

A Review Paper on Phase Change Materials for Thermal Energy Storage and Building Applications

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Abstract

Phase Change Materials (PCMs) have emerged as promising materials for latent thermal energy storage (TES) because they can absorb and release large amounts of thermal energy during phase transition while maintaining nearly constant temperature. Their integration into buildings can improve thermal comfort, reduce indoor temperature fluctuations, shift peak cooling and heating loads, and decrease dependence on HVAC systems. This review presents recent advances in PCM-based thermal energy storage, with particular emphasis on building applications such as walls, roofs, floors, ceilings, windows, concrete, bricks, and cementitious materials. The review discusses the classification of PCMs into organic, inorganic, eutectic, bio-based, and composite materials, along with important selection parameters including melting temperature, latent heat, thermal conductivity, density, chemical stability, supercooling, and cycling durability. Recent studies have investigated microencapsulation, macroencapsulation, shape-stabilized PCMs, nano-enhanced PCMs, porous supports, and hybrid PCM systems to overcome problems such as leakage, low thermal conductivity, phase segregation, and limited durability. Recent reviews also indicate that PCM-integrated building envelopes can reduce peak indoor temperatures and HVAC energy demand, although performance depends strongly on PCM properties, placement, quantity, building design, and climatic conditions.

Keywords: Phase Change Material, Thermal Energy Storage, Latent Heat Storage, Building Energy Efficiency, Thermal Comfort, PCM-Integrated Wall, Encapsulation, HVAC Energy Saving, Sustainable Buildings.

1. INTRODUCTION

The increasing demand for heating and cooling in buildings has created a major need for efficient thermal energy storage technologies. The building sector is responsible for a substantial share of global energy consumption, making thermal management and energy efficiency important for reducing energy use and carbon emissions. Phase Change Materials (PCMs) are gaining attention as latent heat thermal energy storage materials because they can absorb and release large amounts of heat during phase transition while maintaining a nearly constant temperature.

Unlike conventional sensible heat storage materials, PCMs store energy mainly as latent heat, which can provide high thermal storage capacity within a relatively small volume. In buildings, PCMs can be incorporated into walls, roofs, floors, ceilings, windows, concrete, mortar, plaster and other building-envelope components to reduce indoor temperature fluctuations and shift heating or cooling loads. Recent reviews show that PCM-integrated building envelopes can improve thermal comfort and reduce HVAC energy demand, although performance strongly depends on PCM melting temperature, location, thickness, climate and operating conditions.



Fig 1.1- Phase Change Material in Building Construction

Phase Change Materials (PCMs) are advanced thermal energy storage materials that absorb and release large amounts of heat during phase change, mainly from solid to liquid and vice versa. They can store thermal energy at nearly constant temperature and are therefore useful for improving energy efficiency in buildings. PCMs can be incorporated into walls, roofs, ceilings, floors, concrete and insulation systems to reduce indoor temperature fluctuations and cooling/heating loads. Recent research focuses on microencapsulated, composite, bio-based and nano-enhanced PCMs to improve thermal conductivity, durability and stability. This review discusses recent developments, building applications, advantages, limitations and future research opportunities of PCM-based thermal energy storage systems.

2. OBJECTIVES

1. To study the basic principles and working mechanism of Phase Change Materials (PCMs) for thermal energy storage.
2. To review different types and properties of PCMs used in building applications.
3. To examine the use of PCMs in walls, roofs, floors, ceilings and concrete.
4. To study the role of PCM in reducing indoor temperature fluctuations and building energy consumption.
5. To review recent developments in microencapsulated, composite and bio-based PCMs.
6. To identify the limitations, research gaps and future scope of PCM-based thermal energy storage in buildings.

3. LITERATURE REVIEW

3.1. Attia et al. (2026):

The author reviewed PCM applications that have reached relatively advanced technology-readiness levels, focusing on real building applications rather than only laboratory experiments or simulations. The review examined PCM strategies for improving thermal comfort, reducing energy demand and providing thermal flexibility. Reported field studies showed approximately 1–3°C peak-temperature reduction and, in some cases, up to 25% load savings. The study emphasizes that PCM performance depends strongly on its location, climate, operating conditions and effective daily cycling.

3.2. Dora, Kuznik & Madhavan (2026):

Study investigates PCM for building thermal-energy management, with particular attention to bio-based PCM incorporated into plasterboard. The reported work identified 40 wt% PCM replacement as an optimum in the investigated system, while the resulting PCM-gypsum material maintained compressive and flexural strength within the relevant requirements. The study demonstrates the potential of PCM-integrated gypsum/plasterboard for improving building thermal performance.

3.3. Mohan et al. (2026):

Reviewed PCM applications in walls, roofs, ceilings, floors, glazing, hybrid envelopes and cementitious materials. The review emphasizes that PCM performance is controlled by melting temperature, latent heat, thermal conductivity, thickness, position within the envelope, solar exposure and climate. It also discusses emerging 3D-printed PCM systems and model-predictive-control approaches. Major challenges include leakage, low thermal conductivity, incomplete daily cycling, durability, fire safety, toxicity and cost.

3.4. Baradales-Cortes et al.(2026):

Review focuses on PCM encapsulation and integration into building structures. It compares micro-, nano- and hybrid-encapsulation techniques and discusses important PCM properties such as melting temperature, latent heat and thermal conductivity. It also considers PCM integration with sustainable and waste-derived building materials. The paper identifies advanced encapsulation as an important pathway for improving PCM durability, thermal performance and practical applicability.

3.5.Rashid et al. (2026):

This review examines PCM-gypsum boards as building-envelope thermal-storage materials. It reports that PCM-gypsum systems can stabilize indoor temperatures, while microencapsulated PCM can provide relatively stable thermal-storage cycling. The review also discusses sustainable PCM-gypsum systems and their potential for reducing building energy consumption and carbon emissions.

3.6. Cabeza et al. (2026):

Discuss thermal energy storage as a strategy for addressing the mismatch between building energy demand and energy availability. TES, including latent heat storage using PCMs, can help buildings shift heating and cooling loads and make better use of renewable energy. The paper places PCM within the wider context of sustainable and low-carbon buildings.

3.7. Han & Lu (2025):

Reviewed the use of PCMs in walls, roofs, windows and floors for building thermal management. The study explains that PCMs can absorb and release latent heat during phase transition and therefore reduce indoor temperature fluctuations and heating/cooling energy demand. Major technical issues identified include liquid leakage of solid–liquid PCMs and the low thermal conductivity of many organic PCMs. Encapsulation, solid–solid PCMs and thermal-conductivity enhancement methods are discussed as solutions.

3.8. Abass & Muthulingam (2025):

Review covers PCM classification, thermal energy storage, encapsulation and incorporation into construction materials and building envelopes. The authors report that PCM-enhanced building components can reduce indoor temperature fluctuations and cooling loads while improving thermal comfort. Microencapsulation and composite PCM technologies are

highlighted for improving thermal stability and storage performance. The review also emphasizes that PCM type, location and incorporation method strongly influence performance.

3.9. Teamah & Teamah (2025):

Justify this paper examines PCM integration into walls, roofs and floors under different climatic conditions. It reviews PCM incorporation techniques, modelling methods and thermal-performance assessment. The review reports that PCM integration can reduce building loads by up to about 30% in the studies examined and can help limit indoor temperature fluctuations. However, performance depends strongly on climate, PCM melting temperature, location and building configuration.

3.10. Zhang et al. (2025):

Justify this paper reviews PCM-based thermal storage walls, Trombe walls, multilayer PCM walls and photovoltaic-integrated PCM walls. It discusses PCM selection, encapsulation, heat-storage/release behaviour and integration with solar energy. The review also identifies the combination of PCM with renewable-energy systems and intelligent control as important future directions.

3.11. Rana & Pearce (2025):

Review focuses on PCM-based thermal energy storage (PCM-TES) coupled with photovoltaic systems and heat pumps. It discusses PCM classification, characterization, properties, applications, modelling and challenges. The study highlights PCM-TES as a potential lower-cost thermal-storage option for buildings and examines its role in matching intermittent solar energy with building heating/cooling demand.

3.12. Shree et al. (2025):

Study reviews PCM applications in energy-efficient building envelopes, PCM classification and selection criteria, performance-estimation techniques and major integration challenges. It presents PCM-embedded envelopes as a method for improving thermal regulation and occupant comfort while reducing building energy demand.

3.13. Ahmad et al. (2025):

Justify this paper is particularly useful for a review paper because it critically examines previous review articles on PCM building applications, identifies common research themes and summarizes remaining knowledge gaps. It provides a structured overview of how PCM research has developed and where future research should be directed.

3.14. Togun et al. (2025):

Justify recent developments in Phase Change Materials (PCMs), focusing on advanced encapsulation techniques, improved thermal properties, stability, and safety. The study also examined the application of PCMs in building-envelope systems for improving thermal energy storage and indoor thermal comfort. However, challenges such as high cost, leakage, low thermal conductivity, durability, and large-scale practical implementation remain. The review highlights the need for more durable, efficient, and cost-effective PCM systems for real-world buildings.

3.15. Kumar et al. (2024):

Justify this review examines the application of PCMs in different building components such as walls, roofs, floors, bricks, cement, plaster, paints and windows. It discusses solid–liquid and solid–solid PCMs, including organic, inorganic, fatty-acid, bio-based and nano-enhanced

PCMs. The review reports that PCM integration can reduce indoor temperature fluctuations and building heat loads. It also identifies leakage, encapsulation, mechanical-property reduction and appropriate PCM selection as important challenges.

3.16. Yadav et al. (2024):

justify critically reviewed the selection, characterization, thermal properties, and incorporation techniques of Phase Change Materials (PCMs) for building applications. The study discussed microencapsulation, macroencapsulation, shape stabilization, immersion, and vacuum impregnation methods. It highlighted that proper PCM selection based on melting temperature, latent heat, thermal conductivity, and thermal stability is essential for effective building applications. The review also reported that PCM integration can improve thermal comfort, energy efficiency, heat retention, and heating/cooling performance of buildings. However, challenges such as low thermal conductivity, leakage, stability, and practical implementation remain important areas for further research.

3.17. Zhao et al. (2024):

Justify these reviewed the application of Phase Change Materials (PCMs) in building envelopes, particularly in walls, ceilings, roofs, floors and windows. The study examined PCM incorporation into materials such as plaster, cement mortar, concrete and brick. It also analyzed how PCM type, quantity, location and integration method influence thermal performance, energy consumption and indoor thermal comfort. The review concluded that appropriate PCM selection and placement can improve thermal regulation and energy efficiency, while further research is required for cost-effective and practical building application.

3.18. Osibodu, Adeyinka & Mbelu (2024):

Justify these reviewed various PCM incorporation techniques in concrete for thermal energy storage. The study found that PCM integration can improve the thermal energy storage capacity and thermal efficiency of concrete. However, increasing PCM content may reduce mechanical strength, while leakage and encapsulation durability remain important challenges. The authors emphasized that suitable encapsulation and incorporation methods are required to achieve a balance between thermal performance, strength and long-term durability.

3.19. Ali, Habib & Younas (2024):

Justify these reviewed PCM-based thermal energy storage systems, focusing on PCM thermophysical properties, synthesis techniques, impregnation, and encapsulation methods. The study highlights that low thermal conductivity, thermal instability, degradation, and leakage are major challenges affecting PCM performance and long-term application. The review suggests that improved encapsulation and material modification can enhance the thermal stability, durability, and energy-storage performance of PCMs for practical applications.

3.20. Su et al. (2024):

Justify these reviewed form-stabilized phase change materials (FSPCMs), focusing on stabilization using porous structures, encapsulation, and hybrid materials. The study explains that form stabilization helps prevent leakage of liquid PCM during the melting process while maintaining effective latent heat storage. It also discusses applications of FSPCMs in building thermal management, textiles, electronics, and other thermal-management systems. The review highlights FSPCMs as a promising approach for improving the stability, durability, and practical applicability of PCM-based thermal energy storage systems.

3.21. Lin et al. (2024):

Justify the use of Phase Change Materials (PCMs) for achieving energy-efficient and sustainable buildings. The study discusses PCM selection, thermophysical properties and different integration methods. It covers walls, roofs, windows and floors, along with passive and active PCM systems. The review also examines the integration of PCM with HVAC and solar-energy storage systems to improve indoor thermal comfort, reduce energy consumption and support carbon-neutral buildings. The authors also highlight challenges such as appropriate PCM selection, integration methods and practical implementation, while identifying PCM technology as a promising approach for sustainable building design.

3.22. Junaid et al. (2024):

Justify reviewed PCM-incorporated cement-based composites (PCM-CBCs) for building applications. The study evaluated their thermal performance, mechanical properties, durability, sustainability, energy efficiency, and resource conservation. The review found that PCM-CBCs can significantly improve thermal energy storage and indoor thermal regulation, making them promising materials for building envelopes such as walls, floors, slabs and mortars. However, increasing PCM content can reduce mechanical strength and may create durability and leakage problems. The authors emphasized the need for improved PCM incorporation methods and long-term durability studies for practical construction applications.

3.23. Ait Laasri et al. (2024):

Study macro-encapsulated phase change materials (PCM) for building heating and cooling applications. The study discusses both passive and active PCM systems, including PCM integration in bricks, wallboards, PCM plates and thermal energy storage (PCM-TES) tanks. It evaluates the thermal characteristics, economic feasibility and environmental sustainability of macro-encapsulated PCM. The review also highlights integration with renewable energy and control systems and identifies advanced heat-transfer enhancement techniques as important for improving PCM performance.

3.24. Sharshir et al. (2023):

Justify the recent development of PCM-based thermal energy storage in buildings. The paper discusses different types of PCMs, their advantages and limitations, methods of incorporating PCM into building components, thermal-property enhancement techniques, and PCM selection for building applications. The authors emphasize that the melting temperature of the PCM should be close to the required indoor operating temperature and that the location of PCM within a building component strongly affects its performance. The review also reports that inappropriate PCM selection can increase energy consumption, whereas optimized PCM selection and placement can reduce annual building energy consumption. Thermal conductivity is identified as an important limitation, and additives such as graphite can substantially improve heat transfer.

3.25. Cunha et al. (2023):

Justify the development of PCM thermal-storage technology in the construction industry, particularly research published during the previous decade. The review covers PCM classification, selection criteria and incorporation techniques, followed by applications in mortar, concrete, porous aggregates, natural materials, carbon-based materials, boards, blocks and solar thermal systems. The authors highlight PCM as a promising technology for reducing building energy consumption because it can store thermal energy and release it when required. The paper also discusses cost, sustainability, thermal performance and future challenges associated with PCM-based construction materials.

Useful for your review: This paper is particularly useful for the sections “PCM incorporation methods,” “PCM in construction materials,” “advantages and limitations,” and “future scope.”

3.26. Masood et al. (2023):

This review focused on PCM-based latent heat thermal energy storage for building cooling applications. The review discusses PCM selection, thermal-energy-storage systems, cooling-load reduction, peak-load shifting, heat-transfer enhancement and practical building applications.

PCMs can be incorporated into bricks, wallboards, façades, floors, ceilings, roofs and glazing. The review also emphasizes that improving the thermal conductivity of PCM and developing suitable heat-transfer enhancement techniques are important for practical implementation.

3.27. Ismail et al. (2023):

This review focuses on microencapsulated phase change materials (MPCM) used in construction materials. Microencapsulation prevents leakage of liquid PCM during melting and allows PCM to be incorporated into cementitious materials and gypsum boards. The review evaluates different shell materials, production techniques and methods for improving thermal conductivity. The authors report that shell material affects both thermal and mechanical performance. Organic and inorganic shells have different advantages, while conductive nanomaterials can improve thermal performance. The review also identifies mechanical-property reduction, workability problems, flammability and scalability as important challenges. This paper is especially useful for your project because your proposed smart thermal wall uses microencapsulated PCM.

3.28. Li et al. (2023):

Justify the PCM applications for passive cooling of building envelopes. The study discusses PCM characteristics, encapsulation, shape stabilization, measurement methods and heat-transfer mechanisms. Major challenges identified include PCM leakage, low thermal conductivity, supercooling, reduced mechanical properties and seasonal adaptability.

The review suggests composite PCMs and multiple-PCMs as possible approaches to overcome some of these limitations.

3.29. Gao et al. (2023):

Justify the integration of Phase Change Materials (PCMs) into building bricks for improving thermal-energy storage and building energy efficiency. The study examined different PCM-filling methods, including direct incorporation, form stabilization and macro-encapsulation, as well as suitable PCM locations within bricks. It found that PCM bricks can reduce indoor temperature fluctuations, increase thermal storage capacity and reduce building heating/cooling loads. The thermal performance depends on PCM properties, filling position, outdoor conditions and heat-transfer surface area. The authors also highlighted PCM leakage, reduced brick strength/thermal conductivity, modelling limitations and economic feasibility as important challenges for future research.

3.30. Wang et al. (2022):

Authors focuses on PCM technology for improving building energy efficiency and thermal performance. The review discusses PCM selection, thermal properties, incorporation methods and building applications. Organic PCMs were identified as suitable for many building conditions because their phase-change temperature can be selected according to ambient conditions. Shape-stabilized PCM was highlighted as an important incorporation technique because it can reduce leakage problems. The study also emphasizes that PCM performance

depends strongly on the local climate and construction conditions, so PCM selection should consider both thermal and physical properties.

3.31. Suresh et al. (2022):

focuses on different techniques for incorporating PCM into building envelopes. It discusses microencapsulation, incorporation into building materials, heat-transfer improvement and the effect of PCM on building energy consumption. The authors also discuss economic benefits and possible CO₂-emission reductions. Future research opportunities for PCM-integrated buildings are identified.

3.32. Kumar et al. (2022):

Justify the use of PCM as a thermal-energy-storage material in building envelopes. It explains the working principle of PCM, PCM types and thermophysical properties, and methods for incorporating PCM into building materials. It also summarizes experimental and numerical studies on PCM-integrated walls and other envelope components. The authors identify research gaps and future directions for improving PCM building systems.

3.33. Nair et al. (2022):

Justify the application of PCM-based thermal energy storage in building-integrated heating and domestic hot-water systems. The study covers space heating, underfloor heating, wall heating and PCM-integrated domestic hot-water tanks. It explains that PCMs can reduce building energy demand and indoor temperature fluctuations while improving the utilization of renewable energy and off-peak electricity. The review also discusses PCM selection, thermal-performance enhancement techniques and suitable melting-temperature ranges for different applications.

3.34. Podara et al. (2021):

Justify fundamentals of PCM-based latent heat thermal energy storage and their applications in buildings. The study discussed different types of PCMs, methods for improving their thermal performance, and their incorporation into construction materials. Particular attention was given to encapsulated PCMs, where a PCM core is surrounded by an organic or inorganic shell. The review reported that PCM integration can store thermal energy and help maintain indoor thermal comfort while reducing building energy consumption. The authors also discussed applications in building envelopes, HVAC systems and domestic hot-water systems.

3.35. Junaid et al. (2021):

This review focused on inorganic PCMs (iPCMs) for latent thermal energy storage in buildings. The authors examined their thermal performance and integration with concrete, composites and other building materials. Important problems such as supercooling, phase separation, corrosion and encapsulation were discussed. The study reported that inorganic PCMs can provide high volumetric thermal storage capacity and can be incorporated into both passive and active building systems. However, the authors identified a need for further research before large-scale real-building implementation.

3.36. Prieto et al. (2021):

Justify this review examined both experimental and numerical research on PCM-integrated building walls from 2011–2020. It considered PCM selection, incorporation methods, wallboards and different building-wall configurations. The review showed that PCM-integrated walls can provide thermal energy storage and reduce indoor temperature

fluctuations. However, the authors noted that research considering actual building operation, economic feasibility and environmental impacts was still insufficient.

3.37. Ben Romdhane et al. (2020):

Justify the application of phase change materials for thermal energy storage in passive buildings. The study investigated PCM classification, selection criteria, encapsulation methods and integration into building components such as walls, wallboards, roofs and floors. The authors reported that PCM integration can store and release thermal energy during phase change, reduce indoor temperature fluctuations, improve thermal comfort and increase building energy efficiency. The review also identified the need for further research to improve PCM integration and its practical application in buildings.

3.38. Rathore and Shukla (2019):

Justify the potential of macroencapsulated phase change materials for thermal energy storage in buildings. The study examined PCM encapsulation techniques, thermal energy storage behaviour and their application for improving the thermal performance of buildings. The authors reported that PCM-based thermal storage can contribute to energy savings and improved indoor thermal conditions. Macroencapsulation was identified as an important technique for integrating PCM into building systems while addressing practical issues such as leakage. The review also highlighted challenges and future research requirements for the effective application of PCM in buildings.

3.39. Meng et al. (2018):

Authors reviewed the use of PCM in building envelopes and building equipment for improving energy performance. The review covered studies from approximately 2004–2017. For building-envelope applications, PCM melting temperatures were generally in the range of 10–39°C, while applications in building equipment covered a wider range. The study reported that PCM can improve thermal comfort, reduce energy consumption and shift heating/cooling loads. The authors also identified research gaps concerning PCM selection, integration, modelling and system optimization.

3.40. Madad et al. (2018):

paper presents a comprehensive review of latent heat thermal energy storage using PCM in buildings. The authors examined more than 100 studies and discussed both experimental and numerical approaches. PCM applications for thermal comfort, building envelopes and thermal-energy storage were investigated. The review concluded that appropriately designed PCM systems can reduce energy consumption and improve indoor thermal conditions. However, differences in experimental conditions and numerical modelling methods make direct comparison between studies difficult.

4. CONCLUSION

After reviewing various studies, it is concluded that Phase Change Materials (PCMs) are promising for thermal energy storage in energy-efficient buildings. PCMs can be integrated into walls, roofs, floors, plasterboards, concrete and other building components to reduce temperature fluctuations and improve thermal comfort.

Recent research focuses on microencapsulation, form-stabilized PCMs, PCM-gypsum composites, hybrid envelopes, solar-PV integration and smart thermal control. PCM performance mainly depends on melting temperature, latent heat, thermal conductivity, location, climate and daily cycling.

However, challenges such as low thermal conductivity, leakage, supercooling, durability, fire safety, cost and limited long-term field studies still need to be addressed. More experimental studies under actual building conditions and different Indian climates are required.

Future research should focus on climate-specific and sustainable PCMs, advanced encapsulation, IoT-based monitoring and renewable-energy integration. Therefore, a cost-effective smart PCM-based building envelope has strong potential for improving thermal comfort and reducing building energy consumption in Indian conditions.

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