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Energy retrofitting using advanced building envelope materials for sustainable housing: A review

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ABSTRACT

Global energy consumption by buildings represents 34% of final energy use and 37% of energy-related CO_2 emissions, emphasising the critical need for sustainable, energy-efficient housing solutions. Despite significant advancements, there is a substantial gap in effectively applying advanced materials within building envelopes to achieve optimal energy efficiency, particularly in hot climates. This study focuses on the residential sector's excessive energy consumption and greenhouse gas emissions, primarily caused by inadequate insulation and outdated construction practices. The objective is to systematically evaluate the effectiveness, performance, economic and environmental impacts, retrofitting techniques and challenges of using advanced building envelope materials, phase change materials, aerogels, vacuum insulation panels, and heat-reflective coatings for energy retrofitting in residential buildings. A comprehensive systematic review was conducted following PRISMA guidelines using the Scopus database. Rigorous inclusion and exclusion criteria produced 76 high-quality studies. The analysis synthesises findings on material performance under various climatic conditions and application strategies and their impacts on energy efficiency, thermal comfort, durability, cost-effectiveness, and sustainability. Results show that advanced materials have immense potential. They can significantly improve thermal regulation, reduce energy usage for heating and cooling, and lower CO_2 emissions with benefits varying across climates and application strategies. Challenges include high initial costs, long-term performance uncertainties, implementation issues, and broader applicability. This research uniquely contributes by comprehensively synthesising recent advancements, analysing economic feasibility and environmental impacts, offering valuable insights for stakeholders. It also emphasises the need for future research to address limitations and promote sustainable, energy-efficient building solutions.

1. Introduction

As global energy consumption continues to rise, it is a subject of serious study worldwide. In 2022, global buildings account for approximately 34% of final energy use and 37% of energy-related carbon dioxide (CO_2) emissions, accentuating their substantial environmental impact [75]. The need for sustainable and energy-efficient housing solutions has become increasingly urgent as the impacts of climate change become more apparent. In this context, the residential sector accounted for 21% of the total energy demand and 17% of emissions, emphasising its significant role. The building construction industry contributed an additional 7%, and the bricks and glass industry was responsible for 3% of emissions, highlighting the extensive environmental footprint of these sectors [75]. These sectors' emissions contribute to global warming, lead to climate change, and result in severe weather conditions, as well as adverse health effects, emphasising the critical need for reduced greenhouse gas outputs and sustainable practices [31]. Despite this significant impact, energy consumption is expected to rise in the coming years, particularly in the construction sector [10]. However, the construction sector has substantial potential for energy savings, as many existing buildings face multiple energy efficiency issues, having been designed before implementing modern regulations [81].

Consequently, targeting existing buildings for energy retrofitting presents a significant opportunity. Research indicates that energy savings in existing buildings can reach significant levels. Additionally, more than 50 per cent of heat and energy loss in buildings occurs through the building envelope [33]. The building envelope plays a critical role in

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heat transfer between the interior and exterior, and inadequate insulation can lead to substantial energy loss. Enhancing the building envelope and increasing thermal mass effectively reduces heat loss and gain, achieves indoor thermal comfort, and lowers building energy consumption [42]. Therefore, retrofitting energy in existing buildings is essential to reduce energy consumption and improve efficiency in the construction sector. Furthermore, to align with the goals of the Paris Agreement, particularly a 50% reduction in carbon emissions by 2030, there needs to be a significant increase in retrofitting rates [60].

Energy retrofitting can enhance operational energy efficiency and extend the lifespan of the current building stock, reducing environmental impact and achieving social and economic benefits [63]. A critical component of these efforts is using advanced building envelope materials as a transformative strategy. These advanced materials possess unique properties that effectively improve buildings' thermal performance [49]. Among these advanced materials, several stand out for their transformative potential. For instance, phase change materials (PCMs) are a transformative technology poised to revolutionize building design and construction due to their ability to absorb and release large amounts of thermal energy during phase transitions [13]. Similarly, aerogels have emerged as a significant focus due to their exceptional thermal insulation properties, substantially boosting building energy efficiency [58]. Vacuum insulation panels (VIPs) also represent advanced thermal insulation materials with low thermal conductivity, offering significant potential for enhancing energy efficiency, particularly in lightweight steel-framed buildings [36].

Despite their superior thermal efficiency, practical challenges associated with these materials, such as edge thermal bridging and susceptibility to damage, require careful handling and further research to improve their application [77]. Recent advancements in sustainable building retrofitting also include the integration of cool paints and radiant coatings, have demonstrated substantial energy savings in various climates, albeit with challenges related to material longevity and economic feasibility [54]. Finally, integrating advanced materials simultaneously to leverage their advantages and address potential drawbacks [49].

In light of the aforementioned considerations, this review aims to systematically evaluate recent literature on the effectiveness, performance, economic and environmental impacts, and challenges of using advanced building envelope materials for energy retrofitting in the residential building sector. The review focuses on various materials, including PCMs, aerogels, VIPs, and Heat-Reflective Coatings (HRCs). It aims to analyse the potential of advanced building materials to enhance energy efficiency, thermal comfort, long-term durability, cost-effectiveness, and sustainability in buildings. It focuses on understanding the performance of these materials under different climatic conditions and application strategies.

This research paper uniquely contributes to the existing body of knowledge by systematically evaluating recent advancements in using advanced building envelope materials for energy retrofitting in the residential sector. While most previous scientific review papers in the field focus on one or two advanced building materials, this study compares the benefits and challenges of four advanced materials and furthermore explores the integration of more than one of them. This study uses the PRISMA Flow Diagram guidelines [59] to conduct a thorough analysis of the effectiveness, performance and types of the advanced materials. It also explores their economic feasibility and environmental impacts. Particularly, this paper elucidates key factors impacting the performance of advanced materials in real-world scenarios and architectural configurations across various climatic conditions, addressing a gap in the existing literature. Moreover, it examines the challenges and obstacles that impede their implementation in residential building retrofitting. Addressing these issues is anticipated to enhance the widespread adoption of these materials, fostering a broader integration in the field. Furthermore, this paper's insights may be valuable for architects, engineers, and decision-makers who aim to implement more energy-efficient building solutions.

2. Methodology

A systematic review was conducted adhering to the PRISMA Flow Diagram guidelines [59] to investigate the efficacy of advanced materials in the energy retrofitting of building envelopes. A comprehensive search was executed within the Scopus database, employing a precise combination of keywords: (insulation OR envelope) AND (energy OR saving OR retrofit*) AND (building), which were applied to the article title, abstract, and keyword fields. The temporal scope was limited to publications from 2017 to 2023, focusing exclusively on English-language articles and conference papers to ensure the inclusion of recent and relevant literature.

Initially, a total of 9993 documents were retrieved. Subsequently, rigorous exclusion criteria were applied to refine this corpus, eliminating studies pertaining to window-specific enhancements, office building applications, active systems, renewable energy technologies, specific aspects of material manufacturing and chemical compositions, ventilated and double-skin façades, secondary sources, dynamic thermal insulation, greenery systems, material historical studies, and initial design phases. This selective exclusion process significantly narrowed the field of investigation.

Afterwards, 137 full-text documents were carefully evaluated for eligibility. Further exclusions were meticulously implemented, ensuring that only the most relevant and high-quality documents were selected. Criteria included an emphasis on structural insulated panels, utilisation of lightweight concrete insulated panels, superfluous technical detail, a focus on commercial building applications, studies relevant solely to cold climates, and comparative analyses of different interior material manufacturing processes. These strict criteria ensured that the remaining 68 documents, which included 55 peer-reviewed articles and 13 conference papers, were of the highest relevance and quality. An additional eight articles were identified through citation tracking, augmenting the corpus to a total of 76 documents. These documents were subjected to a rigorous analysis, the results of which are synthesised in the subsequent sections of this paper (Fig. 1).

3. Results

To summarise the findings of the systematic review, this section provides a general overview and analysis of the results. Figs. 2, 3 and 4 illustrate the number of articles published regarding the impact of the advanced materials across different countries, the publication trends and comparative analysis of various materials including PCMs, Aerogel, VIPs, and HRCs over the period from 2017 to 2023.

Fig. 2 reveals that the United States exhibits the highest number of articles, followed by India with seven articles and China with six articles, reflecting significant interest in the advanced materials within these major nations. Conversely, countries such as Saudi Arabia, Kuwait, Qatar, the United Arab Emirates, Oman, and South China appear with only one article, potentially indicating a need to increase in these areas. Countries in Mediterranean climate zones, such as Italy, Spain, and Greece, show moderate numbers. Moreover, some articles investigate multiple climates. These findings are valuable for understanding how research interest in the materials is distributed globally and can be utilised to identify research needs in regions that may be underrepresented in the scientific literature.

In examining the publication trends, Fig. 3 illustrates the publication trends for PCMs, Aerogel, VIPs, and HRCs from 2017 to 2023. The data reveals an overall increase in research, with PCMs showing the most significant growth, particularly in 2022. This suggests that PCMs are increasingly becoming a popular focus of research, probably because of their potential applications in energy storage and efficiency. HRCs research also steadily rises, indicating growing research interest and activity in these material types. However, VIPs maintain a relatively

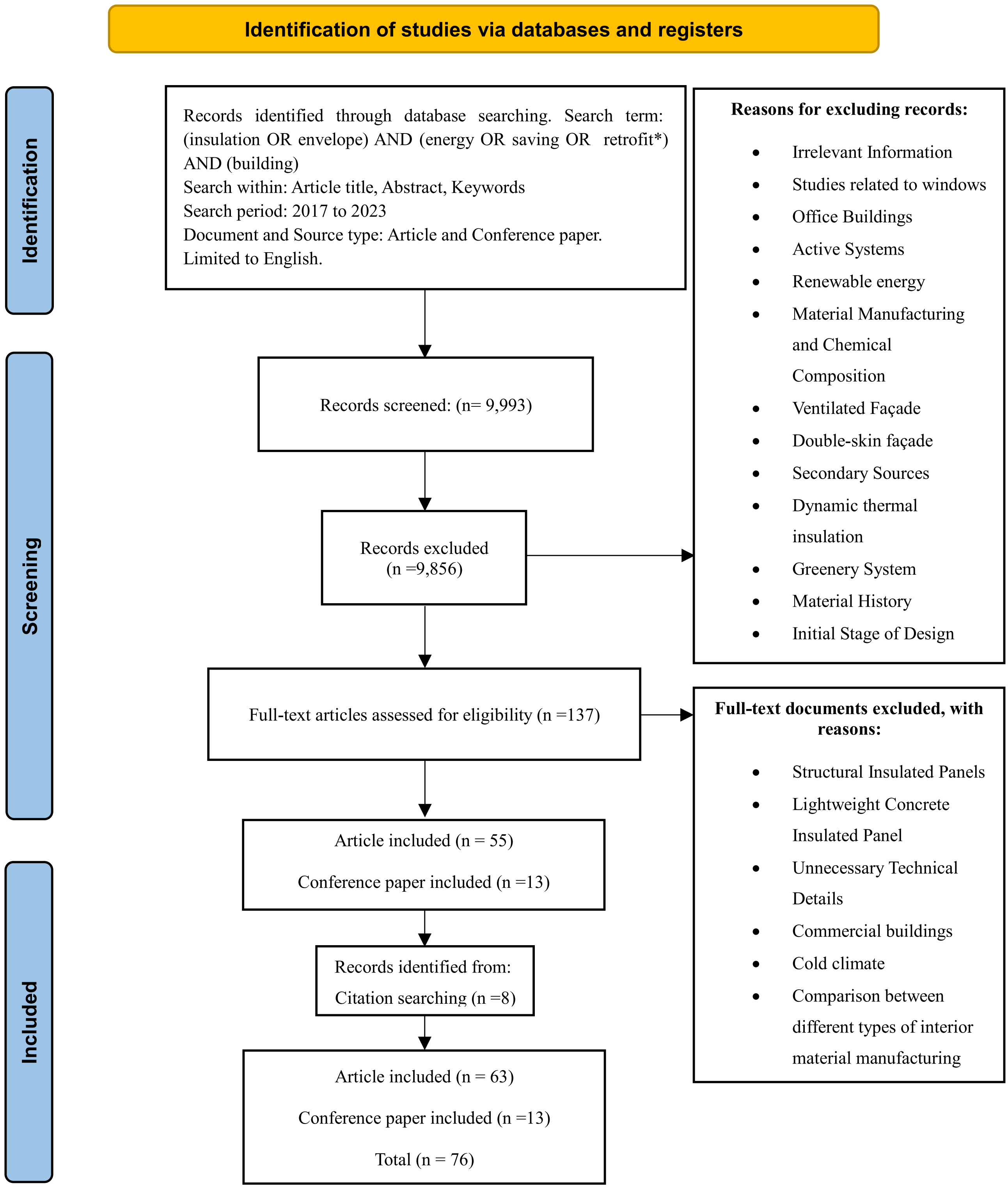

Fig. 1. Implementation of the systematic literature review according to PRISMA Flow Diagram.

stable publication rate with minor fluctuations, and Aerogel exhibit a modest increase.

Further analysing the focus of the literature, Fig. 4 compares different materials PCMs, Aerogel, VIPs, and HRCs based on several metrics: Operative Temperature Reduction (OTR), Heat Gain Reduction (HGR), CO2 emission saving, energy savings, Life Cycle Cost (LCC), and Thermal Comfort. The y-axis represents the "Number of Articles, indicating the frequency of studies focused on each metric for the respective materials, some studies encompass more than one material and evaluate multiple metrics. PCMs are the most researched material across all topics, particularly in Energy Savings, where the number of articles exceeds 30. HRCs also show a significant presence. This distribution suggests a strong interest in the potential of PCMs and HRCs for enhancing energy efficiency and thermal performance in buildings, reflecting their critical role in current research efforts aimed at sustainability and energy conservation. In contrast, Aerogel and VIPs have

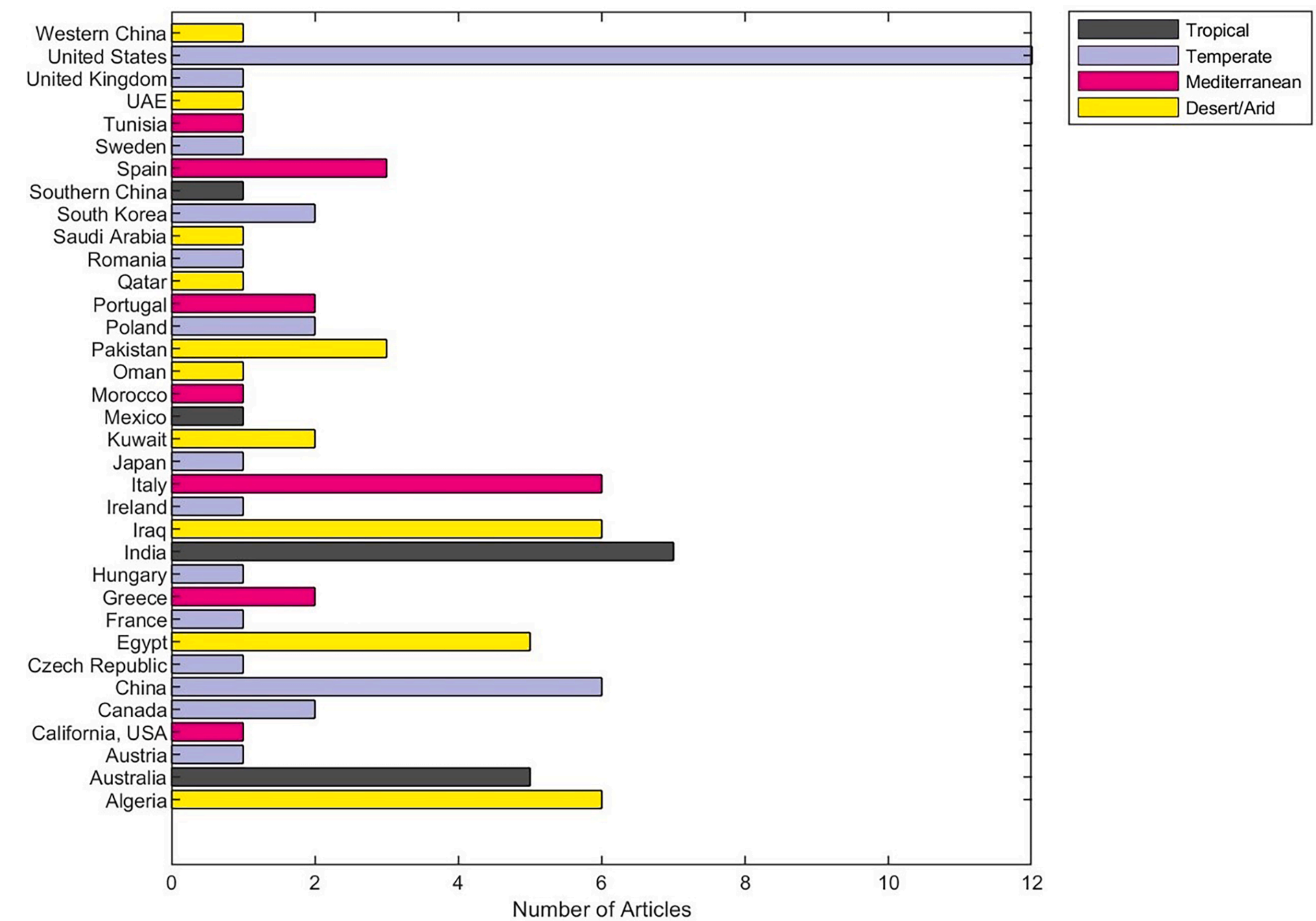

Fig. 2. Study setting per country.

fewer studies. Furthermore, CO2 Savings and LCC metrics generally have fewer articles across all materials, indicating less focus in these areas compared to others such as HGR and Energy Savings. This analysis emphasizes specific materials and metrics in the research, revealing trends and potential gaps in the literature.

4. Discussion

This section discusses and presents key findings from previous studies, organized by sub-headings based on the type of material studied in the reviewed literature.

4.1. Phase change materials

4.1.1. Energy efficiency

PCMs have emerged as a transformative technology in building design and construction, heralding a new era of energy efficiency and environmental sustainability. These materials are distinguished by their ability to absorb and discharge substantial quantities of thermal energy during phase transition processes, making them a significant advanced technique in application building. PCMs have the potential to significantly enhance thermal comfort, reduce energy consumption, and improve the environmental sustainability of buildings [13]. This section will provide an overview and discussion of recent studies and findings related to using PCMs in building envelopes. The discussion will focus on their effectiveness in enhancing energy efficiency, thermal comfort, comparisons with traditional materials, long-term insulation performance, variability across climates, improvements in energy flexibility, and economic as well as environmental considerations.

Integrating PCMs into building envelopes could significantly reduce energy exchange, leading to improved energy efficiency. A recent study indicates the significant benefits of integrating PCMs into thin building envelopes in extremely hot climates for thermal comfort and energy efficiency. The incorporation of PCMs reduces average temperature fluctuations by 5–6 °C and reduces daily total average heat gain by 66.6% to 76.5%. This leads to a reduction in thermal load levelling by 38–59%, and operative temperature by 6 °C, the roof shows the highest reduction in heat gain [13].

Expanding on this foundation, combining PCMs with insulation materials has proven to be an exceptionally effective strategy for enhancing thermal comfort while simultaneously reducing energy use. Integrating PCMs with expanded polystyrene (EPS) within the building envelope significantly enhances thermal performance compared to using PCMs alone. This method reduces indoor temperature fluctuations, extends thermal inertia and lowers operative temperature. Specifically, the integration of PCM-EPS in a room has led to significant improvements, manifesting as up to 143%, 177.2%, 35%, and 8.5% enhancements in maximum indoor temperature reduction, time lag extension, average temperature fluctuation diminution, and average operative temperature decrease, respectively. Using PCM-EPS also enhances the envelope resistance, with an average heat gain reduction of up to 103.8% [11].

Additionally, increasing the thickness of the EPS layer up to 2 cm has been found to improve the thermal efficiency of the room that use PCMs during daylight hours. However, a thickness of 1 cm has been identified as more effective in reducing the average temperature fluctuation and

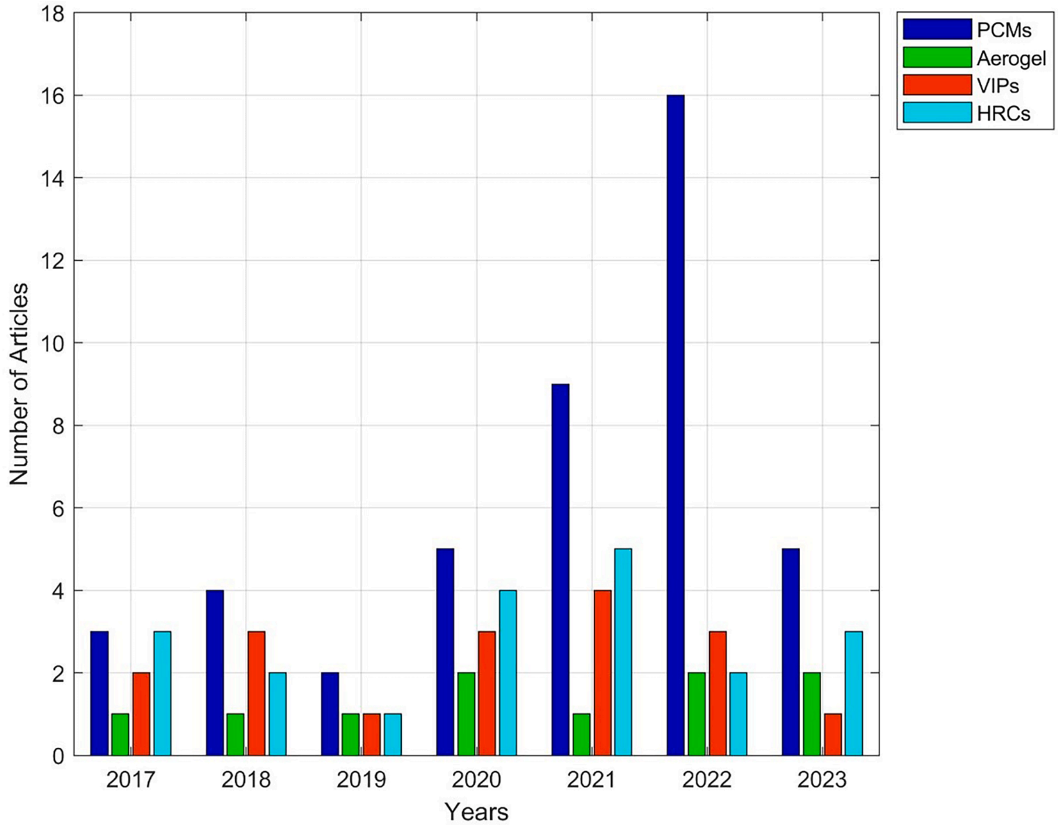

Fig. 3. Number of Articles per Year by Material.

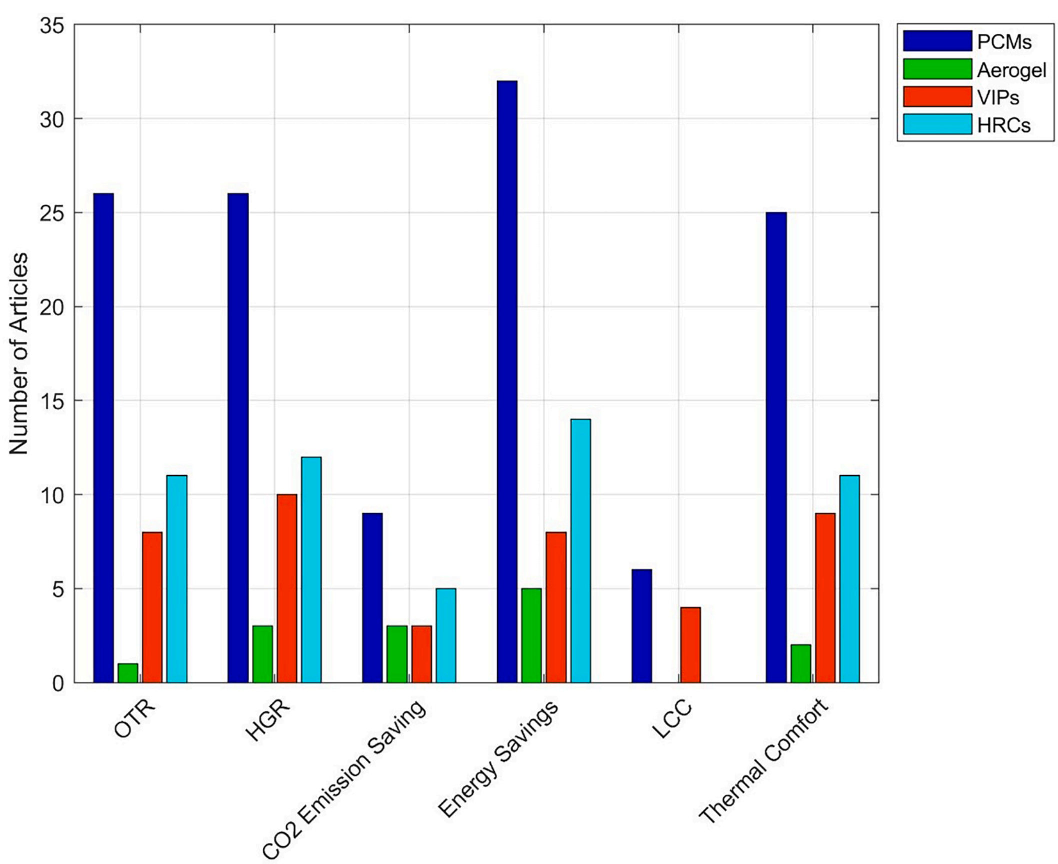

Fig. 4. Metrics for Different Materials Studied.

the average operative temperature throughout the complete thermal cycles [11]. Moreover, the study emphasises that a 1 cm layer of PCM applied evenly to walls was the most effective, achieving a 2.18 °C reduction in indoor temperatures and a 20.9% reduction in peak cooling loads, contributing significantly to electricity savings [34]. These results highlight the potential of targeted retrofits and material improvements to reduce energy consumption in hot climates and offer a practical solution to improve building energy efficiency and thermal comfort, although the efficiency also depends on the thickness and orientation of the application.

Moreover, incorporating PCMs into building walls has significantly enhanced energy efficiency. For example, using a 15-mm thick PCM layer in a conventional 185-mm thick wall can reduce the maximum instantaneous temperature by up to 30% compared to a wall without PCMs [48]. In addition, according to Ferster et al. [30], optimising PCMs application for cooling in South Texas involves considering factors such as the PCM's melting temperature, placement within the building envelope, and wall orientation. The study indicates a 26–31% decrease in annual cooling load, offering insight into the performance of PCMs in hot and humid environments.

Highlighting the comparative advantage, studies have found that incorporating PCMs with traditional building materials that have high thermal capacity can effectively reduce indoor temperatures during summer in temperate climates [41]. Expanding the use of PCMs in tropical regions, PCMs are a well-established method of improving indoor thermal regulation and reducing cooling requirements. For example, microencapsulated PCMs can be integrated into gypsum-based wallboards with a thickness of 2 cm. This integration results in a 1.5% reduction in the cooling load of a building in Darwin, Australia. Additionally, energy usage was reduced by 7.6%, leading to significant financial savings of 4.76% per square meter annually in energy costs [70].

In addition, PCMs integration into building envelopes significantly improves thermal efficiency. It reduces heat loss and lowers the energy requirements of air handling units (AHUs), with the most effective PCMs achieving energy savings of up to 11.73%. During the winter months, specifically December, January, and February, this optimal PCMs application has led to significant energy efficiency improvements, quantified at 11.25%, 11.23%, and 10.35% correspondingly. The study's numerical methodology is rigorously validated, exhibiting an error margin of less than 1.11 °C compared to experimental data, establishing a robust foundation for PCMs application in enhancing building energy performance [3].

Another study investigated using PCMs in building construction to improve sustainability and thermal efficiency. The research introduced a new type of wall integration called PCM clay hollow-brick composite. The study compared the thermal performances of two identical rooms, one with PCMs and one without PCMs, under warm and humid conditions. The results showed that the PCM-integrated room significantly reduced temperature fluctuations and cooling/heating loads. The temperature in the PCM room dropped between six °C and two °C compared to the non-PCM room, which demonstrated effective passive cooling. However, the effectiveness varied seasonally, with the best performance occurring in winter with up to a six °C reduction. In contrast, summer showed minimal benefits, indicating that higher melting temperature PCM or a dual-layer approach could improve the system's performance [43].

Emphasising the importance of PCM-enhanced building envelopes, particularly medium-weight PCM-enhanced plasterboard types, show significant improvements in energy efficiency for both cooling and heating scenarios. Retrofitting gypsum board with PCMs in building envelopes enhances energy flexibility and power curtailment in heating scenarios, with medium-weight envelopes proving more effective than lightweight ones in maintaining temperature limits during prolonged demand response events. Additionally, medium-weight PCMs with high latent heat capacity and medium-weight PCM-enhanced plasterboard envelopes have been found to be highly efficient and flexible, with a 244% effectiveness rate. Conversely, buildings that rely solely on sensible Thermal Energy Storage (TES) systems are recommended to avoid extended demand response events to maintain optimal thermal comfort levels [67].

In the same vein, Wijesuriya et al. [80] have found that incorporating PCMs into lightweight residential structures' building envelopes can offer significant advantages. These include an increase in annual load flexibility by up to 33.6% and energy savings of up to 10.8%. These results demonstrate effectiveness of using PCMs in modern construction practices. However, the effectiveness of the PCM-enhanced envelopes will depend on several factors, such as the transition temperature of the PCMs, its thermophysical characteristics, thickness, positioning, the strategy for controlling the interior thermostat, and the heat transfer coefficient.

Further research by Cárdenas-Ramírez et al. [22] explores the performance of composites containing solid-solid phase change materials (SS-PCMs) with fatty acid eutectic blends, in both steady-state and dynamic conditions. Their findings reveal that using SS-PCMs in acrylic plaster as a finishing layer on fiber cement siding significantly improves the thermal performance of building exteriors, extending thermal lag by up to 180% and reducing the decrement factor below 0.2. This integration not only delays heat transfer into buildings but also lowers indoor temperatures by 20.8%, a 67.26% increase in thermal lag, and a 9% reduction in decrement factor, improving thermal comfort and energy efficiency. The exceptional insulating characteristics of SS-PCMs, enhanced by the addition of porous clay, hold significant promise for enhancing building insulation. These materials demonstrate thermal transmittance values approximately 5 W/mˆ2 K and possess a heat storage capacity that is 1.5 times greater than that of traditional support materials.

Reflecting on case studies, the effectiveness of PCMs in energy reduction is prominently showcased in NEOM city, Saudi Arabia. a previous study has demonstrated the impact of incorporating PCMs in three buildings within Saudi Arabia's NEOM city. The study revealed that PCMs integration significantly reduces heat exchange, with a 63.5% improvement compared to buildings lacking PCMs. Furthermore, increasing PCMs thickness resulted in enhanced energy savings, showcasing a 16.7%, 28%, and 43.4% reduction in energy exchange at PCMs thicknesses of 5, 10, and 20 cm, respectively [29]. Additionally, utilising solid-liquid PCMs outperformed others with 63.5%, 73.6%, and 78.7% energy savings at similar PCMs thicknesses. Remarkably, this achieved 3.8 times more energy savings than the previous results due to the phase change transformation [29].

Further exploring the interaction between PCMs and building ventilation, this experimental study explored the thermal performance of PCMs and natural ventilation in semi-arid climate roofs, revealing that PCMs could reduce indoor air temperatures by up to 7.02% and delay peak temperatures by 10 to 70 min. A significant finding was that a 30 cm air gap without ventilation substantially improved PCMs' efficacy, lowering indoor temperatures by 2.5 °C, reducing cooling loads by 6.85%, and decreasing roof surface temperatures by up to 3.82 °C. Although natural ventilation extended the PCM solidification process, it did not significantly alter the reduction in maximum indoor temperatures. Furthermore, the strategic placement of air gaps significantly influenced heat flux through the roof, optimising thermal load management and enhancing thermal comfort by prolonging the duration within comfortable temperature ranges by 20 min to 1 h [62].

In addition, integrating a triple layer of PCMs with mechanical ventilation enhances thermal performance in buildings during summer, extending comfort periods, as emphasised by Salihi et al. [69]. Building on Berardi and Soudian [20], who found that a composite PCMs system in high-rise apartments with an 80% window-to-wall ratio could reduce peak temperatures by up to 6 °C, especially during peak solar gain and loss, indicating effectiveness under severe temperature fluctuations. They also noted the importance of orientation, shading, and nocturnal cooling in temperature variability.

Echoing the theme of thermal efficiency, a study shows that incorporating PCMs into building designs by employing PCM-integrated hollow concrete blocks and roofs can effectively reduce cooling loads. Among the five PCMs investigated, the organic mixtures-30 integrated composite wall and roof tile demonstrated superior thermoeconomic performance. In particular, the building model configuration that combines PCM composite wall (W-3) and PCM roof tile (R-2) exhibited the highest annual air conditioning cost savings and carbon emission reductions [15]. The study highlights the potential of PCM-integrated building materials to generate significant energy savings and reductions in CO2 emissions, especially in hot-dry climates.

Similarly, incorporating PCM-enhanced tiles in building envelopes in the Arabian Gulf has had a positive effect on the environment. It has helped to moderate the mean radiant temperature, operative temperature, Predicted Mean Vote (PMV), and Predicted Percentage of Dissatisfied (PPD). During peak occupancy, these tiles have effectively shifted PMV values closer to the comfort range, thus improving thermal comfort. This innovative approach has led to a noteworthy reduction in the daily thermal cooling energy demand by 3.3%, decreasing from 30.6 kWh to 29.6 kWh. Furthermore, the peak PPD experienced a substantial decline from 20.8% to 16.6 [74]. Thus, PCM-enhanced tiles have proven their effectiveness in creating more comfortable and energy-efficient living environments in the Arabian Gulf, highlighting their value in improving thermal comfort and contributing to energy conservation efforts.

Integrating of PCMs into building envelopes is a strategic approach to improving energy efficiency, with significant variations in performance observed throughout the day. In particular, east-facing walls and roofs are more efficient in the morning; in unventilated conditions, east-facing walls with PCMs show the greatest reductions in temperature and heat gain, with reductions of up to 9.1% and 16% respectively. Conversely, west-facing walls are more efficient in the afternoon, with the second highest average reduction in interior surface temperature according to the same study [12].

Adding to the understanding of PCMs' impact, further studies explore the sensitivity of different wall orientations to the presence of PCMs. Fig. 5 compares heating gain reduction by orientation, comparing conventional construction with buildings retrofitted using PCM RT-42. The most significant reductions appear on the roof and the west facade, suggesting that PCMs might be particularly effective in these areas [9]. Additionally, Fagehi and Hadidi [29] indicate that west and north walls are the most and least affected, respectively, by the incorporation of PCMs. Linking these findings, another study by Elmarghany et al. [27] reports that roofs experienced the greatest heat gain, with east and west walls following closely behind. Moreover, Salihi et al. [69] demonstrate that south-facing walls with PCMs offer enhanced energy efficiency compared to other orientations, emphasise the strategic advantage of aligning PCMs with specific building orientations for optimal energy conservation.

Emphasising the importance of roofing materials, the use of PCMs in roofs emerges as a critical element in reducing temperature and heat gain, with reductions of 15.1% and 34.9%, respectively. This accounts for about one-third of the total reduction in these metrics, although the roof's thermal efficiency faces challenges during the solidification phase due to accumulated thermal energy from sunlight. In addition, the investigation revealed that the maximum indoor temperature was reduced by up to 10.6% (approximately four °C lower than the referential unit) [12].

Expanding on the potential of PCMs, an advanced exploration of PCM integration, Elmarghany et al. [27] address the incorporation of PCMs into common bricks, significantly improving their thermal properties. Among the different PCMs, N-Eicosane stands out for its superior performance, with the lowest maximum temperature at 37.86 °C, a 29% reduction in peak indoor heat flux and a 9.28% shift in peak times. This integration results in a 1.5% reduction in average indoor surface temperatures and an 8% reduction in total energy transfer, with energy savings of up to 18.69% in year-long simulations.

Reflecting on the broader implications, incorporating PCMs into building designs offers a multifaceted strategy that not only improves energy efficiency and thermal comfort but also plays a crucial role in reducing CO2 emissions. According to Salihi et al. [69], the optimal integration of PCMs can lead to a substantial reduction in CO2 emissions, by up to 38.74%. Moreover, Al-Yasiri and Szabó [13] highlight the

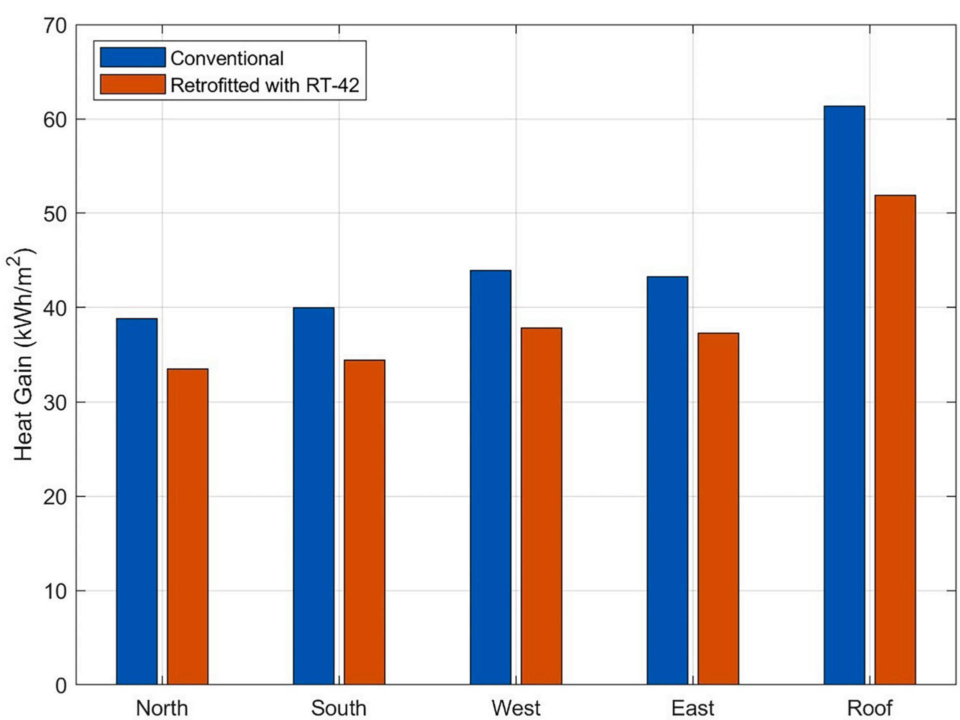

Fig. 5. Comparative Analysis of Heat Gain Reduction Across Orientations (Produced from Data in [9]).

tangible environmental and economic advantages of PCMs integration, including a daily reduction of CO2 emissions by 2 kg. These benefits demonstrate the potential of PCMs to contribute significantly to sustainable building practices and the global effort to combat climate change.

Further research emphasises the crucial role of PCMs in enhancing the ecological sustainability of architectural constructions in arid environments. Research in arid climates, as detailed by [10], has further emphasized the critical role of PCMs in building envelopes for reducing annual Heating, Ventilation, and Air Conditioning (HVAC) power usage. The application of PCMs has resulted in significant reductions in CO2 emissions. Specifically, Dubai saw a decrease of 56.27%, Jeddah 44.81%, Kuwait City 45.27%, and Lahore City 58.5%. Such findings emphasise the efficacy of PCMs in diverse geographic locations, particularly in regions with extreme temperatures.

Accentuating the efficacy of a particular PCM, RT-31 has emerged as a standout for its exceptional performance in energy and CO2 emissions savings. A specific PCM, identified as RT-31, which has a phase change temperature range of 27–33 °C, has been found to outperform others in terms of energy and CO2 emissions savings. Al-Rashed et al. [9] found that RT-31 installed on vertical walls and the roof led to annual savings of 481 kWh/m^2 of energy and 198.65 kg CO2/m^2 of emissions. Particularly, in July, the CO2 emission savings for RT-31 reached 14.32%, compared to 14.1% for RT-35 and 13.34% for RT-42. This demonstrates the superior performance of RT-31 in reducing CO2 emissions, further validating its effectiveness over other PCMs.

Furthermore, Saikia et al. [68] developed a sophisticated genetic algorithm to optimise multi-retrofit envelopes include PCMs in the hot climate of India, they found that PCMs can significantly reducing indoor heat gain by up to 33.5% and achieving daily electricity savings of 9.2 kWh, with the optimal retrofit configuration varying depending on the building orientation. Similarly, Hasan et al. [34] conducted an experimental study on the incorporation of PCMs, specifically paraffin wax with a melting point of 44 °C, into building walls and ceilings. This addition significantly improved the thermal performance and comfort of the buildings.

4.1.2. Melting point

The critical role of aligning PCMs melting temperatures with local climates and seasonal variations cannot be overstated, serving as a cornerstone for maximizing PCM performance in building applications. The research highlights that integrating PCMs into building components such as walls and roofs can lead to significant reductions in energy consumption, with potential savings of up to 41.6%, depending on the specific application techniques. PCMs with a lower melting point of 21 °C are effective for energy conservation when heating, while those with a higher melting point of 29 °C are more suitable for energy reduction when cooling [76]. This approach highlights the importance of adapting PCMs melting points to the specific thermal loading conditions, implying a need for a higher PCMs melting point in building envelopes exposed to elevated input temperatures associated with specific climate zones [47].

Building upon this foundational understanding, deploying PCM systems in extreme climates, particularly hot and arid regions, demonstrates a clear preference for multi-layer configurations over single-layer setups. The double-layer PCM system performs better than the single-layer system [76]. Moreover, triple-layer PCMs configurations are more effective than single and double layers. The composition of the triple-layer shows exceptional performance [69]. Utilisation of triple and double-layer PCMs systems leads to greater energy savings compared to single-layer applications. Additionally, the optimal PCM configurations can reduce cooling energy requirements by up to 11.6% and heating energy requirements by 10.2% compared to a base case without PCM [16].

Transitioning from the general advantages of PCM layering, the focus shifts to how these benefits manifest in specific climates, such as those found in Australian cities. The optimal melting temperatures for PCMs range from 25 to 28 °C and vary depending on the climate and the thickness of Form Stable PCMs (FSPCM) boards. Combining FSPCMs boards with EPS insulation is a practical solution for reducing thermal energy consumption, which is more effective than simply increasing insulation thickness. This approach is particularly useful in Darwin, Alice Springs, and Sydney, but may not be as efficient in cooler climates such as Hobart, Tasmania [2].

Further emphasising the adaptability of PCM applications, the internal incorporation of PCMs layers within buildings stands out as a particularly effective strategy for enhancing energy efficiency. According to research conducted by Khan et al. [38], incorporating PCMs layers inside buildings with a melting temperature of 24 °C and a thickness of 40 mm can significantly improve energy efficiency. This strategy optimises energy savings by placing PCMs layers internally. Single-story buildings can achieve monthly savings between 32% and 49.6% across different cities, while two-story buildings can achieve savings ranging from 12% to 21.4%.

The extensive benefits of PCMs integration are perhaps most strikingly illustrated through targeted research on the thermal performance of buildings in severely hot climates, such as that conducted in Aswan, Egypt. Results indicate PCMs significantly lowers indoor heat flow, keeping wall temperatures nearer to preferred conditions. The study highlights that thicker PCM layers enhance thermal regulation, with a 40 mm RT31-PCM layer cutting average indoor wall temperature from 32.5 °C to 29.4 °C, reducing energy influx by about 40%, showcasing substantial energy savings [26].

The amount of energy saved largely depends on how PCMs are applied within walls and roofs, and the selection of the most suitable PCMs with the right melting temperature is crucial, especially in hot climates [1]. The study by Li et al. [47]. highlights the importance of selecting an appropriate PCMs melting point based on design parameters to minimise indoor peak temperatures, temperature fluctuations, and subsequently, HVAC system energy consumption. It suggests that PCMs with a melting point within the occupant thermal comfort range can effectively extend indoor comfort periods under moderate climate loading conditions.

Furthermore, research conducted by Al-Rashed et al. [10] has shown that incorporating PCMs into the construction of buildings in arid regions can lead to significant reductions in annual HVAC energy consumption. The study found that in cities such as Dubai, Jeddah, Kuwait City, and Lahore City, there were exceptional reductions of 55.47%, 53.89%, 58.86%, and 53.57%, respectively. This finding highlights the potential of PCM integration to mitigate the energy demands of cooling systems in regions characterised by high temperatures. As a result, buildings can achieve a more balanced and energy-efficient thermal environment. This can contribute to the overall resilience and sustainability of urban infrastructure in arid regions.

In addition, the integration of Phase Change Envelopes (PCE) with HVAC systems has emerged as an effective approach to reducing energy consumption in buildings throughout Western China. It has been observed that the optimal Phase Change Temperature (PCT) is different for each city, ranging from PCT 23 in Lhasa to PCT 27 in cities as such Kunming, Xi'an, Chengdu, and Urumchi. Kunming, with its mild climate, presents the highest potential for energy conservation. The study suggests that the strategic use of PCE in HVAC-equipped buildings is an effective way to save energy [52].

Further investigation by Al-Rashed et al. [9] emphasizes the efficiency of embedding a 20 mm PCM layer within building walls and roofs can decrease heat gain by 14.21% for RT-42 (38–43 °C), 15% for RT-35 (29–36 °C), and 15.25% for RT-31(27–33 °C), during July. This modification also leads to substantial energy savings of 32.32 kWh/mˆ2 for RT-42, 34.12 kWh/mˆ2 for RT-35, and 34.68 kWh/mˆ2 for RT-31 within the same month. The study found that PCMs RT-31, which has a phase change temperature range of 27–33 °C, was the most effective PCMs in mitigating heat.

The effectiveness of PCMs relies on key properties such as the melting point, which is important for optimizing energy efficiency. An optimal selection is usually 1–2 °C above indoor air temperature to match local climate conditions and thermal comfort requirements. Moreover, the heat of fusion and strategic placement close to the interior surface amplifies this potential. However, the thermal conductivity of PCM plays a lesser role in energy storage. Additionally, building energy performance can be further improved by employing multiple PCM layers with varying melting points that align with averaged indoor and outdoor air temperatures [48].

Furthermore, as illustrated in Fig. 6, optimal heating advantages are realised by positioning the PCMs adjacent to the interior surface (right side), whereas situating them near the exterior surface (left side) proves more energy-efficient for cooling purposes [69,76]. This approach influences the building's heating and cooling energy consumption by varying the phase transition temperatures. Furthermore, it confirms that the location and application of these materials are crucial and have a significant impact.

Another research highlights the efficacy of PCMs with higher melting points in improving thermal performance in buildings located in hot climates. Incorporating PCMs into the external layers of building envelopes, there is a significant decrease in peak internal wall temperatures and heat gain, reducing the need for cooling energy. A comparative analysis shows that buildings equipped with PCM technology have lower internal air temperatures and experience a delayed onset of peak temperatures by up to five hours. This delay significantly reduces cooling energy demands. The study recommends using PCMs, particularly those with a melting temperature around 35 °C, in residential building envelopes to effectively reduce cooling energy consumption in regions with hot climate conditions [8].

4.1.3. Cost efficiency

Exploring cost-effective solutions, the potential of PCMs in enhancing building energy efficiency is increasingly recognised, yet the economic viability of their implementation necessitates a nuanced understanding of various influencing factors. These factors span climatic conditions, energy costs, building practices, as well as the initial investment and ongoing maintenance costs. Additionally, the broader context of energy policies and market demand plays a critical role in determining the feasibility and effectiveness of PCMs in construction projects.

Al-Yasiri and Szabó [13] contribute to the ongoing discussion about the benefits of PCMs by reporting that the use of PCMs can lead to a reduction in electricity costs by up to $0.17 per day. In a closely related study, Hasan et al. [34] demonstrate the potential for significant cost savings in electricity by strategically applying PCMs in building insulation. Their research reveals that applying a 1 cm thickness of PCM to all walls can result savings of up to $1.35 per day per cubic meter, with variations in savings depending on different configurations and orientations of PCM application.

Additionally, employing PCMs and pre-cooling techniques can significantly reduce cooling energy consumption during peak periods, leading to up to 29.4% cost savings [81]. These findings emphasise the strategic importance of PCM placement and thickness in maximising energy savings, highlighting the economic advantages of PCM technology in reducing energy costs. Building on this concept, Salihi et al. [69] further emphasise the efficiency and financial viability of PCMs, identifying that a layer of PCMs 1.5 cm thick is a cost-effective and high-performing solution. This indicates that optimising the specifications of PCM layers, such as their thickness, is crucial for significantly influencing their performance and return on investment.

In the specific context of Pakistan, Khan et al. [38] examine the impact of PCM applications on energy efficiency in residential buildings. They observe that employing PCMs with a melting temperature of 24 °C and a thickness of 40 mm significantly enhances the energy performance of residential building envelopes. Nevertheless, the return on such investments varies across locations, with payback periods ranging from 20 to 23 years in Lahore to 22 to 27 years in Karachi due to differences in external temperature conditions, energy costs, and building design and construction characteristics.

In order to achieve optimal thermal comfort in heavy-structure buildings in hot climates, PCMs with melting points of 25 °C and 29 °C are most effective for air-conditioned and free-floating modes, respectively. Incorporating PCMs into walls with a thermal resistance of $0.5m^2$ K/W significantly reduces exceedance hours by 373% compared to traditional insulation. A combination of 1 cm PCM layer and 3 cm thermal insulation reduces exceedance hours by 65.5%, lowers air conditioning energy consumption by 27.2%, and decreases payback period by 54%. Remarkably, it has been observed that the effectiveness of PCMs diminishes concomitantly with the expansion of the building envelope's thermal resistance from 0.3 to $1.02m^2$ K/W, with the experimental validation of the model demonstrating a maximum error of 4.44% [1].

Building on this economic perspective, Acuña-Díaz et al. [4] explore the financial strategies necessary for the successful deployment of PCMs. Their research suggests that for PCMs to be economically feasible, either significant subsidies approximately 50% of the initial capital investment are required, or more cost-effective technologies must be adopted. This analysis demonstrates that both strategies can be profitable, with the subsidy approach yielding a Benefit-Cost (BC) ratio of 1.2 and an Equity

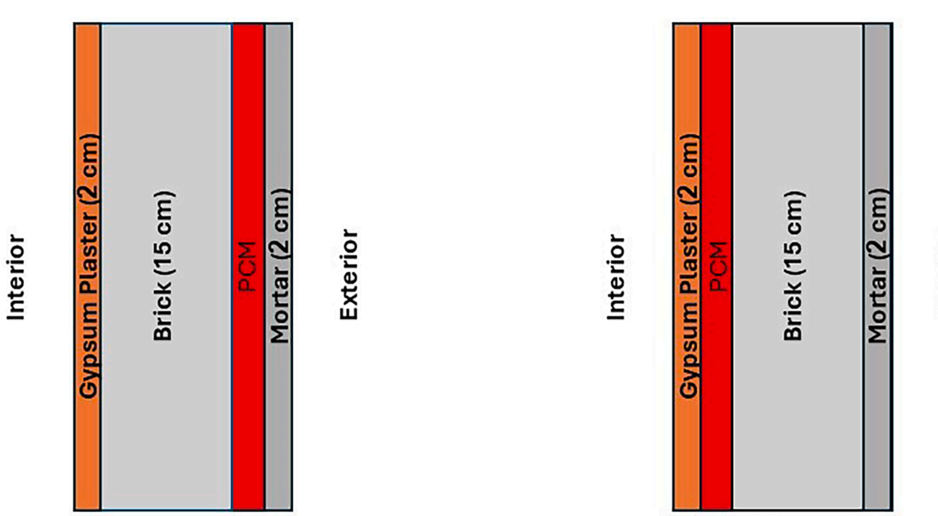

Fig. 6. Application and Arrangement of PCMs in Building Design for Optimal Energy Efficiency) Produced from Data in [69](.

Payback (EP) period of 9.3 years, while the adoption of cost-effective technologies results in the BC ratio of 1.7 and the EP period of 8.3 years.

Moreover, the lengthy payback periods observed, such as the 18.6 years under optimal conditions noted by Abu-Hamdeh et al. [3], emphasise the critical need for long-term financial planning and the introduction of incentives to promote PCMs adoption in the construction industry. This insight into the financial dynamics surrounding PCM technologies highlights the complexity of integrating such materials into mainstream building practices. Despite the promising energy-saving potential, the economic feasibility of PCMs hinges on a delicate balance of initial costs, ongoing savings, and external financial and policy support. It is clear that while the technical benefits of PCMs are well documented, their widespread adoption requires a comprehensive strategy that addresses economic challenges by developing more cost-effective PCM solutions.

Recognising these economic challenges, research has also shed light on the practical benefits of PCMs in energy conservation, as demonstrated in a study by Paranjothi et al. [57]. The study examines the effectiveness of using PCMs plaster/paste composites to achieve significant energy and cost savings in new and existing buildings. In Honolulu, using PCMs in a baseline scenario resulted in a 2.02% reduction in annual electricity consumption for heating and cooling. In addition, plaster containing 20% PCM was shown to significantly reduce interior surface temperature fluctuations by up to 51% and thermal flux by up to 43%, highlighting the potential of the composite to significantly improve the energy efficiency of buildings. This approach would accelerate their integration into energy-efficient building designs, contributing significantly to reducing energy consumption and promoting sustainable building practices worldwide.

On the other hand, Kuczyński and Staszczuk [41] conducted a study comparing the effectiveness of PCMs to traditional materials with high thermal mass in regulating indoor temperatures during summer in a temperate climate. The study found that traditional high thermal mass materials were significantly better at maintaining lower indoor temperatures than PCMs. During the hottest days of the study, when there were no heatwave conditions, replacing lightweight structural elements with conventional high-mass materials resulted in a significant decrease in indoor temperatures, by more than 3.5 °C. In contrast, using PCMs only resulted in a marginal reduction of 0.5 °C, the research found that using PCMs on roofs or walls did not significantly improve cooling energy efficiency.

In addition, according to Sharma and Rai, [71], incorporating a PCMs layer into roofing can reduce summer heat gain by 12.6% to 36.2%. Meanwhile, a layer of insulation enhanced with the same thickness can significantly reduce heat gains by 41.0% to 71.4% compared to standard construction methods. Similarly, incorporating PCMs into walls resulted in a reduction of heat gain by 10.4% to 26.6%, while insulation-enhanced walls can reduce heat gain by 32.4% to 64.0%. Applying these findings to a city-wide scale shows that using PCMs and insulation enhanced to improve buildings could lead to a decrease in Delhi's annual greenhouse gas emissions and electricity consumption by about 0.2% to 1.0% and 0.3% to 1.5%, respectively.

Furthermore, integration PCMs in building insulation is a promising way to reduce annual electricity costs. Based on the study conducted in various Australian cities, the potential savings range from 10.6% to 19%. However, it is worth noting that incorporating PCMs has an unexpected and counterproductive effect, leading to a reduction in Photovoltaic (PV) self-consumption by 1.5% to 2.7%. On a more positive note, PCMs exhibit a significant reduction in HVAC consumption, particularly when integrated with a Home Energy Management System (HEMS) [61].

Additionally, Kočí et al. [40] conducted a study exploring the integration of PCMs modified plasters in the building envelopes across Europe, aiming to mitigate energy consumption under diverse climatic conditions and compositions. It unveils the variable effectiveness of PCM systems, which is contingent upon material composition and geographical location, underscoring the necessity for tailored applications. Although the potential energy savings from PCM plaster applications are estimated to range from 3.7 to 6.5 kWh per square meter of façade annually, the feasibility from economic and environmental perspectives varies. The study advocates for a meticulous selection of wall assemblies and climatic conditions to optimize PCM's energy-saving potential while also cautioning against overestimation of its benefits, highlighting that significant percentages might not equate to substantial real-world advantages.

Table 1 presents a comprehensive range of details on various Retrofit techniques to enhance building energy efficiency. These techniques are implemented through different methods, each with unique benefits, including the percentage of savings in energy consumption, CO2 emissions, or associated costs. The techniques mentioned use PCMs with

Table 1
Comparative Analysis of Retrofit Techniques Utilising Phase Change Materials.

References	Method	Retrofit Techniques	Savings
[13]	S, EnergyPlus	PCMs (paraffin wax 40–44 °C) in thin building envelope	2 kg/day (CO2) 0.17$ /day (Electricity Costs)
[34]	E, (room)	1 cm thickness of PCM 44 [C]	20.9% (Cooling Load) $1.35/day/m^3 (Electricity Costs)
[30]	S, EnergyPlus	PCMs (15 [C], 31 [C])	26%, 31% (Annual Cooling Load)
[70]	S, EnergyPlus, Revit software	PCM mixed with gypsum in wallboards thicknesses of 2 cm	1.5% (Cooling Load) 7.6% (Energy) 4.76%/m^2/year (Electricity Costs)
[80]	S, EnergyPlus	PCM (200 kJ/kg latent heat)	10.8% (Energy)
[29]	S, (mathematical)	Roof and walls/5, 10 and 20 cm Solid PCMS solid-liquid PCMS	78.7% (Energy)
[62].	E, (room)	PCM (29 °C)with 30 cm air gap	6.85% (Cooling)
[27]	B, (laboratory)	PCM filled Brick (n-Eicosane)	18.69% (Annual Energy)
[69]	S, EnergyPlus	The PCM RT-28 1.5 cm	13.77% (Annual Energy)
[10]	S, (numerical)	20 mm PCM layer (25–27 °C)	44.81% (CO2) 53.89% (Annual Energy)
[9]	S, (numerical)	20 mm PCM RT-31 layer	481 kWh/m^2 (Annual Energy) 198.65 kg /m^2 (Annual CO2)
[76]	S, EnergyPlus	PCM (double-layer 21°and 29 °C)	41.6% (Energy)
[16]	B, (room)	PCM layer (26 °C)	29% (Cooling) 57% (Heating)
[38]	S, EnergyPlus	40 mm PCM layer (24 °C)	49.6% (Monthly Energy Single-story) 21.4% (Monthly Energy Two-story)
[26]	B, (laboratory)	40 mm RT31-PCM layer	40% (Energy)
[81]	S, EnergyPlus	PCMs (22.2 - 25.6 °C) and pre-cooling techniques	29.4% (Electricity Costs)
[1]	B, (laboratory)	1 cm PCM-25 and 3 cm thermal insulation	27.2% (air cond)
[61]	S, MADP	PCM layer (21 °C)	19% (Annual Energy)
[40]	S, Meteonorm	SS-PCM plaster	6.5 kWh/m^2/year (Annual Energy)

varying thicknesses and types and design modifications, such as adding insulating layers to walls and roofs. The techniques are assessed using numerical simulations or experiments. Some methods are employed in the laboratory, while others are conducted in experimental rooms. All of these assessments are based on laboratory-scale experiments, as no full-scale measurements were conducted.

4.2. Aerogel

Improving building envelope properties using aerogels has become a significant topic in sustainable construction. Integrating advanced materials such as aerogel-based renders and cement aerogels has significantly influenced the development of building materials, particularly in energy efficiency. Recent studies have revealed the exceptional properties of these materials, ranging from improved hygrothermal characteristics to substantial reductions in energy consumption. This is primarily due to the materials' reduced capillary absorption and increased water vapour permeability. These enhancements are both technical and practical, as fibre-enhanced renders have shown potential for use in various weather conditions [58]. Specifically, fibre-enhanced renders have improved energy efficiency by as much as 20% compared to traditional solutions, representing a considerable advancement in sustainable building retrofitting.

Pedroso et al. [58] conducted a study evaluating the total water content and drying potential of fibre-enhanced aerogel-based renders, which are crucial factors in hygrothermal analysis. The study indicates that these renders could significantly improve the energy efficiency of building envelopes, making them a practicable option for energy retrofitting. However, the study does not consider the long-term durability and performance of the fibre-enhanced renders, nor does it account for variations in building design and construction practices that could influence their performance. Additionally, the study does not address the cost-effectiveness and practicality of using fibre-enhanced renders in large-scale construction or explore the environmental impact of producing and disposing of these renders.

Further exploring the potential of aerogel-based renders in combination with other advanced materials, the integration of PCMs with aerogel renders has been found to significantly improve the thermal performance and energy efficiency of building envelopes. Applying aerogel renders and PCM on the outer parts of walls and PCM and insulation in the ceiling showed the highest reduction in severe discomfort hours (up to 82%) and substantial energy savings (total energy consumption reduction by 40%). The optimal PCM phase change temperature for maximum energy savings was around 23–26 °C, aligning closely with cooling set points. Ceiling insulation was crucial for reducing peak cooling loads and improving overall energy performance. This combination effectively reduces heat stress risks, energy use, peak cooling demand, CO_2 emissions, and operational energy costs [42].

The study concludes that using PCMs and aerogel renders for retrofitting existing buildings is a highly effective strategy for enhancing thermal comfort and reducing energy consumption. However, practical application could face challenges such as cost and complexity of installation. Moreover, the optimal phase change temperature for cooling and heating varies, complicating the selection process for PCMs. Despite these challenges, the findings support the viability of PCMs, and aerogel renders as a superior retrofitting solution for improving building energy efficiency and comfort, especially in climates with high diurnal temperature variations.

In addition to these advancements, aerogel insulation is also highly effective in reducing energy consumption. A 10 mm layer can decrease energy use by 23%, and a 20 mm layer can achieve a 38% annual reduction. In addition, applying multiple layers of aerogel insulation can lead to further heating energy savings of up to 10%. EnergyPlus simulations have validated these findings, showing consistency between simulated and actual heating bills when aerogel layers are applied to apartment walls. Despite these benefits, uncertainties in building usage patterns can affect the accuracy of energy savings calculations [28]. This reduction in energy demand is crucial in reducing the environmental impact of buildings, which account for a significant portion of global energy use.

Moreover, further advancing the field is the development of a cement aerogel inspired by cuttlefish bone. This pioneering material exhibits exceptional fire-retardant properties, as indicated by a limiting oxygen index of 46.26%. It enhances safety and reduces the environmental impact of fire damage and subsequent repairs. In addition, it achieved a significant 94.7% reduction in carbon emissions during its manufacturing process, sharply contrasting with conventional cement production methods. Furthermore, the aerogel's lightweight nature substantially reduces the environmental impact associated with transportation, marking a shift from heavier traditional insulation materials such as mineral wool or fibreglass [24]. This bioinspired design of cement aerogel aims to use less raw material while maintaining high performance, aligning with sustainable manufacturing practices.

Despite these advancements, studies have shown that environmental conditions significantly affect the thermal properties of aerogel insulation. Heat treatment can lead to crystallisation, grain growth, and increased thermal conductivity. Additionally, moisture sorption increased after heat treatments, and both thermal conductivity and thermal transmittance (U-value) increased under varying environmental conditions [45].

Furthermore, a comparative study reviewed the thermal performance of six insulating materials, identifying aerogel as the most effective insulator, followed by extruded polystyrene foam boards (XPS), straw boards, and glass-ceramic, with efficiencies of 48.33%, 38.36%, 36.46%, and 34.38%, respectively [25]. The study concluded that using thermal insulation in buildings can significantly reduce energy consumption and costs. However, this study primarily focused on summer energy consumption and did not account for seasonal variations, practical implementation challenges, or detailed cost analyses. These factors are crucial for determining the overall feasibility and effectiveness of these materials in different climates and building types.

Additionally, another study compared the thermal performances of an apartment insulated with common materials such as expanded polystyrene and nano-insulation materials such as aerogel and vacuum insulation panels. The findings indicated that the objectives of reducing primary energy consumption and carbon dioxide emissions were met predominantly by the thickest common insulations or the most efficient nano-insulations [21]. In particular, the most efficient nano-insulations were considered a better choice in terms of material quantity, suggesting a potential shift towards these materials for future nearly Zero Energy Building (nZEB). Due to their high insulating properties even at minimal thicknesses, nano-insulations such as aerogel can save valuable space in building designs, which is particularly beneficial in retrofitting existing structures where space is limited. This indicates a growing recognition of the superior performance of nano-insulation materials, particularly in applications aiming for high energy efficiency and reduced environmental impact. As shown in Fig. 7, aerogel insulation can be effective even at a thickness of 5 mm, illustrating its potential for space-saving applications.

Moreover, extending the focus to the application of aerogel in different forms, aerogel-based rendering applied to exterior surfaces can significantly lower heat losses, with reductions ranging from 23% to 36%, depending on the layer thickness. Furthermore, applying a 3 cm thickness of insulation plaster leads to a 21% reduction in heating load, although the rate of decrease drops as the insulation thickness increases [6]. However, end-of-life disposal of aerogel-based materials can pose challenges due to the presence of synthetic components that might not be biodegradable [5]. Therefore, while the initial results show promising effectiveness for aerogel as an energy-efficient material, there remains a critical need for comprehensive studies that consider these important factors to provide a well-rounded and realistic evaluation of the use of this technology in energy optimisation applications.

Fig. 7. A 5 mm thick layer of aerogel insulation material, demonstrating its potential for space-saving applications in construction due to its high efficiency at minimal thickness.

In the context of indoor applications, for indoor applications, aerogel-based wallpaper has shown high thermal performance and water vapour permeability, making it suitable for indoor energy retrofitting without causing condensation. Furthermore, the Life Cycle Assessment (LCA) approach provided valuable insights for the design and comparison of different indoor retrofitted kits, contributing to the development of environmentally efficient solutions [5]. Nevertheless, the position of aerogel plaster plays a crucial role in reducing condensation risks; for instance, interior thermal insulation systems can induce moisture issues and condensation risk. Moreover, indoor insulation solutions are generally less effective than external applications due to interruptions at wall and floor slab connections. These interruptions can lead to increased heat losses and potential moisture issues, particularly in certain climates [5]. Furthermore, properly installed aerogel can minimise risks of condensation and mould growth, which contributes to a healthier indoor environment and longer material lifespan [6].

The advancements in aerogel-based materials for building envelopes present significant potential for improving energy efficiency and sustainability in construction. However, several gaps remain, including the need for long-term durability studies, comprehensive cost analyses, and evaluations of environmental impacts beyond carbon emissions. Addressing these issues will provide a more holistic understanding of the viability of these advanced materials and support their broader adoption in sustainable construction practices.

4.3. Vacuum insulation panels

VIPs have emerged as a highly effective thermal insulation solution in building construction due to their particularly low thermal conductivity, typically less than 2.0 mW/(m·K), which is approximately one-tenth that of traditional thermal insulation materials [36]. This significant reduction in thermal conductivity positions VIPs as superior insulation materials for various applications, particularly where space constraints exist. VIPs can achieve the same thermal performance as traditional insulation materials while reducing wall thickness by up to 77.3% [49].

However, the performance of VIPs over time can be affected by factors such as the permeation of moist air, which increases their thermal conductivity. The rate of this increase is influenced by the type of barrier envelope and environmental temperature. Over the first decade, VIPs experienced an ageing rate of approximately 4.5% annually, which decelerated thereafter, demonstrating long-term durability despite higher initial degradation compared to EPS [49]. Studies have observed that the thermal conductivity of VIPs increases due to the permeation of moist air, with the rate influenced by the barrier envelope type and temperature [36].

Building upon the understanding of VIPs' thermal properties, studies have evaluated their performance in real-world applications. Atsonios et al. [18] conducted a comprehensive study on a lightweight steel-framed building insulated with VIPs. The key findings demonstrated that the VIP layer substantially reduced the U-value of the wall by approximately 52% and decreased the linear thermal transmittance (Ψ-value) by about 70%. The edge effect was found to increase the effective thermal conductivity of VIPs by 18–23%, contributing 2% to the overall heat transfer coefficient (HD) of the building envelope.

Thermography and temperature measurements indicated that VIPs mitigated thermal bridges caused by the metal structure, resulting in a 53% reduction in the U-value of the walls compared to those without VIPs [18]. Despite dimensional inaccuracies and panel damage during installation, VIPs effectively enhanced the thermal performance of the steel-framed building. Similarly, the use of VIPs significantly lowered the U-value of solid brick walls by up to 77%, making them particularly suitable for applications requiring high insulation performance [46].

In the context of energy efficiency, VIPs have been assessed for their effectiveness in meeting nZEB requirements. VIPs provide exceptional thermal insulation, achieving reductions in primary energy consumption by up to 65% and CO2 emissions by approximately 60% [21]. Furthermore, VIPs have shown differential performance impacts under various climatic conditions. VIPs significantly reduced heating energy demand in cold climates such as Vienna by up to 38%. In contrast, warmer climates such as Catania increased cooling energy demand by 13% due to reduced night cooling. Energy savings of 23% were reported in Bilbao and 36% in Malmö, with VIP solutions achieving low thermal transmittance values around 0.2 W/(m^2·K) in slim retrofitting systems. However, some VIPs were damaged during installation, highlighting the material's deficiencies during implementation [23].

Despite their advantages, VIPs present specific challenges that hinder their widespread adoption. Practical challenges such as installation costs, complexity, and the need for specialised installation techniques can limit the feasibility of these solutions. VIPs cannot be cut on-site and are susceptible to damage during handling and installation, which can affect their performance. Additionally, the risk of thermal bridging at junctions between panels or when combined with other materials necessitates careful design and installation practices [77]. Addressing these challenges is critical for optimising the use of VIPs in practical applications.

To mitigate thermal bridge effects, encapsulating VIPs with EPS can be effective. Encapsulated VIPs reduced linear thermal transmittance by 34% and effective U-value by 26% compared to standard VIPs, enhancing thermal performance and providing better protection for the panels [39]. Furthermore, integrating VIPs with External Thermal Insulation Composite Systems (ETICS) has shown promise. However, challenges such as edge thermal bridging, installation difficulties, and high costs have been highlighted [72]. VIP-based ETICS solutions offer significantly higher thermal resistance than conventional EPS-based ETICS, making them viable options for building energy-efficient retrofits [32]. However, the high cost of VIPs might limit their use to high-budget projects or specific applications where their benefits can justify the cost.

Integrating VIPs with other advanced materials, such as PCMs, has significantly enhanced the thermal performance and energy efficiency of building envelopes. This combined approach leverages the unique properties of each material to overcome individual limitations and achieve superior energy efficiency in buildings. For instance, combining VIPs with PCMs results in decreased heat flux through walls due to the high insulation provided by VIPs and the latent heat storage capacity of PCMs. PCMs offer a time-delay effect that shifts HVAC loads to off-peak hours, reducing operational costs. Optimal performance is achieved by positioning the PCM layer inside the VIP layer and tailoring the PCM melting temperature to local climatic conditions to maximise latent heat storage [49].

In the Mediterranean climate, Papadaki et al. [56] evaluated the LCA of using PCMs and VIPs in buildings in Crete, Greece. Two demonstration houses were constructed: one with conventional materials and the other incorporating PCMs and VIPs. The findings revealed that while the construction of the house with PCMs and VIPs resulted in a 34% higher initial environmental footprint during the construction phase, the energy savings during the operational phase offset this impact within just over a year. Over a 25-year lifespan, the PCM and VIP-enhanced house demonstrated a 57% lower environmental footprint than the conventional house. This demonstrates that despite the higher initial environmental impact, the use of PCMs and VIPs offers long-term energy savings and environmental benefits, making these materials a viable strategy for improving energy efficiency in the building sector.

Compared to traditional insulation materials such as XPS, VIPs demonstrate superior thermal performance under various conditions. The thermal resistance of 50 mm XPS was 32% lower than that of 12 mm VIPs, and punctured VIPs showed significantly reduced thermal resistance, especially in wet conditions. Moreover, dry-hung VIP walls had higher thermal resistance than pasted VIP walls due to the static air interlayer [50]. The durability and ageing of VIPs have been studied, demonstrating that VIPs maintain high thermal resistance over time, with a service life exceeding 25 years. Accelerated ageing tests confirmed this longevity, validating the reliability of VIPs in the building sector [19].

Further investigations reveal the innovative design of VIPs, including the use of double envelopes, which significantly reduces gas permeation, therefore, maintaining stable internal pressure and minimal decline in thermal resistance over a period of 25 years [37]. Another study found that advanced materials such as VIPs offer favorable payback times in high space-value scenarios [7]. Despite challenges such as surface cracking and condensation due to temperature fluctuations, VIPs still outperform traditional insulation, making them ideal for enhancing energy efficiency in residential structures [21,72].

From an environmental perspective, addressing the end-of-life disposal of VIPs and associated materials is critical. The production of VIPs involves energy-intensive processes and materials such as metals and plastics for barrier envelopes and cores. LCA indicates that the manufacturing and construction phases contribute substantially to VIPs' overall environmental footprint due to high embodied energy and associated greenhouse gas emissions. VIPs' composite nature makes recycling challenging, which could result in increased landfill waste if not managed properly. Developing recycling or safe disposal strategies can mitigate the potential environmental harm from waste. Additionally, a comprehensive LCA that considers the production, operational, and disposal phases is needed to fully understand the environmental impact of using VIPs and integrated advanced materials [56].

VIPs offer significant advantages in enhancing building envelopes' thermal performance and energy efficiency, particularly when integrated with other advanced materials such as PCMs. While the production and disposal of these materials pose environmental challenges, the significant energy savings during operation can counterbalance the initial environmental impacts over the building's lifespan, resulting in an overall positive environmental impact. Addressing practical challenges such as installation techniques, damage prevention, and thermal bridging is crucial for the widespread adoption of VIPs. With careful consideration of these factors, VIPs offer a promising solution for achieving high energy efficiency in building retrofitting.

4.4. Heat reflective coatings

Recent research has significantly advanced the field of sustainable building retrofitting, focusing on methods to reduce energy consumption. For instance, Nutakki et al. [54] conducted a comprehensive study demonstrating the efficacy of cool paints in reducing energy usage in buildings. Their research showed a significant 34% reduction in annual energy consumption, achieved through the use of cool roofs and walls, which contributed 39% and 38% to total energy savings, respectively. This highlights cool paints as an effective and straightforward technique for sustainable building retrofitting.

However, the longevity of these materials presents a challenge. The study identified a decline in the Solar Reflectance Index (SRI) values of these paints over time, with cool roofs experiencing a 36% reduction and walls a 25% reduction in reflective efficiency over three years. This degradation in reflective efficiency must be considered when evaluating the long-term applicability of these materials. The findings are particularly relevant for hot climates, although the aging effect of SRI paints poses a significant limitation to their long-term energy-saving potential. Thus, continuous research and development are needed to enhance the durability and effectiveness of these sustainable building materials.

In addition to cool paints, advancements in coating solutions have led to significant discoveries in energy efficiency. Venturelli et al. [78] demonstrated that the implementation of proposed coating solutions, the application of external wall insulation could lead to substantial savings in heating fuel (approximately 37%) and electric energy for air conditioning systems (over 51%). The study emphasises the importance of balancing thermal efficiency with economic viability, identifying coat insulations as the optimal solution. These insulations offer the best balance between thermal performance improvement and economic effort, with a payback time close to 20 years.

Furthermore, the impact of radiative coatings on energy efficiency has been explored. Wijesuriya et al. [82] found that these coatings significantly enhance energy efficiency, though their efficacy is influenced by climatic and atmospheric conditions. Their research indicated substantial energy consumption reductions in the Southern, United States, while Northern locales experienced increased energy consumption, termed as energy penalties. Specifically, arid and torrid environments, such as Phoenix, Arizona, recorded the highest energy savings, amounting to 426 kWh and a 6.2% reduction in energy usage. However, while beneficial in hot and dry climates, radiative coatings may incur heating penalties in colder climates.

Similar findings were observed in India, where Jain & Pathak, [35] conducted a study on the impact of solar reflective materials in Bhopal. The research showed that using these materials on the exteriors of residential buildings reduced internal temperatures by around 3.5 °C on walls and 3.4 °C on roofs. This improved thermal comfort and decreased the need for air conditioning, leading to lower energy consumption and reduced greenhouse gas emissions. As a result, it supports global sustainability objectives and alleviates pressure on electrical grids during peak periods. However, these materials typically have a limited lifespan of 5–10 years; therefore, conducting thorough life cycle assessments to evaluate their environmental costs, including production, transportation, installation, maintenance, and disposal, is essential. While the immediate benefits include significant energy savings and reduced emissions, challenges remain in waste management and environmental implications.

The use of alternative building materials has also shown promise. Sravani et al. [73] posited that using materials such as autoclaved aerated concrete blocks for walls and various tiles for roof slabs can significantly mitigate the impacts of acidification, eutrophication, CO2 emissions, and ozone depletion by approximately 2–6%. This study utilised digital tools such as LCA and Building Information Modeling (BIM) to measure the environmental impact of building envelope materials. However, the study was limited to a two-storied residential building, and the results may vary for different building types and locations.

Different passive cooling techniques have been examined, as shown in a study by Athmani et al. [17]. in Biskra, Algeria. They explored cool reflective white paint, white ceramic tiles, and cool-ventilated roofs, finding the cool-ventilated roof to be the most effective. It reduced cooling loads by 66.06%, CO2 emissions by 481.90 kg during peak summer, and the average indoor temperature by 4.95 °C. Cool reflective paint and ceramic tiles also significantly improved thermal comfort, reducing cooling energy consumption by 45.45% and 37.24%, respectively. These findings suggest that these affordable and easy-to-implement techniques could significantly decrease indoor temperatures and energy usage.

Another aspect of cool roofs was studied by Rawat and Singh [64], who analysed their thermal performance versus conventional RCC roofs in a composite climate. Cool roofs significantly lowered both exterior (4.8 °C-6.8 °C) and interior (3.9 °C-6.3 °C) surface temperatures, reduced indoor thermal amplitude by 16.10% to 27.94%, and peak indoor temperatures by 2.1 °C-3.2 °C. Cool roofs exhibited superior thermal performance, with higher thermal damping (7.5%−13.4%), longer time lag (3–4 h more), and lower decrement factors than RCC roofs. Energy savings ranged from 11.73% to 13.73% in April and 10.58% to 11.53% in May, attributed to the high reflectance and emissivity of the cool paints used. The conclusions affirm the effectiveness of cool roofs in reducing heat gain, improving indoor thermal comfort, and conserving energy.

In a study focused on hot climates, the integration of PCMs with Aluminum Radiation Reflector (ARR) cool roofs demonstrated significant thermal performance improvements. Key findings include reductions in room air temperature by 3.63 °C (9.08%), interior roof surface temperature by 12.68 °C (30.1%), and exterior roof surface temperature by 16.92 °C (37.3%) compared to a standard concrete roof. The dynamic air ventilation between the PCM and ARR enhanced convective heat flux, leading to an average heat flux reduction of 18 W/m^2. This study concludes that a PCM-ARR roof with dynamic air ventilation effectively reduces indoor temperatures and enhances energy efficiency in hot climates such as Oman [44].

Research on the integration of HRCs and PCMs indicates significant reductions in indoor temperatures and enhanced passive cooling. Applying HRC on the exterior surface proves more effective, and incorporating an insulation layer between HRC and PCMs is crucial. PCMs with lower thermal conductivity, such as RT31/SiO2 (0.09 W/m K), reduce indoor temperatures more effectively than those with higher conductivity, such as RT31/expanded graphite (1.25 W/m K). The optimal thickness for both PCM and air cavities is no more than 8 mm, reducing indoor temperatures by up to 3.6 °C [51].

In addition, Innovative coatings, such as thermally responsive Optic-Variable Wall (OVW) coatings, have also been researched. Wang et al. [79] found that these coatings significantly improve building energy efficiency and indoor comfort. In Shanghai, OVW reduced heating and cooling energy consumption by up to 14.8% and 14.2%, respectively, while in Paris, it provided a 7.3% reduction in heating energy consumption. However, the ideal OVW (albedo 0.1/0.8) outperformed the actual OVW (albedo 0.1/0.45) in energy savings. OVW also reduced Discomfort Degree Hours (DDH) by 639–735 °C·h and Discomfort Hours (DH) by 15.7% for overcool discomfort and 8.3% for overheating discomfort during intermediate seasons. In Paris, however, the ideal OVW unexpectedly increased discomfort hours to 52% due to the mismatch between the coating's instantaneous albedo adjustment and the building's thermal mass response. It can be concluded that OVW is more effective in climates with balanced heating and cooling demands, such as Shanghai.

The albedo effect of external surfaces has also been investigated, as demonstrated by [53]. The study, conducted in a Mediterranean climate zone in Algeria, revealed that high solar reflectance combined with proper insulation reduced cooling energy needs by 22%, although heating needs increased by 18.61%. Building orientation had minimal impact on energy requirements, while material type and insulation significantly affected thermal performance. The study concludes that light-colored coatings with albedo values over 0.5, combined with appropriate insulation, optimize energy efficiency and thermal comfort. However, broader geographic and climatic data are needed to generalize these findings, and more nuanced recommendations should consider the varied impacts of different building elements on overall energy performance and comfort.

In warm regions such as Miami and Phoenix, Rosado and Levinson [66] found that cool walls significantly reduce HVAC energy use, energy costs, and pollutant emissions. In California, cool walls lowered annual HVAC energy use by 3.0–25% in single-family homes. Nationally, cool walls in warm climates decreased HVAC source energy use by up to 8.5% in homes. Older buildings saw more significant benefits due to lower insulation and less efficient HVAC systems, supporting the inclusion of cool walls in building energy standards, especially in warm climates. However, the impact of natural aging on cool walls has also been studied. Paolini et al. [55] focused on the effects over four years, observing a decrease in solar reflectance from 0.75 to 0.55 for white coats and from 0.46 to 0.38 for beige coats, while thermal emittance remained unchanged. Aging increased cooling energy needs by 5% to 11% and surface temperatures by up to 6 °C.

In addition, Thermochromic roofs (TC), which adjust their solar reflectance based on temperature, have shown to significantly enhance the energy efficiency of residential buildings compared to conventional roofs. Zinzi et al. [83] found that high-switching TC materials provided the best performance, particularly in climates with balanced heating and cooling needs, such as Palermo and Barcelona, achieving annual energy savings up to 25 kWh/m^2 and relative improvements of 4% to 19%. While TC roofs outperform static cool roofs in various scenarios, their effectiveness is reduced in cooling-dominated regions.

In tropical areas, Rong et al. [65] developed a low-brightness, high-reflective coating, achieving significant reductions in exterior surface temperature (6–8 °C) and an annual energy saving rate of 12.9%. Using a combination of hollow glass beads, nano-TiO2, and iron oxide red, the optimal formulation was determined to be in the ratio of 8:12:2. Balancing high reflectivity with visual comfort, the study suggests controlling visible light reflectance below 50% to prevent glare. These results indicate that by balancing high reflectivity with visual comfort, the coating has great potential for energy-saving in tropical areas, it effectively reduces exterior surface temperatures and significantly saves energy. Furthermore, increasing rooftop solar reflectivity, as studied by Anand and Sailor [14], can reduce summer cooling loads by 10–30%, but may increase winter heating demand by 5–15%, making such properties less suitable for colder regions. This implies a trade-off that must be considered when selecting materials for different climates, as these materials may not be suitable for regions with significant heating demands during colder months.

Another comprehensive study on solar-reflective surfaces, conducted by Rastegar and Chang [63], found these coatings to be economical and effective for energy retrofitting, especially for older buildings with poor insulation. Applying high solar reflectance to both walls and roofs resulted in the most energy savings, with the roof having a greater influence on energy consumption than the walls. This indicates that focusing on solar-reflective roofing could result in significant energy savings. However, the effectiveness of these coatings depends on several factors, such as location, climate, and building geometry. This highlights their potential to lower energy costs and reduce environmental impact, making them suitable and cost-effective for improving the thermal performance of older buildings. Furthermore, a critical issue identified is that enhanced building envelope reflection might inadvertently warm the surrounding environment, escalating the building's cooling energy demand. They recommend using optimal rooftop radiative properties suitable for the building type and climate zone to minimize annual energy costs and urban warming.

Recent research emphasises the significant potential of alternative building materials, such as PCMs, aerogels, VIPs, and HRCs, in reducing energy consumption in building retrofits. As shown in Fig. 8, these materials demonstrate varying levels of maximum energy savings, with PCMs and HRCs showing significant effectiveness. Fig. 9 further clarifies

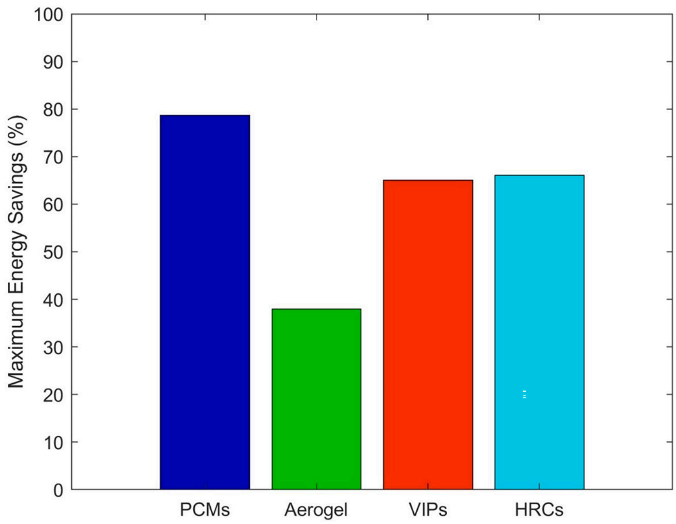

Fig. 8. Maximum Energy Savings by Building Materials) Produced from Data in [21], Athmani et al. [17,28] and [29]).

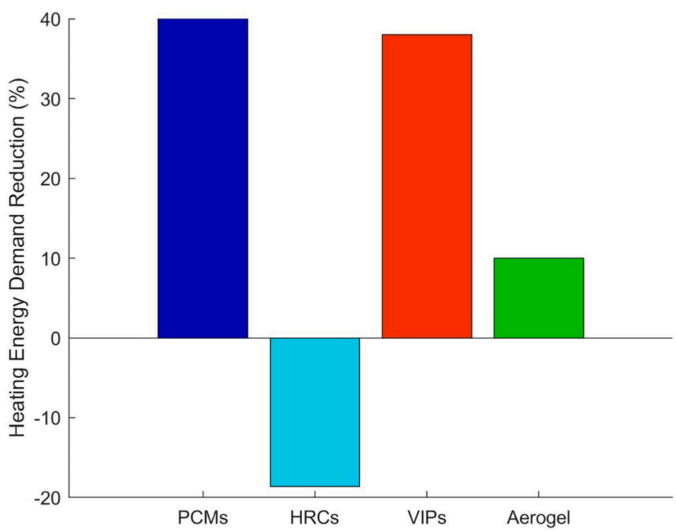

Fig. 9. Reduction in Heating Energy Demand by Material) Produced from Data in [23,16,28] and [78]).

the impact of reducing heating energy demand, particularly emphasising the significant effectiveness of PCMs and VIPs. However, while HRCs offer advantages in terms of reflectivity and energy efficiency, they inadvertently contribute to increased heating energy demand. This phenomenon requires further investigation. This potential disadvantage emphasises the need for careful and context-specific use of these technologies, taking into account geographical and environmental factors. Finally, although these retrofitting techniques improve energy efficiency and enhance indoor thermal comfort, especially in hot climates, they are also accompanied by significant challenges. Issues such as material longevity, economic viability, and environmental impacts require careful consideration. The gradual decrease in reflective efficiency over time and the necessity for customised solutions highlight the intricacy of developing sustainable retrofitting methods that are both effective and adaptable across various climatic and geographical conditions.

5. Conclusions

Reevaluating energy consumption in the residential sector has become increasingly crucial due to the escalating impacts of climate change. This sector considerably contributes to natural resource depletion and greenhouse gas emissions; however, it also offers immense potential for energy savings. This study systematically reviews recent literature on applying advanced building envelope materials for energy retrofitting in residential buildings, specifically PCMs, aerogels, VIPs, and HRCs. A comprehensive examination evaluated the effectiveness, performance, economic and environmental implications, and challenges of implementing these materials. This study elaborates on several pivotal benefits and considerations:

- Integrating PCMs effectively decreases indoor temperature fluctuations and extends thermal inertia, leading to improved occupant comfort and enhanced heating and cooling system efficiency. This results in significant cost savings and reduced peak energy demands, easing the strain on energy infrastructure.
- Aerogels provide exceptional insulating properties, reducing heat transfer while maintaining thinner wall profiles. This feature is particularly beneficial for retrofit projects where space conservation is crucial.
- VIPs offer superior insulation performance; however, they require meticulous handling and installation to prevent damage and mitigate edge thermal bridging, which can compromise their efficiency.
- By reflecting solar radiation, HRCs contribute to substantial energy savings, especially in warmer climates, by reducing cooling loads. However, they may lead to increased heating demands during colder months and the potential for unintentional warming of surroundings. Moreover, HRCs' SRI can decrease due to natural ageing and weathering.
- Environmentally, adopting these materials leads to significant reductions in CO_2 emissions and greenhouse gases, supporting sustainability goals and contributing to global efforts to combat climate change.
- Economically, while the initial investment for these advanced materials can be substantial, the long-term energy savings frequently offset the initial costs. Potential subsidies enhance the economic feasibility for homeowners and investors.
- Reduced payback periods increase the attractiveness of these advanced materials, encouraging their adoption and investment in the construction industry.
- Selecting the appropriate type of material, considering its properties and configurations tailored to specific building requirements and climatic conditions, is crucial. For instance, choosing a PCM with a melting point aligned with local temperature profiles maximises its thermal storage capacity.
- The effectiveness of these materials can be amplified when combined, as demonstrated in studies where PCMs were integrated with aerogels, VIPs or HRCs, resulting in synergistic improvements in energy efficiency and occupant comfort.
- Despite the promising benefits, practical application challenges remain. Issues such as high initial costs, long-term performance uncertainties, and technical difficulties in installation can impede widespread adoption.

5.1. Limitations and future work

Building thermal behaviour has been extensively studied in the context of these materials, contributing significantly to the understanding of this field; however, several limitations and areas for future research need to be addressed.

1. Focus on Energy Consumption: The current emphasis on energy consumption overlooks overall building performance factors, such as material durability, indoor air quality, and long-term thermal comfort impacts. Integrating these considerations will provide a more comprehensive assessment of the materials' benefits and limitations.

2. Neglect of Real-World Variables: Studies often overlook variables such as dynamic weather conditions, fluctuations in humidity, and patterns of occupant behavior is essential. Therefore, future research might enhance accuracy and applicability by including these real-world factors.
3. Lack of Long-Term Performance Data: Long-term performance studies are necessary to assess the durability and effectiveness of these materials over extended periods. Research on material degradation, maintenance requirements, and lifecycle performance will facilitate better decision-making and enhance confidence in the materials' longevity.
4. Limited Climatic and Regional Applicability: Expanding research to diverse climatic conditions and building geometries will increase the generalisability of findings. This broader applicability is crucial for developing guidelines and standards that can be implemented globally, catering to various environmental contexts and architectural designs.
5. Overlooked Lifecycle and Economic Factors: Comprehensive lifecycle assessments and economic analyses are essential to evaluate these advanced materials' long-term benefits and costs. Understanding the environmental impacts from production to disposal and the economic trade-offs will facilitate more informed choices by policymakers and industry professionals.
6. Requirement for Extensive Empirical Evaluations: The deficiency of large-scale demonstrations to assess and substantiate the effectiveness of materials in practical, real-world contexts indicating the potential need for such empirical applications in forthcoming research endeavors.
7. Development of Scalable Assessment Methods: Existing methods for integrating advanced materials into building retrofits often need to be more scalable and practical for widespread adoption. Future research should aim to develop standardised, simplified installation techniques and scalable assessment methods to enhance feasibility and encourage mass implementation.
8. Manufacturing Challenges: Addressing manufacturing challenges by focusing on production processes, cost reduction strategies, and scalability is critical. Future studies may concentrate on improving manufacturing techniques, exploring cost-reduction strategies, and utilising sustainable materials to make these materials affordable and easily accessible, promoting broader adoption in the construction industry.

By pursuing these future research directions, the building industry can overcome current limitations and fully exploit the potential of advanced envelope materials to achieve enhanced energy efficiency, sustainability, and occupant comfort. Adopting a comprehensive approach encompassing all aspects of material performance, implementation strategies, and overall impact will facilitate the broader adoption of these technologies, significantly contributing to global sustainability goals.

CRediT authorship contribution statement

Khalid Ghazwani: Writing – original draft. **Thomas Beach:** Supervision, Writing – review & editing. **Yacine Rezgui:** Supervision.

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

Data will be made available on request.

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