use by 12 % in coastal offices. External shading and insulation reduce cooling by 19 %. PV panels contribute 43–79 % of total energy.	[148]
Dynamic Solar Shading Device with alveolar polycarbonate panels filled with PCMs.	Turin, Italy.	Mediterranean	• 40 % reduction in cooling energy, enhanced window thermal inertia, and improved indoor comfort.	[149]

* The percentage savings presented in the table provided in the referenced papers are indicative and should not be used for explicit work. These numbers serve as estimations based on the specific contexts of the studies cited and may not directly apply to all scenarios.

3.1.4. *Wall construction*

The integration of PCMs in wall construction has emerged as a promising avenue for effectively managing excess solar heat gains and enhancing energy efficiency in buildings. The PCM-Enhanced Wall System, investigated through theoretical modeling and energy demand analysis, explores the nuanced relationship between energy savings and factors such as optimal melting points and ventilation strategies [150–152]. Double Skin Façades (DSF) take center stage as mathematical modeling and simulations in temperate continental climates underscore their potential, emphasizing key configurations like dual-PCM melting temperatures, thicknesses, and multistep placements for optimal performance [153,154]. Cavity walls, a crucial component in building envelopes, play a pivotal role in reducing energy loss. Parametric studies and numerical models elucidate the importance of PCM layer locations within the cavity, with optimal thicknesses and phase transition temperatures identified for efficient space cooling [155,156]. This thorough examination, as indicated in Table 5, delves into the cooperative initiatives aimed at progressing sustainable and energy-efficient building methods.

3.1.5. *Window*

Windows play a significant role in a building's heating and cooling load, regardless of advancements in coatings, sealed glazing, and tight gaskets [157]. The ventilated window (VW) concept focuses on regulating outdoor airflow through the double window cavity, aiming to reduce solar heat gain in summer, minimize room heating load, and enhance thermal comfort by utilizing solar radiation to preheat ventilation air in winter [158]. However, challenges arise as the pretreated supply air temperature often falls short of reaching room temperature [159]. To address this limitation, PCM emerges as a promising solution. PCM can provide additional thermal storage in the VW, forming an active system for enhanced performance. Table 6 showcases a variety of research outcomes associated with the utilization of windows for sunlight exposure in passive cooling techniques.

3.2. *Passive desiccant cooling*

Passive desiccant cooling systems, an innovative answer to energy-efficient air conditioning, have gained prominence in recent literature. They are highlighted for their potential to achieve precise control over indoor temperature and humidity by combining desiccants with other passive strategies. Significant progress has been made, particularly in integrating PCMs and desiccants. These two elements work together synergistically, effectively managing dynamic thermal conditions. Table 7 presents research findings on the subject, delving into various investigations in this field.

3.3. *Heat dissipation techniques*

3.3.1. *Evaporative cooling*

Tailored for hot and arid climates as well as temperate regions, evaporative cooling offers an alluring alternative to conventional air conditioning systems such as vapor compression, absorption, or thermoelectric refrigeration, providing not only economic advantages but also contributing to environmental sustainability [168]. The fundamental principle revolves around leveraging the substantial enthalpy of water evaporation to effectively absorb heat from the surrounding air,

Table 5
PCM Integration in Wall Construction.

Type of wall	Research Approaches	Key Findings*	Ref
PCM-Enhanced Wall System.	Theoretical Modeling, Energy Demand Analysis.	• Optimal PCM melting point varies (18–19.5 °C), yielding minimum energy demand at 19 °C. Highest savings for pattern C at 18 °C without ventilation, reduced with active ventilation.	[150]
PCM integration in building walls and roof studied in hot climate of Aswan, Egypt.	Experimental Employed a 2D thermal model in ANSYS 2020 R1.	• PCM achieves 2 °C Average Indoor Temperature Reduction, up to 8.71 % Thermal Load Levelling Reduction, 56 W Average Heat Gain Reduction, 1.35 kg/day CO2 Emissions Saving, and 80.64 IQD/day Energy Cost Saving. Roof application proves more effective.	[151]
PCM on inside and outside of exterior walls.	Parametric and economic analysis Sichuan hills, China.	• Inside wall PCM placement achieves 16.89 % higher energy savings. Optimal combo cuts demand by 21.07 %. PCM thickness, conductivity key for energy and economic benefits. Investment balanced in 25 years below 6.75 CNY/kg.	[152]
DSF	Mathematical modeling, simulation, evaluation under a temperate continental climate.	• Optimal DPCM configuration: 28 °C and 16 °C melting temperatures, 36 mm thickness, multistep placement, yielding lowest heat transfer rate (30.03 W). In Urumqi's climate, daytime ventilation peaks at 91.4 % efficiency. Optimal flow velocity for energy performance and climate balance is 1.09 m/s, achieving 79.7 % respiratory efficiency.	[153]
DSF	Energy Performance Study in Three Climates.	• Tehran (Mediterranean): Peak energy savings 1439 kWh (77.2 %) in November. Tabriz (Cold/Semi-arid): Peak savings 453 kWh (61.4 %) in May. Kish (Hot/Semi-arid): Peak savings 120 kWh (30.5 %) in February.	[154]
Cavity wall	Parametric Study, Numerical Model, Experimental Verification.	• Optimal PCM location crucial for over 50 % heat flux reduction, shifting outward with increased wall insulation. Peak reductions at 7 mm thickness offer installation flexibility. Efficient cooling requires PCM transition temperature of 27 °C-31 °C, aligning closely with experimental data, showing a 3.5 % average peak heat flux difference.	[155]
Cavity wall	Experimental and Numerical Analyzes.	• 5 % reduction in energy consumption to maintain indoor air temperatures between 24 °C and 26 °C.	[156]

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resulting in a significant reduction in air temperature and a simultaneous increase in humidity [169]. This technique's adaptability is showcased through its classification into two primary types: direct evaporative cooling (DEC) and indirect evaporative cooling (IEC) [170]. Experiments conducted in Bangalore, India, exhibit enhanced solidification behavior, faster-charging duration, and increased heat transfer rate in the hybrid system PCM-based storage system, highlighting its potential for efficient and sustainable cooling solutions. The integrated system outperforms the conventional FC system, presenting a promising approach for energy-efficient building cooling or integration with existing HVAC systems, with further research avenues identified for optimization and parameter analysis [171]. DEC entails direct interaction between the air stream and water, utilizing the sensible heat of air to facilitate water evaporation. This process induces a drop in air temperature and an elevation in humidity, with its efficiency contingent on the moisture content of the intake air [172,173].

Conversely, IEC employs a heat-exchanging wall to segregate dry and wet air streams, preventing additional moisture in the product air [173]. Suggested guidance proposes combining IEC with additional cooling systems to enhance overall performance, emphasizing factors such as cooling effectiveness, temperature reduction, and reliance on climatic conditions [174]. The results of a study on a solar-powered solid desiccant air conditioning (SPSDAC) with a PCM unit, employing two modes of indirect evaporative cooling (IEC), demonstrated energy efficiency. COP surpassed the exergy efficiency, ranging from 1.83 % to 1.99 %, and in mode-2, the mean overall thermal storage capacity reached 1817.7 W, highlighting the effectiveness of the system and its potential for sustainable cooling solutions [175].

3.3.2. Convective cooling

PCMs are pivotal in enhancing convective cooling across various ventilation strategies. In Natural Ventilation, PCMs strategically integrated into building materials optimize cooling by absorbing and releasing heat, stabilizing indoor temperatures and enhancing overall comfort [176]. Mechanical Ventilation systems, including Trombe walls, Solar chimneys, and Buoyancy-driven stack ventilation, incorporate PCMs to absorb and release solar heat, facilitating convective airflow. PCM-enabled Solar chimneys strategically release stored heat to enhance cooling, and in Buoyancy-driven stack ventilation, PCMs optimize air circulation [177]. Nocturnal Ventilation, designed for nighttime cooling, benefits significantly from PCMs, which absorb excess heat during the day and release it at night, improving air exchange and thermal radiation. PCM-enabled nocturnal ventilation enhances energy efficiency by utilizing the material's capacity to store and release energy, contributing to effective convective cooling methods [178]. Table 8 reviews multiple studies in this field and provides a condensed overview of their findings.

Table 6

PCM Integration in Windows.

Type of wall	Research Approaches	Key Findings*	Ref
PCM-VW	EnergyPlus model validated, control strategies tested for Danish climate.	• Energy savings up to 62.3 % and 9.4 % compared to primitive strategies for summer and winter applications, respectively. • Window orientation influences energy savings, with southwest-facing windows showing higher savings.	[158]
double-glazed window-PCM and solar control glass.	Examined numerically its thermal characteristics during summer in northern China.	• A PCM double-glazed window with solar control glass exhibits energy savings of 14.25 % on sunny days and 26.31 % on cloudy days with a glass absorption coefficient of 160 m^{-1}. With a glass refractive index of 3, the energy savings increase to 41.53 % on sunny days and 24.33 % on cloudy days.	[160]
PCM in high-rise apartments with 80 % window-to-wall ratio.	Investigated reducing solar absorptivity and enhancing latent heat storage.	• Significant reduction in peak temperatures by up to 6 °C. PCM system exhibited 15.6–47.6 % decrease in heat transfer with efficient thermal storage for retrofit projects.	[161]
PCM-Enhanced Window with Solar Reflector.	Large-scale climate simulator and dynamic cycles.	• PCM-window activates phase change at 28.5 °C, yielding $>$ 4 °C temperature difference; incomplete transition results in $<$ 2 °C. In Test 9, TES decreases, showing $<$ 3 °C temperature difference after solar pulses; PCM-window's thermal inertia requires at least 24-hour relaxation for steady state.	[162]

* The percentage savings presented in the table provided in the referenced papers are indicative and should not be used for explicit work. These numbers serve as estimations based on the specific contexts of the studies cited and may not directly apply to all scenarios.

3.3.3. *Radiative cooling*

RC utilizing the Earth's atmosphere and sky as a heat sink, has been employed for centuries, notably in ancient ice-making practices [192]. This passive cooling method gains contemporary significance in building energy efficiency. Solar reflectance, emissive radiators, and materials like polymers and inorganic particles influence RC during the day [193]. Yet, challenges persist in realizing novel radiative radiators, potentially leading to supercooling and increased heating demands [194]. Integrating PCMs into building envelopes offers a solution, buffering against supercooling and enhancing thermal capacity [195]. Studies by various authors, summarized in Table 9, underscore the potential and applications of RC, emphasizing system optimization, climatic considerations, and material constraints.

Table 7

PCM Integration in Passive Desiccant Cooling Systems.

Research Methods	Key Findings*	Ref
Numerical comparison of air desiccant cooling system performance with three thermal energy sources of Cairo-Egypt.	• average Energy savings ~ 75.82 %. • the highest percentage savings in electrical energy consumption, ranging from 60.87 % to 90 %. • At an energy cost of 0.55 LE/kWh, the economic analysis reveals a reduced annual operating cost of 626 LE, resulting in a shorter payback time and amplified life cycle savings.	[163]
Simulation assesses 2-phase passive cooling in a Harare office, combining desiccants and PCMs for comfort.	• The study emphasizes desiccants' collaborative role in achieving comfort with PCMs in passive cooling. • Load management maintains 60 % relative humidity and around 27 ∘C; without PCM and desiccant, discomfort arises with 80 % humidity and 30 ∘C.	[164]
Novel solar-powered desiccant air conditioning system enhanced with PCM in PVT solar collector for a typical day in August.	• Maximum cooling COP (Coefficient of Performance) and distillate water production were 0.411 and 4.9 l/h, respectively, at an air mass flow rate of 0.78 kg/s. Maximum electrical power generation and efficiency of the PV collector were 0.72 kWh and 13.7 %, respectively, at 13:00. PCM delivered approximately 0.89 kWh of thermal energy to the air conditioning system. • Thermal COP ranged from 0.12 to 0.411, with freshwater production varying from 0.76 l/h to 4.9 l/h for different air mass flow rates.	[165]
PVT solar collector, PCM, transient simulations assess seasonal performance.	• Maximum PV module electricity generation occurs in October at 0.77 kW, with minimum electrical efficiency in September at 13.6 %. • Implemented for solar desiccant air conditioning system enhanced by PCM, utilizing solar energy for desiccant wheel regeneration, and reducing auxiliary heater energy consumption.	[166]
PCM-based Solar Desiccant Cooling (PSDC) and Heat Pump Hybridized with PCM-based Solar Desiccant Cooling (HP-PSDC) in various cities.	• The PCM-PSDC demonstrated a COP of 1.44 in Toronto and 1.05 in Vancouver. In contrast, the Heat Pump Hybridized with PCM-HP-PSDC achieved a COP of 4.98 in Doha and 4.5 in Bangkok, with PMV and PPD values meeting comfort criteria.	[167]

* The percentage savings presented in the table provided in the referenced papers are indicative and should not be used for explicit work. These numbers serve as estimations based on the specific contexts of the studies cited and may not directly apply to all scenarios.

3.4. *Heat modulation*

3.4.1. *Free cooling*

FC an essential facet of passive cooling, capitalizes on nocturnal coolness to counter daytime heat in buildings. This technique exploits a structure's thermal mass, and its efficacy can be significantly augmented by incorporating PCMs. PCMs, with their latent heat storage capabilities, optimize FC, reducing system sizes and enhancing overall efficiency. Thoughtful selection of PCM melting temperatures ensures tailored application across various climates. This harmonious integration of FC and PCMs represents an innovative, sustainable solution, providing cost-effective management of daytime heat accumulation through strategic nocturnal cooling processes in building design [171,200,201]. Table 10

Table 8
PCM Integration in Convective cooling Systems.

Methods of Research	Key Findings*	Ref
Natural Ventilation with PCM.	• High energy savings were obtained in the scenario with PCM and controlled ventilation e.g. Brisbane (59.19 %), Seville (31.5 %), Cagliari (35 %), Madrid (39.86 %), Cedula (48 %), and Antofagasta (54.57 %). • In moderate climates, combining a PCM passive system with NV led to an improvement in effectiveness, escalating from 3.32 % to 25.62 %.	[179]
Natural Ventilation with PCM.	• Increase contact area by 3.6 times. • Utilizing encapsulation shapes like fins, cylinders, and spheres continues to enhance convective heat transfer coefficients, ensuring the efficient utilization of substantial amounts of PCM.	[180]
Natural Ventilation with PCM.	• Wind speed as a key parameter for maximizing coolness at night. • Controlled fan operation based on outdoor temperature (Optimum fan operation time between 19:00 and 7:00). • PCM thickness of 6 mm was identified as optimum for hot and humid conditions.	[181]
Mechanical Ventilation Trombe wall with integrated PCM wallboards.	• Reduction in annual cooling energy consumption by 20.8 % at an indoor air temperature of 22 °C and 18.6 % at 24 °C compared to classical Trombe wall systems. • The use of high-reflective coating and nighttime ventilation resulted in an average cooling energy release of 43.5 W/m^2 for interior PCM and 44.2 W/m^2 for exterior PCM in severe summer conditions.	[182]
Mechanical Ventilation with double-layer PCM Trombe wall	• In summer, the new double layers PCM Trombe wall reduced average room temperature by 1.09–2.91 °C, delayed peak temperature occurrence, and decreased heat flux by 9.1 %-92 %. • In winter, the new double layers PCM Trombe wall outperformed in maintaining higher maximal temperature, reducing heat flux, and achieving better decrement factor, discomfort degree, and fluctuation number compared to other walls.	[183]
Solar chimneys with a PCM	• CFD models optimized solar chimney sizing, indicating an optimal channel width of 10–30 cm and a chimney height of 2–3 m to prevent recirculation. Limited development of transient CFD models with PCM, due to computational challenges, and GEB models integrating PCM suggested potential for enhancing nocturnal ventilation.	[184]
PCM integrated solar chimney under laboratory conditions.	• PCM-integrated solar chimney maintains 40 °C + surface temperature for 6 hrs without heat, marking a 33 % increase over the non-PCM counterpart. • In the charging phases, PCM and No-PCM cycles show similar mass flow rates, but in ventilation phases, PCM achieves over 60 m^3/h consistently.	[185]
Buoyancy-driven- with encapsulated PCM.	• where convection dominates heat transfer, there is a significant reduction in melting time—up to 500 % in vertical orientation and a remarkable 1600 % in horizontal orientation. • For low Prandtl number PCMs, the impact of convection is minimal due to the high conductivity of the PCM. This results in a melting time change of less than 7 % in the vertical orientation and 22 % in the horizontal orientation.	[186]
Buoyancy-driven melting around horizontal cylinder in PCM.	• The study extensively examines melt characteristics and thermal development around a 2D circular cylinder in lauric acid-filled square enclosure under laminar natural convection. It optimizes lauric acid melting with cost-effective heat transfer, emphasizing the cylinder position's impact on convective heat transport, melt fraction, and energy storage.	[187]
Wind-driven (PCM-VW).	• Optimizing the melting temperature of PCMs in building envelopes, combined with temperature-controlled natural ventilation, achieves significant cooling energy savings, up to approximately 300 kWh/year in mild climates.	[12]
(PCM-VW).	• During ventilation pre-cooling, the PCM heat exchanger lowers room inlet air temperature by 1.4 °C for 7 h, saving 0.7 MJ/day. In ventilation preheating, the PCM raises inlet air temperature by 2.0 °C for 12 h, saving 1.6 MJ/day. The PCM-VW, with self-cooling, mitigates overheating compared to a standard ventilated window.	[188]
PCM-nocturnal sky radiator.	• A novel PCM-embedded wall with a nocturnal sky radiator enhances building energy performance, reducing internal surface temperature by 1.6 °C. Compared to a common wall, it reduces cooling demand by 37.8–57.8 %, achieving 15.7–24.1 % energy savings.	[189]
Pipe-encapsulated PCM wall and nocturnal sky.	• In the cooling season, the coupled wall system reduces the average internal surface temperature by 0.7 °C, internal surface heat flux by 53.0 %, and required cooling energy consumption by 16.1 %, indicating its potential for low-energy buildings.	[190]
PCM-NV for cooling in different climates.	• Optimal PCM transition temperatures are influenced by thermal insulation, cooling set points, and climate. In hot-dry and sub-tropical climates, well-insulated envelopes improve PCM effectiveness, reducing optimal transition temperature by 1 °C. PCM thickness affects energy savings, with thicker PCMs yielding incremental gains.	[191]

* The percentage savings presented in the table provided in the referenced papers are indicative and should not be used for explicit work. These numbers serve as estimations based on the specific contexts of the studies cited and may not directly apply to all scenarios.

showcases the outcomes of multiple investigations scrutinizing the integration of PCM PCM-FC by principles of energy efficiency.

3.4.2. *Thermal mass*

The incorporation of PCMs into thermal mass components, such as wallboards, windows, roofs, and ceilings, presents a compelling avenue for optimizing these strategies. The diverse techniques for PCM

Table 9
PCM Integration in Radiative cooling Systems.

Research Methods	Key Findings*	Ref
Coupling effect of RC-PCM on building wall.	• Combining PCM with RC on building walls achieves a substantial exterior temperature reduction of up to 13.63 °C, demonstrating enhanced passive cooling and improved thermal control for energy-efficient buildings.	[193]
RC-PCM wall, integrating microchannel heat pipes.	• Experiments and a mathematical model demonstrated that RC-PCM, with parameters like wind speed, emissivity, and PCM thickness considered, exhibited a negative correlation between interior surface temperature and wind speed. RC-PCM cooling loads were 25 % lower than a brick wall and 42 % under ideal conditions. A 20-mm PCM thickness yielded 6 % lower cooling loads than a 15-mm thickness.	[196]
Microencapsulated PCM slurry storage system combined with a nocturnal RC.	• Using ACCURACY and MATLAB, simulations across five Chinese cities showed substantial energy savings potential, with Lanzhou and Urumqi reaching 77 % and 62 % for low-rise buildings. The hybrid system, recommended for dry and cool climates, demonstrated significant energy-saving impacts in northern and central China.	[197]
RC-PCM-wall.	• Field tests showed peak interior surface temperatures of 40.7 °C (Room A), 34.9 °C (Room B), and 32.5 °C (Room C). Daily average temperatures were 27.8 °C, 27.3 °C, and 27.0 °C, respectively, with PCM melting time in Room C extended by 2.3 h. Cooling loads from the south wall decreased by 47.9 % and 23.8 % in Room C compared to Rooms A and B.	[198]
integrating daytime RC-PCM storage for an office in a hot, dry climate.	• Implementing diurnal RC for daytime load reduction results in a significant 14 kg reduction in PCM mass, leading to a notable 10 % overall cost saving. The system not only improves comfort conditions by minimizing radiant asymmetry but also demonstrates potential applications for pre-cooling ventilation air.	[199]

* The percentage savings presented in the table provided in the referenced papers are indicative and should not be used for explicit work. These numbers serve as estimations based on the specific contexts of the studies cited and may not directly apply to all scenarios.

Table 10
PCM Integration in Free cooling Systems.

Methods of Research	Key Findings*	Ref
PCM-FC, Ventilation system studied numerically.	• a 4-hour complete freezing of PCM during the charging process at 20 °C and 7 m/s air speed; a 0.5-hour decrease in melting time with a 17 % increase in Reynolds number during the discharge process, and a 1-hour increase with a 25 % reduction in Stephen's number; optimal ventilation occurring at the lowest Reynolds number (4660) and Stephen number (0.075) during discharge, providing 5 h of melting time and 2.1 h of optimal air for room ventilation at 420 m3/h with an average cooling air injection of 1.4 kW.	[200]
Hybrid cooling: PCM, water spray in cylindrical tank.	• reduction in charging duration (up to 34.8 %) and improved heat transfer rate observed compared to conventional FC systems. The integration of the evaporative cooling unit accelerates PCM solidification and enhances thermal performance.	[171]
Optimizing PCM solidification with increased thermal conductivity and heat transfer fluid (HTF).	• increasing PCM thermal conductivity reduces charging duration, with more significant effects at lower HTF temperatures. Higher HTF velocities are beneficial when the inlet HTF temperature is higher, and beyond 4 m/s, there is no significant difference in charging duration. The research emphasizes optimizing both PCM thermal conductivity and HTF velocity for improved latent heat TES system performance.	[201]
Year-round operation of PCM-based FC in the tropics studied.	• Enhanced FC systems (EFCS), integrating FC with direct evaporative cooling, demonstrate enhanced cooling potential, particularly in hot-dry and warm-humid climates. A study assessing major Indian cities indicates year-round operational feasibility in temperate climates. Experimental validation highlights EFCS advantages, reducing PCM solidification time and achieving complete solidification in challenging climates.	[202]

* The percentage savings presented in the table provided in the referenced papers are indicative and should not be used for explicit work. These numbers serve as estimations based on the specific contexts of the studies cited and may not directly apply to all scenarios.

integration, including direct incorporation, immersion, vacuum impregnation, encapsulation, and shape stabilization, cater to different building elements, ensuring a comprehensive approach to passive cooling.

The specific application of PCMs in various building components is crucial for achieving targeted passive cooling benefits. For instance, in walls, PCM-infused materials absorb and release latent heat, stabilizing indoor temperatures [203]. Windows with PCM coatings mitigate heat gain during daylight hours, contributing to reduced reliance on active cooling systems [204]. Roofing materials with embedded PCMs enhance the building's ability to absorb and release solar heat [205], while PCM integration in ceilings contributes to thermal stability [66]. These instances showcase the flexibility and effectiveness of PCMs in various building components, underscoring their significance in the design of sustainable and energy-efficient buildings, as outlined in Table 11.

4. Conclusion

The integration of PCMs into building envelopes offers a promising solution for enhancing energy efficiency and thermal comfort. However, challenges such as scalability, compatibility with various building materials, reliability in real-world conditions, and end-of-life considerations for responsible disposal or recycling must be addressed [44,219–221]. Overcoming these hurdles through targeted research efforts is essential to fully leverage the benefits of PCMs. Future research avenues encompass exploring bio-based and composite PCMs to

Table 11
PCM Integration in Thermal mass Systems.

Type of wall	Research Approaches	Key Findings	Ref
PCM Wall.	PCM in lightweight construction.	• PCM induces 2-hour time lag; Numerical model 5 % deviation. • reduced external temperature amplitudes.	[206]
PCM Energy-Storing Wallboard.	Experimental, Numerical.	• New PCM wallboard enhances thermal comfort and reduces heating energy by 17 % with specific parameters.	[207]
chamber equipped with PCM.	Investigated thermal performance through complete cycle experiments.	• PCM boards lower interior wall surface temperature. • Almost twice the heat flux density compared to standard walls. • Superior insulation during charging. • Enhanced heat release during discharging. • Higher convective heat transfer coefficient.	[208]
PCM-Integrated Wall.	Experimental, Simulation, (EnergyPlus).	• PCM boards enhance energy efficiency, and reduce temperature fluctuations. Effective in Montreal from February, potential for 20 % energy reduction. • Adaptations needed for Mediterranean climates.	[209]
3 cm of PCM plaster on all building exposures.	Simulation, Energy Analysis. Five cities considered: Ankara, Athens, Naples, Marseille, Seville.	• Cooling energy reduction in Ankara is 7.2 % at 29 °C, while Seville and Naples see less than 3.0 % benefit. Not-overheating time increases comfort hours, particularly at 26 °C and 29 °C melting temperatures. Comfort time rises from 11.2 % to 21.9 % in Athens and from 32.9 % to 51.0 % in Marseille at 26 °C. Further improvement at 29 °C is noted in Seville (15.4 %) and Naples (22.9 %).	[210]
PCMs into the conventional walls of buildings.	Numerical simulation Thirteen different PCMs incorporated into conventional walls in Isfahan, Iran.	• Increasing PCM percentage enhances energy storage, but the relationship is not linear. • Doubling PCM thickness results in less than a twofold reduction in heat transfer.	[211]
Lightweight Building Walls (LBW) with PCM.	Numerical simulation of heat transfer model.	• Ideal PCM placement in LBW at a suitable phase-transition temperature, with a thickness under 10 mm, reduces temperature fluctuations, improving thermal performance by minimizing heat flux and energy consumption.	[212]
PCM Window Panel.	Experimental, Numerical Dynamic Thermal Performance Investigation.	• PCM-filled window panels reduce heat transfer by 66 %, store solar energy, and improve thermal performance. • PCM window panels maintain interior surface temperature (21–23 °C) in summer, reducing heat transfer compared to double glazing.	[204]
VW with PCM Heat Exchanger.	Numerical Modeling and Full-Scale Experiment.	• Configuration optimization is climate-dependent, and in a Copenhagen case study, a 10 mm plate thickness heat exchanger achieves optimal cooling, saving 3.19 MJ/day with 16.87 % material cost reduction compared to a 20 mm plate. A 5 mm plate provides faster thermal response and 37.35 % material cost savings for shorter discharge times.	[213]
Triple-Glazed Window with PCM (TW − PCM).	Simulation and Mathematical Modeling.	• TW + PCM reduces energy consumption by 21.30 % and 32.80 % compared to DW + PCM and TW on sunny summer days. It performs well in winter, minimizing interior surface temperature fluctuations and saving heating energy.	[214]
Sloped Roofs and Adjacent Attics.	Analysis, Testing, and Field Testing.	• Advanced roof configurations achieve over 90 % reductions in peak-hour cooling loads and close to 60 % reductions in overall cooling loads. Various strategies, including thermal mass and reflective technologies, contribute to significant energy savings.	[215]
Roofs with PCM.	Numerical Investigation.	• PCM roofs in Northeast China show a robust temperature delay, over 3 h compared to common roofs. • Transition temperature and latent heat impact are weak, while roof slope, PCM thickness, and absorption coefficients significantly influence performance, emphasizing the importance of optimizing these factors for enhanced thermal energy storage, reduced heat loss, and improved comfort.	[216]

(continued on next page)

Table 11 (*continued*)

Type of wall	Research Approaches	Key Findings	Ref
Multiple-Glazing Roof with PCM.	Numerical Study in a cold climate (Daqing, China).	• Energy savings reach 14.08 % in summer and 33.74 % in winter, with a total cost saving of 217 Yuan/m^2 over the full life cycle compared to a traditional air-filled multiple-glazing roof. The integration of low-e glass is crucial for winter energy efficiency.	[217]
Ceiling System with PCM.	Computational Fluid Dynamics (Morocco).	• 17.07 % and 16.30 % energy savings in Csa and Csb climates.	[218]

* The percentage savings presented in the table provided in the referenced papers are indicative and should not be used for explicit work. These numbers serve as estimations based on the specific contexts of the studies cited and may not directly apply to all scenarios.

enhance thermal conductivity, optimizing PCM layer positioning and configuration, and developing tailored encapsulation methods for diverse building components [222]. Additionally, investigating the combination of multiple PCMs with staggered melting points holds the potential for improved thermal regulation. Ensuring seamless integration with conventional building materials, rigorous testing, and sustainability considerations, including life cycle assessments and eco-friendly alternatives, are paramount [57,115,223,224]. Furthermore, the development of a universal design rule or workflow would serve as a valuable reference for navigating energy-efficient building design challenges across different climates and architectural styles [225].

The analysis highlights the transformative impact of PCMs on energy efficiency and thermal performance across various applications, such as solar control techniques (reducing heat loads by up to 75 %), building orientation (achieving 70–90 % energy savings in south-facing walls during peak summer), shading devices (reducing cooling energy consumption by up to 44 %), wall construction (energy savings of 15 % to 47.6 %), window design (energy savings of up to 62.3 % and 41.53 %), climate-specific applications (reducing annual heat gain and mitigating temperature swings), passive desiccant cooling (achieving up to 75.82 % energy savings and peak electrical reductions from 60.87 % to 90 %), evaporative cooling, convective cooling strategies (reducing cooling energy consumption by 3.32 % to 59.19 %), radiative cooling (achieving a 10 % overall cost saving), heat modulation techniques (reducing charging duration by 34.8 %), and thermal mass optimization (reducing energy consumption by up to 90 %).

The integration of PCMs has demonstrated significant potential for contributing to the development of intelligent, nearly zero-energy buildings and aligning with ambitious energy reduction goals, such as the EU's target of an 80 % reduction. However, addressing the identified challenges and pursuing the outlined research directions are crucial to unlock the full potential of this innovative technology and pave the way for widespread adoption in the construction industry, ultimately promoting sustainable and energy-efficient buildings.

CRediT authorship contribution statement

Mehrdad Ghamari: Writing – review & editing, Writing – original draft, Validation, Methodology. **Chan Hwang See:** . **David Hughes:** Writing – review & editing, Validation. **Tapas Mallick:** Writing – review & editing, Methodology. **K Srinivas Reddy:** . **Kumar Patchigolla:** Writing – review & editing, Validation. **Senthilarasu Sundaram:** Writing – review & editing, Validation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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