https://jsras.rcc.edu.ly/
Vol.3 No.2 (2026), 132-155
Article history:
Received:22/6/2026
Accepted: 17/7/2026
Published: 13/8/2026

Journal of Sustainable Research in Applied Sciences

JSRAS

Climate-Responsive Integration of Phase Change Materials in Building Envelopes: A Systematic Review and Libya-Focused Roadmap for Hot-Arid and Mediterranean Climates

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DOI https://doi.org/10.36602/jsras.2026.3.2.15
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Index Terms

building envelope, climate-responsive design, latent thermal energy storage, phase change materials, systematic review

Abstract

Buildings in hot-arid and Mediterranean regions experience substantial cooling loads, pronounced daily temperature swings, and growing exposure to climate-related heat stress. Phase change materials (PCMs) can moderate these effects through latent thermal energy storage, yet their performance depends on climate, phase-transition temperature, integration position, building operation, and methodological assumptions. This systematic review synthesizes a deduplicated evidence base of 90 unique studies published primarily during 2020–2025. Bibliographic, climatic, material, envelope, methodological, and performance variables were harmonized and analyzed using a PRISMA-aligned workflow. Studies published in 2024–2025 represented 58.9% of the evidence base. Hot-arid/desert and Mediterranean climates accounted for 23.3% and 21.1%, respectively. Organic PCMs dominated (64.4%), walls or façades were investigated in 73.3% of studies, and numerical or simulation-based methods represented 58.9%. Quantitative energy-saving values were reported in 37.8% of studies, with substantial heterogeneity in baselines and outcome definitions. The review proposes a climate-responsive integration framework and a Libya-focused roadmap emphasizing multi-city field validation, locally appropriate transition-temperature selection, aging and cycling assessment, techno-economic and life-cycle evaluation, and open benchmark datasets. Available evidence supports targeted Libyan pilot studies but not direct transfer of generalized performance claims.

التكامل المتجاوب مناخيًا لمواد تغيّر الطور في أغلفة المباني: مراجعة منهجية وخارطة طريق تركز على ليبيا للمناخات الحارة الجافة والمتوسطية

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الكلمات المفتاحية

أغلفة المباني، التصميم المتجاوب مناخيًا، تخزين الطاقة الحرارية الكامنة، مواد تغيّر الطور، المراجعة المنهجية

الملخص

تواجه المباني في المناطق الحارة الجافة والمتوسطية أحمال تبريد مرتفعة وتذبذبات يومية ملحوظة في درجات الحرارة وتزايدًا في الإجهاد الحراري المرتبط بالمناخ. تستطيع مواد تغيّر الطور الحد من هذه التأثيرات من خلال تخزين الطاقة الحرارية الكامنة، إلا أن أداءها يعتمد على المناخ ودرجة الانتقال الطوري وموضع الدمج وتشغيل المبنى والافتراضات المنهجية. تجمع هذه المراجعة المنهجية قاعدة أدلة منقحة تضم 90 دراسة فريدة منشورة أساسًا خلال 2020–2025. مثّلت دراسات عامي 2024–2025 نسبة 58.9% من القاعدة، وشكّلت المناخات الحارة الجافة أو الصحراوية 23.3% والمناخات المتوسطية 21.1%. هيمنت المواد العضوية بنسبة 64.4%، ودُرست الجدران أو الواجهات في 73.3% من الدراسات، بينما مثّلت المناهج العددية أو المحاكاة 58.9%. أظهرت النتائج تفاوتًا كبيرًا في خطوط الأساس وتعريفات مؤشرات الأداء. وتقترح المراجعة إطارًا للدمج المتجاوب مناخيًا وخارطة طريق تركز على ليبيا، تشمل التحقق الميداني متعدد المدن، واختيار درجات الانتقال المناسبة محليًا، وتقييم التقادم والدورات الحرارية، والجدوى الاقتصادية والبيئية. تدعم الأدلة تنفيذ دراسات تجريبية ليبية مستهدفة، لكنها لا تبرر النقل المباشر لادعاءات الأداء العامة

1. Introduction

Building energy demand is shaped by a complex interaction between climate, envelope design, occupancy, equipment loads, and operational control. In hot-arid and Mediterranean regions, solar gains and high outdoor temperatures frequently create cooling-dominated conditions, while large diurnal temperature swings can also provide opportunities for passive thermal regulation. Improving the dynamic performance of the building envelope is therefore central to reducing cooling demand and maintaining acceptable indoor conditions (Bolteya et al., 2022; Dardouri et al., 2023; Lahoud et al., 2024; Idouanaou et al., 2025; Hadded et al., 2025).

Phase change materials store and release heat through a reversible phase transition over a relatively narrow temperature interval. When a PCM is properly matched to the indoor comfort range and the thermal conditions of the envelope, latent thermal energy storage can delay heat transfer, reduce temperature peaks, shift loads away from critical hours, and improve the utilization of night-time cooling. These mechanisms have been demonstrated across PCM-enhanced walls, roofs, ceilings, floors, glazing systems, and hybrid building-energy systems (Mechouet et al., 2020; Lakhdari et al., 2020; Babaharra et al., 2022; Hadded et al., 2025; Al-Mudhafar et al., 2025).

However, PCM performance is not an intrinsic constant of the material. The same product may provide substantial benefit in one climate and remain partially inactive or fail to regenerate in another. Performance also changes with melting temperature, latent heat, thermal conductivity, layer thickness, location within the assembly, orientation, ventilation, thermostat settings, and the duration of the assessment. Consequently, results from a single test cell or simulation cannot be transferred reliably without considering the climatic and operational context (Hamidi et al., 2021; Mechouet et al., 2020; Chen et al., 2023; Dardouri et al., 2023; Lahoud et al., 2024; Chan et al., 2025; Nath et al., 2025).

The recent literature has grown rapidly and has become methodologically diverse. Whole-building simulation is commonly used to screen PCM type, thickness, and location, while experiments range from material characterization to component-scale chambers and full-scale test rooms. Hybrid studies combine numerical optimization with experimental validation. This diversity is valuable, but it also produces substantial heterogeneity in baseline definitions, climatic files, boundary conditions, performance indicators, and reporting practices (Mechouet et al., 2020; Dardouri et al., 2023; Gbekou et al., 2024; Laasri et al., 2024; Vedrtnam et al., 2025).

Hot-arid and Mediterranean regions are especially relevant to this debate because they combine high solar exposure with different levels of nocturnal cooling potential and seasonal variability. Coastal Mediterranean locations may support repeated daily charging and discharging when the PCM transition range is appropriately selected, whereas very hot inland climates may require enhanced night ventilation, active regeneration, or hybrid cooling to avoid incomplete solidification. The climate-responsiveness of PCM design is therefore more important than the generic question of whether PCMs are effective (Hamidi et al., 2021; Mechouet et al., 2021; Dardouri et al., 2023; Lahoud et al., 2024; Salihi et al., 2024; Chan et al., 2025).

Libya represents a critical but under-researched context. Its building stock spans coastal Mediterranean, semi-arid transitional, and severe desert conditions. High cooling demand, electricity-system stress, and the need for passive and low-energy solutions create a strong rationale for PCM research. Within the harmonized evidence base, no study was conducted as a dedicated field or full-building investigation under Libyan conditions; the only direct climatic representation was a regional simulation that included Tripoli among eight Mediterranean cities and showed that lower-temperature PCMs could remain fully liquid during the representative summer day (Hamidi et al., 2021). Accordingly, national recommendations must presently be inferred cautiously from climatically comparable evidence in North Africa and the Middle East (Bolteya et al., 2022; Dardouri et al., 2023; Lahoud et al., 2024; Idouanaou et al., 2025; Hadded et al., 2025).

Recent studies have addressed PCM material selection, encapsulation and composite development, envelope integration, cross-climate performance, and interactions with ventilation or reflective surfaces. The literature is also shifting toward multi-objective optimization and integrated energy, economic, carbon, life-cycle, and durability assessment. Nevertheless, important gaps remain in connecting climate, envelope component, methodological quality, and implementation readiness within one harmonized evidence framework (Chen et al., 2023; Mettrick & Ma, 2024; Idouanaou et al., 2025; Hadded et al., 2025; Wadee et al., 2025).

This review addresses these gaps through a harmonized synthesis of 90 unique studies. It does not treat all reported savings as directly comparable; instead, it distinguishes descriptive trends from transferable evidence and explicitly identifies multiple-response variables, reporting uncertainty, and methodological imbalance. This approach is essential because apparent numerical precision can conceal major differences in baseline construction, occupancy, climate files, and system boundaries across cross-climate and whole-building investigations (Dardouri et al., 2023; Mettrick & Ma, 2024; Nath et al., 2025).

2. Research problem and research questions

Despite rapid growth in PCM-building research, the evidence remains fragmented across climates, material categories, envelope components, experimental scales, simulation assumptions, and performance indicators. This fragmentation prevents direct comparison of reported energy and comfort benefits and weakens the transferability of configurations optimized for one climate or building system to another. The problem is particularly important for Libya because dedicated full-scale Libyan investigations remain absent, while the available local climatic evidence is limited to a regional simulation that included Tripoli (Hamidi et al., 2021).

Accordingly, this review addresses the lack of a harmonized evidence synthesis linking climate, PCM type, envelope component, integration strategy, research method, validation quality, and reported performance. It also examines the extent to which findings from Mediterranean and hot-arid analogues can inform a cautious, locally validated roadmap for the Libyan built environment rather than being transferred as universal design rules.

- RQ1. How has recent research on PCM integration in building envelopes evolved geographically, climatically, and methodologically?
- RQ2. Which PCM categories and envelope components dominate the evidence base?
- RQ3. Which performance indicators and analytical tools are most frequently used, and what limitations affect comparability?
- RQ4. What evidence gaps must be addressed before reliable implementation in Libya and other hot-arid or Mediterranean regions?
- RQ5. How can available evidence be translated into a climate-responsive PCM selection and validation framework?

3. Study significance

This review is scientifically significant because it moves beyond a general description of PCM technologies and establishes a harmonized, study-level evidence base linking climate, PCM category, envelope component, research method, validation practice, and reported performance. By reconciling duplicate records and synthesizing 90 unique recent studies, it clarifies where the literature is mature, where reported savings remain difficult to compare, and which conclusions can be transferred only with caution. The resulting synthesis therefore provides a more defensible basis for climate-responsive PCM selection than isolated performance values or material-centred generalizations (Dardouri et al., 2023; Mettrick & Ma, 2024; Nath et al., 2025).

The study also has direct regional and practical significance for Libya. The evidence base contains no dedicated Libyan field or full-building investigation, while the only direct climatic representation is a regional simulation that included Tripoli and demonstrated the risk of incomplete PCM solidification under hot summer conditions (Hamidi et al., 2021). By comparing evidence from Mediterranean, semi-arid, and hot-arid analogues, the review translates international findings into a staged Libyan roadmap covering local material characterization, climate-specific transition temperatures, wall and roof pilots, experimental validation, durability, techno-economics, life-cycle assessment, and future design guidance. This contribution is intended to support research prioritization, monitored demonstration projects, and evidence-based building-energy policy rather than premature nationwide product prescription.

4. Study objectives

- Map the publication, geographic, climatic, material, building, envelope-component, and methodological characteristics of recent PCM-building studies.
- .Quantify the dominant PCM categories, envelope applications, research methods, software platforms, validation practices, and reported performance indicators.
- Critically evaluate methodological quality, outcome comparability, validation reliability, and the limitations affecting transfer of reported PCM performance.
- Identify evidence gaps and assess the relevance of international findings to Libyan coastal Mediterranean, semi-arid inland, and severe desert contexts.
- .Develop a climate-responsive PCM integration framework and a staged future research roadmap for the Libyan built environment and comparable climates.

5. Previous studies and research literature

Recent PCM-building research consistently treats phase-transition temperature and night-time regeneration as climate-dependent design variables. Studies conducted in Mediterranean and hot-arid contexts show that PCM layers can attenuate heat gains and shift cooling loads, but incomplete solidification during warm nights can substantially reduce the following day's storage capacity (Mechouet et al., 2020; Hamidi et al., 2021; Faraj et al., 2021; Bolteya et al., 2022; Dardouri et al., 2023).

External walls and façades form the most developed application stream. Prior studies have investigated PCM boards, mortar or plaster incorporation, hollow-brick cavities, and encapsulated wall panels, demonstrating that

performance depends on layer position, orientation, PCM quantity, transition range, and the surrounding construction assembly (Mechouet et al., 2020; Babaharra et al., 2022; Al-Yasiri & Szabó, 2023a, 2023b; Dardouri et al., 2023; Hadded et al., 2025).

Roof-focused investigations report strong potential under high solar exposure, especially when PCM is combined with insulation, reflective surfaces, or coordinated wall–roof configurations. Nevertheless, severe summer conditions and limited nocturnal cooling can constrain complete regeneration, making local transition-temperature selection essential (Hamidi et al., 2021; Bolteya et al., 2022; Dardouri et al., 2023; Al-Yasiri & Szabó, 2023b; Lahoud et al., 2024; Hadded et al., 2025).

Methodologically, numerical simulation dominates because it enables rapid comparison of materials, positions, thicknesses, and climates. However, the strongest studies combine dynamic simulation with laboratory measurements, test-cell experiments, or monitored building data. This hybrid approach improves calibration, exposes operational constraints, and provides more credible evidence for transfer to real buildings (Mechouet et al., 2020; Bolteya et al., 2022; Al-Yasiri & Szabó, 2023b; Laasri et al., 2024).

Collectively, the literature supports the technical potential of PCM-enhanced envelopes but does not justify universal performance claims. Differences in climate files, baseline assemblies, occupancy schedules, outcome definitions, and validation practices remain major barriers to comparison. The limited Libyan evidence therefore establishes a clear need for locally calibrated field studies and integrated energy, comfort, durability, economic, and life-cycle assessment.

6. Research methodology

This study was designed as a systematic literature review and evidence synthesis. The workflow followed the logic of PRISMA 2020: identification, de-duplication, eligibility assessment, inclusion, structured data extraction, quality assessment, harmonization, and synthesis. The original extraction contained 101 records. DOI reconciliation removed ten redundant rows, and a subsequent normalized-title audit identified one additional duplicate record for Hamidi (2021). The more complete full-text record was retained, yielding a final analytical database of 90 unique primary studies. Review articles, duplicate uploads, studies outside the fixed publication window, and interventions without a direct PCM–building-envelope relationship were excluded from the primary synthesis.

6.1 Eligibility criteria

Table 1. Eligibility criteria applied to the review

Dimension	Inclusion criteria	Exclusion criteria
Publication period	Primarily 2020-2025	Outside the fixed window, except contextual discussion
Document type	Original experimental, numerical, or hybrid primary study	Review, editorial, commentary, duplicate, or non-primary evidence
Intervention	PCM integrated into a building envelope or directly coupled building application	PCM unrelated to buildings or no relevant building-envelope outcome
Outcomes	Thermal, energy, comfort, peak-load, environmental, or economic outcome	No interpretable building-performance outcome
Evidence access	Sufficient bibliographic and technical information for extraction	Insufficient evidence for reliable classification
Language	English-language records or records with sufficient English metadata	Records that could not be assessed consistently

6.2 Search and screening logic

The search strategy combined terms related to phase change materials, latent thermal energy storage, buildings, envelopes, walls, roofs, ceilings, floors, façades, glazing, energy performance, thermal comfort, passive cooling, hot-arid climates, and Mediterranean climates. Screening was conducted at title/abstract and full-text levels. Duplicate DOI and normalized-title records were audited and recorded in the screening log. The final sample comprised 90 unique accepted studies. Figure 1 documents the auditable certification sequence applied to the extracted evidence matrix. Because the upstream search-export and title/abstract exclusion counts were not preserved in the supplied data, the figure is intentionally limited to verified post-extraction deduplication and does not present unverified PRISMA identification counts.

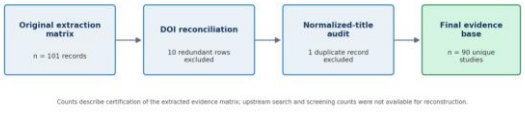


Figure 1. Evidence-base certification and duplicate-reconciliation flow.

6.3 Data extraction and harmonization

A structured extraction matrix was used to capture bibliographic information, study country, climate zone, objective, building type, envelope component, PCM material and category, encapsulation form, melting temperature, latent heat, integration location, research method, software, experimental scale, validation method, performance indicators, reported outcomes, limitations, recommendations, relevance to Libya, evidence status, and reviewer notes. Terminology was harmonized before statistical analysis. Multiple-response variables, including country occurrence, envelope component, software, and performance indicators, were allowed to exceed 100% when one study contributed to more than one category.

6.4 Quality assessment

Methodological quality was assessed using six domains: clarity of aim, appropriateness of method, adequacy of PCM description, validation, clarity of outcome reporting, and acknowledgment of limitations. Each domain was scored on a 0–2 scale. The assessment was used to interpret confidence and research maturity rather than to calculate a pooled effect size. High checklist performance does not eliminate concerns related to simulation dominance, short monitoring periods, incomplete material reporting, and inconsistent outcome definitions.

6.5 Synthesis strategy

Because of major heterogeneity in climates, PCM products, assembly configurations, baselines, occupancy assumptions, and reported metrics, a formal meta-analysis was not considered methodologically defensible. The study therefore used descriptive statistics, structured thematic synthesis, evidence-gap mapping, and climate-responsive interpretation. Counts and percentages used 90 unique studies as the denominator for single-response variables; multiple-response variables are explicitly identified.

7. Results

7.1 Publication trend

The evidence base expanded markedly toward the end of the review period. Nine studies were published in 2020, five in 2021, ten in 2022, twelve in 2023, twenty-six in 2024, and twenty-seven in 2025; one record did not report a usable publication year. Studies published in 2024 and 2025 therefore represented 58.9% of the final evidence base. This concentration indicates rapid recent expansion, but it also means that many technologies have not accumulated long-term field evidence.

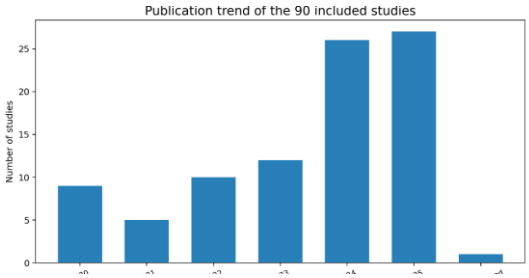


Figure 2. Publication trend of the 90 included studies.

7.2 Geographic distribution

The primary-country distribution was broad but uneven. Multi-country or multi-climate investigations and Morocco each contributed nine studies (10.0%), followed by Iraq and China with eight each (8.9%) and Türkiye with seven (7.8%). Italy, Algeria, and Egypt contributed five studies each (5.6%). Primary-country coding assigned each study once, preserving multi-country studies as a separate category and avoiding the inflation produced by country-occurrence counting.

Table 2. Leading geographic contributors

Primary country / coverage	Studies (n)	Percentage of 90 (%)
Multi-country / multi-climate	9	10.0
Morocco	9	10.0
Iraq	8	8.9
China	8	8.9
Türkiye	7	7.8
Other / not clearly specified	6	6.7
Italy	5	5.6
Algeria	5	5.6
Egypt	5	5.6
Lebanon	4	4.4
Iran	4	4.4
France	4	4.4
Australia	3	3.3
India	3	3.3
Tunisia	2	2.2

Note: Country is a multiple-response variable; one study may cover more than one country.

7.3 Climate representation

Hot-arid/desert climates formed the largest broad climate category (n = 21; 23.3%), followed by Mediterranean climates (n = 19; 21.1%). Cold/cool studies accounted for 12.2%, multiple/mixed and other/unclear climates for 8.9% each, semi-arid/continental climates for 7.8%, and hot-humid/tropical climates for 6.7%. Controlled/no-field-climate and temperate/warm studies each represented 5.6%. The combined hot-arid and Mediterranean share (44.4%) confirms the relevance of the evidence base to Libya while retaining important climatic heterogeneity.

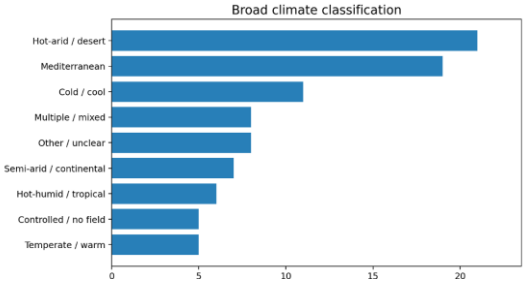


Figure 3. Distribution of included studies by harmonized climate zone.

7.4 PCM categories

Organic PCMs dominated the evidence base (n = 58; 64.4%), followed by composite or shape-stabilized systems (n = 10; 11.1%). Eight studies (8.9%) did not specify the PCM category and another eight (8.9%) were coded as other or unclear. Inorganic PCMs accounted for four studies (4.4%), and eutectic materials for two (2.2%). This concentration reflects the maturity and building-compatible transition ranges of organic systems, but the 17.8% of records without a clearly assignable conventional category limits reproducibility and comparative conclusions concerning safety, conductivity, cost, environmental impact, and durability.

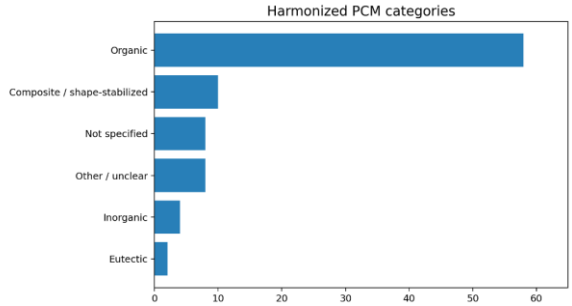


Figure 4. Harmonized categories of phase change materials.

7.5 Envelope components

Walls or façades were investigated in 66 studies (73.3%), making them by far the dominant application. This concentration was consistent across studies of PCM plaster and masonry, hollow-brick cavities, multilayer wall assemblies, macroencapsulated panels, and bio-based wall systems (Mechouet et al., 2020; Hamidi et al., 2021; Babaharra et al., 2022; Dardouri et al., 2023; Gonçalves et al., 2024; Lahoud et al., 2024; Hadded et al., 2025). The prominence of walls is technically plausible because their large exposed area and orientation-dependent solar gains provide substantial opportunity for transient heat storage and heat-flux attenuation. The wider wall evidence also included PCM–insulation combinations, internal mortar linings, concrete–PCM assemblies, dynamic and bio-based walls, pumice blocks, façade coatings, radiative-cooling coupling, and climate-specific optimization (Sarcinella et al., 2020; Abden et al., 2022; Brozzesi et al., 2023; Saylam Canım & Maçka Kalfa, 2023; Li et al., 2024; Zhang et al., 2024; Zhou et al., 2024; Azadani & Ardekani, 2025; Dewi et al., 2025; Goudjil et al., 2025; Itani & Ramadan, 2025; Jellaj et al., 2025; Kharbouch, 2022; Li et al., 2025).

Roofs or ceilings appeared in 24 studies (26.7%). The roof-focused evidence covered PCM-enhanced masonry roofs, combined wall–roof optimization, PCM roof tiles, active slabs, and water-assisted ceiling panels, demonstrating that both passive and active configurations have been examined (Hamidi et al., 2021; Al-Yasiri & Szabó, 2023a, 2023b; Dardouri et al., 2023; Lahoud et al., 2024; Prakash et al., 2024; Hadded et al., 2025; Ali et al., 2025; Almtuly et al., 2025). Nevertheless, roof applications remained substantially less common than wall applications despite the direct exposure of roofs to intense solar radiation in hot climates. Corrugated-sheet roofs, naturally ventilated PCM roofs, and PCM-core ceiling systems further broadened the experimental and hybrid roof evidence (Heniegal et al., 2021; Godoy-Rangel et al., 2024; Kumaraswamy et al., 2024).

Other or whole-envelope configurations were identified in 11 studies (12.2%). These studies generally extended PCM integration across several opaque or transparent envelope elements and evaluated their combined influence at building scale (Al-Yasiri & Szabó, 2023a; Aghoei et al., 2024; Jahangir & Alimohamadi, 2024; Indrani et al., 2025; Zhao et al., 2025). Windows or glazing appeared in nine studies (10.0%), including investigations of PCM-filled double glazing, sunspace glazing, glass curtain walls, and PCM-assisted photovoltaic windows (Jalil & Salih, 2020; Jalil & Salih, 2021; Uludaş et al., 2022; Arasteh et al., 2024; Mangherini et al., 2024; Nsaif et al., 2024; Zheng et al., 2024). This smaller evidence base limits robust comparison of optical–thermal trade-offs, solar transmittance, daylight availability, and long-term sealing performance. Façade-adjacent applications also included PCM-enhanced service-area finishes, solar chimneys, and

PCM-integrated interior shading devices (Nateghi & Jahangir, 2022; Alrashdan et al., 2024; Çelik et al., 2025). Floors appeared in six studies (6.7%). Floor applications ranged from passive PCM layers and interior cladding to hydronic radiant-floor systems and whole-building economic optimization (Faraj et al., 2021; Frahat et al., 2023; Grzybek et al., 2024; T. T. T. T. Lee et al., 2024; Azimi et al., 2025). Since individual studies could examine more than one component, 116 coded occurrences were recorded. The strong imbalance toward walls indicates that glazing, floors, roof–wall interactions, and coordinated envelope-control strategies remain comparatively immature. Future research should therefore prioritize multi-component field validation under representative hot-arid and Mediterranean operating conditions rather than continuing to assess isolated wall configurations alone.

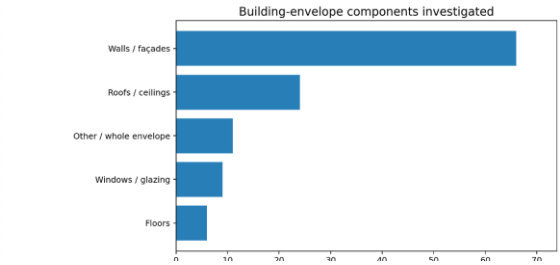


Figure 5. Building-envelope components investigated in the included studies.

7.6 Research methods and validation

Numerical or simulation-based research was the principal methodological category, comprising 53 of the 90 studies (58.9%). These investigations used whole-building energy models, transient heat-transfer formulations, CFD, and parametric or optimization frameworks to explore PCM properties, placement, thickness, climate sensitivity, and envelope configuration (Dardouri et al., 2023; Lahoud et al., 2024; Jaradat et al., 2024; Hadded et al., 2025; Nath et al., 2025). This dominance enables broad scenario testing at comparatively low cost, but the credibility of the resulting energy and comfort estimates remains dependent on the quality of material inputs, boundary conditions, and model validation.

Exclusively experimental studies accounted for 17 records (18.9%), including controlled material or component tests, comparative test-room experiments, and real-environment field investigations (Gholamibozanjani & Farid, 2020; Faraj et al., 2021; Chen et al., 2022; Al-Yasiri & Szabó, 2023b; Gonçalves et al., 2024). A further 20 studies (22.2%) combined experimental and numerical methods, using measured thermal behavior to calibrate, validate, or extend numerical analysis (Mechouet et al., 2020; Jalil & Salih, 2021; Shi et al., 2023; Nsaif et al., 2024; Benzaama et al., 2025; Zhao et al., 2025). These hybrid designs provide a stronger evidential pathway because they combine controlled observation with the ability to assess annual operation, alternative climates, and design conditions beyond the experimental setup.

Validation practice varied substantially. Experimental or measured-data validation was explicitly identified in 27 studies (30.0%), including calibration against facility energy use, direct comparison with monitored temperatures, and validation against full-scale or component experiments (Bolteya et al., 2022; Shi et al., 2023; Gonçalves et al., 2024; Nsaif et al., 2024; Ali et al., 2025; Benzaama et al., 2025). Literature or benchmark validation was used in 17 studies (18.9%), often through comparison with previously published experiments or established PCM formulations (Dardouri et al., 2023; Lahoud et al., 2024; Arasteh et al., 2024; Elmarghany et al., 2022). Numerical verification or sensitivity analysis formed the principal validation approach in five studies (5.6%), whereas six studies (6.7%) did not report an explicit validation procedure; the remaining 35 studies (38.9%) used other approaches, including matched reference cases, material characterization, uncertainty analysis, or internal consistency checks. The persistence of unvalidated and indirectly validated models remains a limitation when transferring reported performance to Libyan buildings.

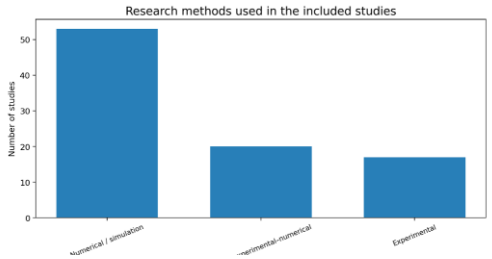


Figure 6. Research methodologies used across the evidence base.

7.7 Software and analytical platforms

Software-family coding was multi-label because several studies combined building-energy engines, graphical interfaces, CFD solvers, material characterization tools, and optimization environments. Other software or experimental equipment formed the largest category, appearing in 33 studies (36.7%); this reflects the substantial use of laboratory instrumentation, data-acquisition systems, and study-specific analytical workflows in experimental research (Gholamibozanjani & Farid, 2020; Faraj et al., 2021; Gonçalves et al., 2024; Almtuly et al., 2025). The EnergyPlus family—including DesignBuilder and OpenStudio interfaces—was identified in 28 studies (31.1%), making it the dominant standardized building-energy platform (Bolteya et al., 2022; Dardouri et

al., 2023; Stasi et al., 2024; Jaradat et al., 2024; Lahoud et al., 2024; Hadded et al., 2025; Nath et al., 2025). Its prominence is consistent with the need for annual, climate-responsive simulation of PCM hysteresis, finite-difference heat conduction, HVAC operation, and whole-building energy demand.

Custom code or mathematical models were used in 13 studies (14.4%), particularly for finite-volume, finite-difference, enthalpy-based, or problem-specific formulations (Lakhdari et al., 2020; Jalil & Salih, 2021; Elmarghany et al., 2022; Tunçbilek et al., 2023; Ahmed et al., 2025). ANSYS Fluent appeared in nine studies (10.0%), principally for CFD and enthalpy–porosity modelling (Ručevskis et al., 2020; Vanaga et al., 2023; Arasteh et al., 2024; Aidi et al., 2025; Yehya et al., 2025). COMSOL Multiphysics was used in four studies (4.4%) (Hamidi et al., 2021; Shi et al., 2023; Mangherini et al., 2024; Abdelkader Laafer, 2025), MATLAB in three (3.3%) (Terrile et al., 2023; Lahoud et al., 2024; Jalghaf & Kovács, 2025), and TRNSYS in one (1.1%) (Di Bari et al., 2020). Five studies (5.6%) did not use or clearly report a simulation platform. This fragmented software landscape broadens methodological capability, but it also complicates direct comparison because PCM formulations, numerical assumptions, time steps, and validation practices differ between platforms.

Table 3. Simulation software and experimental platforms

Platform family	Studies (n)	Percentage of 90 (%)
Other software / experimental equipment	33	36.7
EnergyPlus / DesignBuilder / OpenStudio	28	31.1
Custom code / mathematical model	13	14.4
ANSYS Fluent	9	10.0
Not applicable / not reported	5	5.6
COMSOL Multiphysics	4	4.4
MATLAB	3	3.3
TRNSYS	1	1.1

Note: Software/platform is a multiple-response variable.

7.8 Reported performance outcomes

Quantitative performance reporting was uneven across the 90-study evidence base. Energy savings were reported most often (n = 34; 37.8%), followed by indoor-temperature reduction (n = 30; 33.3%), cooling-load reduction (n = 25; 27.8%), heating-load reduction (n = 15; 16.7%), and peak-load reduction (n = 13; 14.4%). These outcomes were verified against the corresponding quantitative fields in the certified database rather than inferred from general PCM aims (Hamidi et al., 2021; Mechouet et al., 2020; Stasi et al., 2024; Lahoud et al., 2024; Jaradat et al., 2024; Hadded et al., 2025).

Among reporting studies, the median energy saving was 23.0% (range: 6.0–98.63%), while the median cooling- and heating-load reductions were 31.0% (9.0–100.0%) and 33.0% (12.3–96.94%), respectively. The median indoor-temperature reduction was 5.0 °C (0.5–17.5 °C), and the median peak-load reduction was 36.49% (1.14–116.0%). The breadth of these ranges reflects substantial variation in climate, building type, PCM placement, reference cases, and calculation conventions (Al-Yasiri & Szabó, 2023b; Babaharra et al., 2022; Gonçalves et al., 2024; Shi et al., 2023; Liu et al., 2024; Iachachene et al., 2025).

Accordingly, these values should be interpreted as descriptive summaries of the reported results, not as pooled effect estimates. For application in Libya, the database supports the potential for PCM systems to reduce cooling demand and moderate indoor temperatures, but it does not justify transferring the upper-end results directly to Libyan buildings without climate-specific simulation, experimental validation, and harmonized baselines (Bolteya et al., 2022; Mechouet et al., 2020; Laasri et al., 2024; Salihi et al., 2024).

Table 4. Availability and descriptive range of reported performance outcomes

Outcome	Reporting studies (n)	Reporting rate (%)	Minimum	Median	Maximum
Energy saving (%)	34	37.8	6.00	23.00	98.63
Cooling-load reduction (%)	25	27.8	9.00	31.00	100.00
Heating-load reduction (%)	15	16.7	12.30	33.00	96.94

Outcome	Reporting studies (n)	Reporting rate (%)	Minimum	Median	Maximum
Indoor-temperature reduction (°C)	30	33.3	0.50	5.00	17.50
Peak-load reduction (%)	13	14.4	1.14	36.49	116.00

Note: Reporting rates use N = 90 unique studies as the denominator. Values summarize only studies reporting the corresponding outcome. Ranges reflect heterogeneous definitions and test conditions; they are descriptive and should not be interpreted as pooled effect estimates.

7.9 Consolidated quantitative evidence profile

The consolidated profile indicates a recent and rapidly expanding evidence base: 27 of the 90 studies (30.0%) were published in 2025. Organic PCMs dominated material selection (n = 58; 64.4%), walls or façades were the principal envelope application (n = 66; 73.3%), and numerical or simulation-based research remained the prevailing method (n = 53; 58.9%). Among clearly identified building types, residential applications were the largest group (n = 30; 33.3%), while EnergyPlus-related platforms formed the most frequently used defined software family (n = 28; 31.1%) (Mechouet et al., 2020; Hamidi et al., 2021; Lahoud et al., 2024; Stasi et al., 2024; Hadded et al., 2025).

The database is particularly relevant to the Libyan research agenda: 71 studies (78.9%) were classified as having high or very high transferability, and 88 records (97.8%) were verified from full texts. Nevertheless, only 34 studies (37.8%) reported a numerical energy-saving value, and explicit experimental or measured-data validation was identified in 27 studies (30.0%). Thus, the evidence is broad and regionally informative but remains methodologically heterogeneous and only partially comparable; climate similarity cannot replace direct validation using Libyan weather, construction, occupancy, and operational data (Bolteya et al., 2022; Al-Yasiri & Szabó, 2023b; Dardouri et al., 2023; Jaradat et al., 2024).

Table 5. Consolidated evidence profile of the 90-study review

Dimension	Leading category or evidence attribute	n	%
Publication year	2025	27	30.0
Climate zone	Hot-arid / desert	21	23.3
Building type	Residential (largest specified type)	30	33.3
PCM category	Organic	58	64.4
Envelope component	Walls / façades	66	73.3
Research method	Numerical / simulation	53	58.9
Defined software family	EnergyPlus / DesignBuilder / OpenStudio	28	31.1
Measured validation	Experimental / measured-data validation	27	30.0
Relevance to Libya	High + very high	71	78.9
Evidence status	Full text verified	88	97.8
Quantitative outcome	Energy-saving value reported	34	37.8

Note: Percentages use N = 90 unique studies. Envelope components are multi-label. The software row reports the largest clearly defined platform family; heterogeneous 'other software/experimental equipment' records are not treated as one analytical platform.

7.10 Libya-focused research synthesis and future research directions

The synthesis of the 90 retained studies confirms that PCMs have become a prominent passive thermal-energy-storage strategy for improving envelope performance and moderating indoor temperatures. However, the geographical evidence remains uneven. The database is concentrated in Mediterranean, Middle Eastern, North African, Chinese, and Southern European settings, whereas no full-scale experimental study was identified in an occupied or representative building located in Libya. Direct Libyan climatic evidence is largely limited to a regional simulation that included Tripoli among eight cities. Consequently, most Libya-oriented recommendations must presently be inferred from climatic analogues in Morocco, Algeria, Egypt, Tunisia, Lebanon, Türkiye, and Iraq rather than from locally generated field evidence (Hamidi et al., 2021; Mechouet et al., 2020; Bolteya et al., 2022; Dardouri et al., 2023; Al-Yasiri &

Szabó, 2023a, 2023b; Lahoud et al., 2024). Figure 7 maps the named primary-country evidence and distinguishes the Tripoli-inclusive regional simulation from dedicated Libyan field evidence.

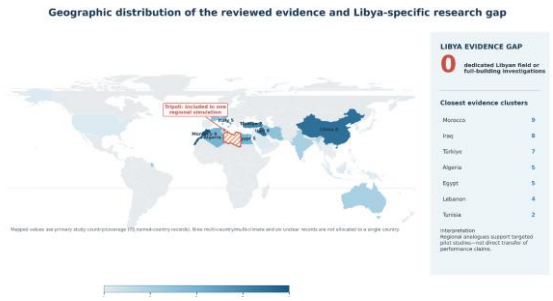


Figure 7. Geographic distribution of the reviewed evidence and the Libya-specific research gap.

The climatic synthesis nevertheless provides a credible basis for targeted Libyan investigation. Hot-arid/desert studies accounted for 21 records (23.3%) and Mediterranean studies for 19 (21.1%), thereby covering the two broad climatic families most relevant to Libya. Across comparable settings, PCM integration frequently reduced cooling demand, attenuated indoor-temperature fluctuations, and delayed heat transfer; however, effectiveness depended on complete night-time regeneration and on matching the phase-transition interval to local operating temperatures. These findings suggest strong potential for both the Mediterranean coastal belt and inland desert regions, but they also rule out a single national PCM specification (Hamidi et al., 2021; Salihi et al., 2022; Jaradat et al., 2024; Hadded et al., 2025).

Initial applications in Libya should prioritize masonry walls and roof assemblies. These components are compatible with common low-rise construction and are supported by the largest bodies of evidence: walls or façades appeared in 66 studies (73.3%) and roofs or ceilings in 24 (26.7%). Organic PCMs were the dominant material class (n = 58; 64.4%), while composite or shape-stabilized materials appeared in 10 studies (11.1%). Organic paraffins therefore offer the most mature starting point, but composites may address leakage, integration, and conductivity limitations. Neither category should be adopted through direct transfer: transition temperature, encapsulation, thickness, and layer position must be optimized separately for coastal, semi-arid, and desert zones using Libyan weather files and locally representative wall and roof assemblies (Mechouet et al., 2020; Babaharra et al., 2022; Al-Yasiri & Szabó, 2023a, 2023b; Dardouri et al., 2023; Hadded et al., 2025).

Methodologically, a Libyan research programme should move beyond uncalibrated numerical studies. Although simulation was the dominant method (n = 53; 58.9%) and EnergyPlus-related platforms were the most common defined software family (n = 28; 31.1%), only 27 studies (30.0%) explicitly used experimental or measured-data validation. The strongest pathway is therefore a hybrid framework in which laboratory or full-scale test-cell measurements calibrate dynamic building models, which are then extended across Libyan cities, orientations, envelope configurations, and future climate scenarios. Models should report material characterization, numerical assumptions, uncertainty, and validation error rather than relying solely on prior software benchmarks (Bolteya et al., 2022; Mechouet et al., 2020; Al-Yasiri & Szabó, 2023b; Laasri et al., 2024).

Future evaluation should also be multidimensional. The certified database shows that numerical energy savings were reported in only 34 studies (37.8%), indoor-temperature reductions in 30 (33.3%), and peak-load reductions in 13 (14.4%). Technical assessment should therefore be expanded to include thermal comfort, peak electrical demand, operational and embodied carbon, life-cycle cost, durability, fire safety, and end-of-life recovery. For Libya, economic analysis must use local electricity tariffs, product availability, installation costs, cooling schedules, and maintenance conditions rather than importing payback estimates from other countries (Stasi et al., 2024; Hadded et al., 2025; Gonçalves et al., 2024; Iachachene et al., 2025).

On this basis, eight priority research gaps should guide a coordinated Libyan PCM research agenda:

Full-scale field evidence: construct and monitor PCM-integrated test cells or occupied buildings under actual Libyan coastal, semi-arid, and desert conditions.

Climate-specific transition temperatures: determine effective melting and solidification ranges for each Libyan climatic zone, including sensitivity to hot night-time conditions.

Local material compatibility: evaluate PCM integration with Libyan hollow brick, concrete block, stone, plaster, insulation, and locally available composite or encapsulation materials.

Long-term durability and safety: quantify thermal-cycling stability, leakage, subcooling, phase segregation, corrosion, fire behaviour, and performance degradation under severe desert exposure.

Libya-specific techno-economics: assess capital cost, installation, maintenance, electricity tariffs, cooling schedules, payback, and affordability for residential and public buildings.

Life-cycle environmental performance: include embodied carbon, manufacturing and transport burdens, service life, replacement, recyclability, and circular-economy pathways.

Codes and design guidance: translate validated evidence into climatic-zone specifications, testing protocols, construction details, and requirements for Libyan building regulations.

Hybrid passive and active systems: investigate PCMs combined with controlled night ventilation, shading, cool or reflective roofs, advanced insulation, photovoltaics, and demand-responsive HVAC control.

Addressing these gaps would establish the evidence needed to move PCM integration in Libya from climatic analogy to validated design practice. A staged programme should begin with material and assembly characterization, proceed to instrumented test cells in representative climatic zones, and culminate in calibrated whole-building demonstrations and national design guidance. This sequence would also generate the consistent datasets required for comparing energy, comfort, environmental, and economic performance.

Overall, PCM performance should be treated as the outcome of a climate-responsive building system rather than as an intrinsic material property. Successful deployment depends on the interaction among climate, thermophysical properties, envelope configuration, building operation, and validation quality. Although direct Libyan evidence remains insufficient, the consistency of results from carefully selected regional analogues indicates substantial potential to reduce cooling demand and improve indoor thermal stability. The immediate research priority is therefore locally calibrated experimental validation coupled with integrated optimization capable of translating international evidence into robust solutions for the Libyan built environment (Hamidi et al., 2021; Dardouri et al., 2023; Al-Yasiri & Szabó, 2023a, 2023b; Hadded et al., 2025).

8. Discussion

The quantitative findings provide the basis for interpreting research maturity, methodological constraints, and practical transferability. The evidence demonstrates strong and growing interest in PCM-enhanced building envelopes, particularly for cooling-dominated climates; however, it remains fragmented, configuration-specific, and dominated by numerical studies (n = 53; 58.9%). Consequently, the discussion emphasizes the boundary conditions that control PCM activation and the extent to which results from climatic analogues can inform—without being assumed to represent—Libyan buildings (Hamidi et al., 2021; Bolteya et al., 2022; Dardouri et al., 2023; Hadded et al., 2025).

8.1 Climate responsiveness as the central design principle

Hot-arid/desert climates (n = 21; 23.3%) and Mediterranean climates (n = 19; 21.1%) were almost equally represented, but these categories are not thermally equivalent. Coastal Mediterranean conditions can provide milder night-time temperatures that facilitate PCM solidification, whereas severe hot-arid conditions may restrict nocturnal regeneration and leave a low-transition-temperature PCM partly or fully melted. This distinction is directly relevant to Libya: simulations including Tripoli showed that low-transition PCMs could remain liquid and even increase heat transfer, while studies in other hot-dry settings also reported weaker savings when the selected transition range was poorly matched to the climate (Hamidi et al., 2021; Mechouet et al., 2021; Jaradat et al., 2024; Salihi et al., 2024).

Climate-responsive design therefore requires matching the effective phase-transition interval to the temperature history at the PCM layer rather than to outdoor air temperature alone. The operative temperature within a wall or roof is modified by orientation, solar absorptance, insulation sequence, thermal mass, PCM position and thickness, indoor set points, and ventilation. Evidence from North African and Middle Eastern climates confirms that changing these parameters alters the preferred PCM and the magnitude of the resulting benefit; increasing thickness, for example, can reach diminishing returns, while the optimal wall or roof position can change between seasons (Mechouet et al., 2020; Bolteya et al., 2022; Al-Yasiri & Szabó, 2023a, 2023b; Dardouri et al., 2023; Salihi et al., 2022).

Multi-season and multi-zone analysis is therefore essential. Lower transition temperatures may support heating-demand reduction in mild winters, whereas higher ranges may be required for summer cooling and reliable cycling in semi-arid or desert locations. Annual energy savings should be interpreted jointly with indoor-temperature moderation, peak-load shifting, and the frequency of complete melting and solidification. For Libya, coastal cities such as Tripoli and Misrata should not share an uncalibrated design specification with inland and southern locations; each climatic zone requires local weather files, representative construction assemblies, and sensitivity testing of transition temperature and night-time regeneration (Lahoud et al., 2024; Stasi et al., 2024; Dardouri et al., 2023; Hamidi et al., 2021).

8.2 Material selection and the dominance of organic PCMs

Organic PCMs dominated the evidence base (n = 58; 64.4%), reflecting the availability of commercial paraffins, their relatively broad transition-temperature range, low corrosiveness, and compatibility with boards, plasters, panels, and masonry cavities. By comparison, composite or shape-stabilized PCMs appeared in 10 studies (11.1%), inorganic PCMs in four (4.4%), and eutectic PCMs in only two (2.2%). This distribution indicates technological

maturity, but it also creates path dependence: familiar paraffin products receive repeated evaluation while potentially advantageous salt hydrates, eutectics, and engineered composites remain weakly represented. Moreover, nine records did not specify the PCM category and eight were classified as other or unclear, demonstrating that incomplete material reporting remains a non-trivial limitation (Mechouet et al., 2020; Al-Yasiri & Szabó, 2023b; Bolteya et al., 2022; Shi et al., 2023; Jaradat et al., 2024). Figure 8 integrates the harmonized PCM taxonomy with the principal encapsulation routes and envelope applications observed in the review.

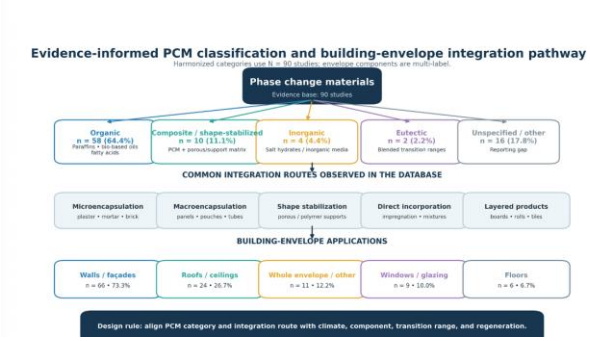


Figure 8. Evidence-informed classification of PCMs and their building-envelope integration pathways.

Bio-based organic PCMs form a promising but still developing subset of the organic category. Plant-derived commercial products, coconut oil, fatty-acid eutectics, beeswax, and wood-supported systems have demonstrated thermal regulation and, in some cases, competitive building-energy performance. Their renewable origin, however, should not be treated as proof of superior environmental performance. Robust comparison with petroleum-derived paraffins requires equivalent functional units and assessment of feedstock sourcing, encapsulation burden, service life, thermal aging, leakage, fire performance, replacement, and end-of-life treatment. The current evidence therefore supports continued investigation rather than a general claim of environmental superiority (Faraj et al., 2021; Frahat et al., 2023; Lahoud et al., 2024; Stasi et al., 2024; Idouanaou et al., 2025).

Material properties must ultimately be evaluated at assembly and building-system scales. Low thermal conductivity can restrict charging and discharging, whereas conductive supports such as expanded graphite can accelerate heat transfer but alter the PCM mass fraction and effective latent capacity. Microencapsulation and form-stabilizing matrices can limit leakage and improve constructability, yet their shells or supports reduce the quantity of active PCM per unit mass or volume. Likewise, nominal latent heat does not ensure useful storage when subcooling, an unsuitable transition range, incomplete cycling, or poor layer placement prevents activation. For Libya, material selection should therefore be based on retained performance after repeated cycles, fire and leakage safety, compatibility with local masonry, and useful latent-heat utilization under representative day–night profiles—not on DSC values alone (Meng et al., 2020; Shi et al., 2023; Medjahed et al., 2024; Laasri et al., 2024; Elghomari & Tilioua, 2025).

8.3 Envelope-component imbalance and integration priorities

The concentration of research on walls or façades (n = 66; 73.3%) reveals a substantial component-level imbalance. Walls are attractive because PCM boards, plasters, bricks, cavity inserts, and encapsulated panels can be integrated with limited alteration to conventional construction and can exploit orientation-dependent solar exposure. Nevertheless, roofs or ceilings appeared in only 24 studies (26.7%), despite their high solar loading and direct importance in low-rise buildings in hot climates. Experimental and simulation evidence indicates that roof integration can equal or exceed wall performance under severe summer conditions, while combined wall–roof configurations can provide a more balanced annual response (Mechouet et al., 2020; Hamidi et al., 2021; Bolteya et al., 2022; Al-Yasiri & Szabó, 2023a, 2023b; Dardouri et al., 2023; Hadded et al., 2025).

Only 11 studies (12.2%) investigated other or whole-envelope configurations. This scarcity is methodologically important because PCM performance interacts with insulation, glazing ratio, shading, infiltration, ventilation, thermal mass, and HVAC control. Optimizing an isolated layer may reduce heat flux through one component without minimizing whole-building energy use or comfort hours; it may also shift loads between heating and cooling seasons. Multi-component studies show that the preferred configuration changes with climate and operating strategy, supporting coupled optimization of the PCM with the remaining envelope and controls rather than component-by-component selection (Al-Yasiri & Szabó, 2023a; Aghoei et al., 2024; Jahangir & Alimohamadi, 2024; Indrani et al., 2025; Zhao et al., 2025).

For Libya, roof–wall combinations should be the first priority because low-rise residential and public buildings can have large exposed roof areas alongside solar-loaded masonry façades. However, the smaller evidence bases for windows or glazing (n = 9; 10.0%) and floors (n = 6; 6.7%) should not be interpreted as evidence of limited potential. PCM glazing and shading may reduce solar gains or delay peak temperatures in offices and public buildings, but optical transmittance, daylight, sealing, overheating after complete melting, and maintenance require explicit evaluation. Floor systems may offer load shifting when coupled with radiant heating or cooling, yet their value

depends strongly on tariffs and control. Libya-specific experiments should therefore compare wall-only and roof-only solutions with coordinated wall–roof–window strategies under realistic occupancy and ventilation conditions (Jalil & Salih, 2021; Faraj et al., 2021; Mangherini et al., 2024; Nsaif et al., 2024; T. T. T. T. Lee et al., 2024).

8.4 Simulation dominance and evidence transferability

Numerical or simulation-based studies formed the largest methodological category (n = 53; 58.9%). Simulation is indispensable for screening transition temperature, thickness, position, orientation, climate, controls, and building archetypes over annual or future-weather periods. However, reported savings remain conditional on the model structure and inputs: idealized thermophysical properties, simplified or omitted hysteresis, perfect layer contact, one-dimensional heat transfer, fixed occupancy and thermostat schedules, standard weather files, and assumed material stability can all produce optimistic estimates. Cross-climate parametric breadth should therefore not be confused with empirical depth (Dardouri et al., 2023; Lahoud et al., 2024; Jaradat et al., 2024; Chan et al., 2025; Nath et al., 2025).

Validation quality must be judged by relevance as well as numerical agreement. Experimental or measured-data validation was explicitly identified in 27 studies (30.0%), literature or benchmark validation in 17 (18.9%), and numerical verification or sensitivity analysis in five (5.6%); six studies (6.7%) reported no explicit validation, while 35 (38.9%) used other approaches. Agreement with a published material curve or laboratory benchmark can verify an algorithm, but it does not establish predictive accuracy for a full-scale building under hot-arid field conditions. Stronger transferability requires study-specific comparison with measured surface and layer temperatures, heat flux, phase-state behaviour, indoor conditions, and energy demand, accompanied by error metrics and uncertainty bounds (Bolteya et al., 2022; Shi et al., 2023; Gonçalves et al., 2024; Nsaif et al., 2024; Ali et al., 2025).

Hybrid experimental–numerical studies (n = 20; 22.2%) offer the most productive pathway for Libya, with exclusively experimental studies (n = 17; 18.9%) providing an essential empirical foundation. A staged validation hierarchy is recommended: first characterize the PCM and composite after repeated cycles; then validate heat transfer in representative Libyan wall and roof assemblies; next calibrate test-cell or occupied-building models across summer and shoulder seasons; and finally extend the validated models across Libyan cities, orientations, archetypes, operating schedules, and future climates. This approach preserves the exploratory power of simulation while preventing conclusions from being transferred beyond the conditions actually supported by measurement (Mechouet et al., 2020; Jalil & Salih, 2021; Al-Yasiri & Szabó, 2023b; Ali et al., 2025; Benzaama et al., 2025; Zhao et al., 2025).

8.5 Performance reporting and comparability

Quantitative reporting was incomplete and heterogeneous. Energy-saving values were available in 34 studies (37.8%), indoor-temperature reductions in 30 (33.3%), cooling-load reductions in 25 (27.8%), heating-load reductions in 15 (16.7%), and peak-load reductions in 13 (14.4%). Even within these fields, studies differed in baseline construction, climate period, thermostat settings, occupancy, system boundary, and whether a percentage referred to component heat flux, cooling demand, total HVAC energy, or whole-building consumption. The resulting ranges—including extreme values and a reported peak-load reduction above 100%—must therefore be treated as descriptive extracted values rather than pooled effects (Hamidi et al., 2021; Mechouet et al., 2020; Al-Yasiri & Szabó, 2023b; Jaradat et al., 2024; Liu et al., 2024).

Temperature attenuation alone is not equivalent to improved thermal comfort. A lower peak air or surface temperature may coexist with uncomfortable humidity, radiant asymmetry, insufficient air movement, or unsuitable night-time conditions; conversely, load shifting may be valuable even when the daily mean temperature changes little. Future studies should report operative temperature, humidity, PMV/PPD or an appropriate adaptive-comfort metric, discomfort hours, and occupied-period conditions alongside energy and heat-flux outcomes. They should also distinguish peak reduction from peak delay and disclose whether the PCM completed its melting–solidification cycle (Faraj et al., 2021; Stasi et al., 2024; Gonçalves et al., 2024; Hadded et al., 2025).

Economic and environmental conclusions are equally context-sensitive. Payback depends on product and encapsulation cost, installation, maintenance, degradation, service life, discount rate, tariffs, and the monetary value assigned to peak-load reduction; life-cycle carbon results additionally depend on manufacturing, transport, replacement, and the electricity mix. For Libya, every performance claim should therefore be accompanied by a minimum reporting set: location and weather file; building and reference-envelope definition; PCM identity, measured properties, thickness and position; schedules and controls; simulation timestep and validation error; absolute and percentage outcomes with a clear denominator; and locally sourced cost and carbon assumptions. Scenario and sensitivity analysis should be mandatory where local prices or supply chains are uncertain (Di Bari et al., 2020; Frahat et al., 2023; Jaradat et al., 2024; Hadded et al., 2025;

Acuña-Díaz et al., 2022). Validated coating-retrofit and life-cycle investigations likewise demonstrate that environmental benefit varies with climate, structural element, and system boundary (Georgiou et al., 2023).

8.6 Climate-responsive PCM integration framework

Building on the quantitative synthesis and critical discussion, this study proposes a climate-responsive framework for selecting, designing, validating, and implementing PCM systems. The framework treats PCM integration as an evidence-gated decision process rather than a material-selection exercise: progression to the next stage depends on demonstrating that the PCM can cycle under the target climate, that the proposed assembly addresses a measured building need, and that predicted benefits are supported at an appropriate validation scale.

The first three stages diagnose climate, building, and PCM compatibility. This order is essential because transition temperature and latent capacity have little practical value if the PCM does not reach its operating interval or cannot solidify at night. The diagnosis should therefore combine local weather and future climate files with monitored or simulated temperatures at the intended wall, roof, floor, or glazing location, followed by a calibrated no-PCM baseline and material data measured after representative cycling (Hamidi et al., 2021; Salihi et al., 2022; Dardouri et al., 2023; Jaradat et al., 2024).

The remaining stages convert material compatibility into a buildable and verifiable system. Integration design must be coordinated with insulation, moisture behaviour, fire safety, constructability, and control; validation must proceed from material and component tests to whole-building measurements; and implementation decisions must jointly consider energy, comfort, peak demand, cost, carbon, durability, and maintenance. Post-occupancy monitoring closes the loop by updating models and design rules when degradation or occupant operation differs from assumptions (Mechouet et al., 2020; Bolteya et al., 2022; Gonçalves et al., 2024; Hadded et al., 2025; Di Bari et al., 2020).

Table 6. Climate-responsive PCM integration framework

Stage	Core decision	Required evidence	Recommended output
1. Climate diagnosis	Cooling/heating dominance, diurnal range, night regeneration, humidity, heat waves, future warming	Observed local weather; representative and future climate files; layer-temperature profiles	Climate stress and regeneration map
2. Building diagnosis	Archetype, occupancy, envelope weaknesses, orientation, HVAC and ventilation operation	Energy audit; monitored loads; calibrated no-PCM baseline model	Target load and priority envelope component
3. PCM matching	Transition interval, usable latent capacity, conductivity, cycling, safety, environmental profile	DSC/T-history and property data after representative cycling	Climate-matched PCM shortlist
4. Integration design	Layer position, thickness, encapsulation, contact, moisture, fire, and constructability	Component simulation; hygrothermal and safety review; assembly testing	Buildable assembly variants
5. Control and regeneration	Night ventilation, thermostat control, active discharge, seasonal and heat-wave operation	Operational simulation; phase-state measurement; pilot monitoring	Charging, discharging, and fallback strategy
6. Validation	Material, component, test-cell, and whole-building predictive performance	Direct measured validation; error metrics; uncertainty and sensitivity analysis	Evidence-confidence and applicability rating

Stage	Core decision	Required evidence	Recommended output
7. Decision assessment	Energy, comfort, peak load, cost, carbon, durability, safety, and maintainability	Multi-criteria analysis using local costs, tariffs, and carbon factors	Transparent implementation decision
8. Post-occupancy verification	Seasonal performance, degradation, occupant response, maintenance, and failure modes	Long-term monitoring, inspection, maintenance, and user feedback	Model update and verified design guidance

Note: The framework is a review-derived decision structure, not a validated Libyan design code. Its thresholds and acceptance criteria require calibration through local experiments, pilot buildings, and stakeholder review before regulatory use.

8.6.1 application to libyan climate and building contexts

The framework should not be applied uniformly across Libya. In northern coastal cities, summer cooling is combined with seasonal variability, marine exposure, and a greater prospect of night-time solidification than in the southern desert. Evidence from Tripoli and Mediterranean analogues suggests that moderate transition ranges can be effective, but low-temperature PCMs may remain liquid during prolonged hot periods. Coastal design should therefore be based on measured layer temperatures, moisture and corrosion compatibility, and annual—not summer-only—performance (Hamidi et al., 2021; Mechouet et al., 2020; Lahoud et al., 2024; Stasi et al., 2024).

Semi-arid inland locations may offer larger day–night temperature swings that can support passive regeneration, but transition temperature, wall or roof position, and ventilation must be optimized together. In severe southern desert conditions, high night-time temperatures create a greater risk of incomplete solidification; higher transition intervals, enhanced heat transfer, controlled night ventilation, or active regeneration may therefore be required. These priorities are supported by evidence from Moroccan, Tunisian, Egyptian, Iraqi, and Jordanian analogues, but their numerical values must be recalibrated for Libyan weather and construction (Bolteya et al., 2022; Salihi et al., 2022; Al-Yasiri & Szabó, 2023a, 2023b; Dardouri et al., 2023; Jaradat et al., 2024).

Building context adds a second decision layer. Existing housing requires thin, safe, modular retrofit solutions that tolerate uncertain workmanship and limited maintenance, whereas schools, offices, and other public buildings may justify more actively controlled systems because daytime occupancy and peak cooling demand are concentrated. In both cases, the reference building must be monitored before PCM selection so that the intervention targets a demonstrated load rather than an assumed envelope weakness (Mechouet et al., 2020; Bolteya et al., 2022; Stasi et al., 2024; Hadded et al., 2025).

Table 7. Indicative PCM priorities for Libya

Context	Primary concern	PCM design priority	Validation priority
Northern coastal / Mediterranean	Cooling-dominated summers, seasonal variation, humidity, marine exposure	Transition range matched to occupied conditions and reliable night-time solidification	Annual field monitoring; moisture, corrosion, and cycling assessment
Semi-arid inland and upland	High summer peaks with potentially useful diurnal temperature range	Couple night cooling with optimized wall-roof position, thickness, and insulation	Full-scale test rooms with controlled and natural-ventilation cases
Severe desert / southern	Very high day and night temperatures; multi-day regeneration failure	Higher transition interval; enhanced transfer; hybrid or active regeneration	Phase-state and heat-flux monitoring through heat waves and hot spells
Existing residential stock	Limited retrofit depth, uncertain assemblies, variable installation and maintenance	Thin, modular, fire-safe, replaceable interior or cavity systems	Installation QA; occupant comfort; durability; local-tariff economics

Context	Primary concern	PCM design priority	Validation priority
Schools, offices, and public buildings	Concentrated daytime occupancy, ventilation needs, and peak electricity demand	Peak-load shifting coordinated with HVAC, shading, and occupancy controls	Metered cooling and peak demand; comfort hours; control verification

Note: These priorities are hypotheses derived from the reviewed evidence and climatic analogues. They should guide testing and scenario design, not substitute for Libya-specific material selection or regulatory requirements.

8.7 Evidence gap matrix

The evidence gaps were derived from the certified descriptive statistics and study-level extraction rather than from the frequency of keywords. The most consequential weakness is the absence of a Libya-based full-scale field study; direct climatic evidence is limited to a regional simulation that included Tripoli. This local deficit is compounded by the dominance of numerical studies, the limited use of measured-data validation, and a strong concentration on wall applications. These gaps reduce confidence in transferring optimized configurations or reported savings directly to Libyan buildings (Hamidi et al., 2021; Mechouet et al., 2020; Bolteya et al., 2022; Al-Yasiri & Szabó, 2023b).

Reporting gaps are equally important. Sixteen studies (17.8%) did not provide a clearly assignable PCM category, while fewer than two-fifths of the evidence base reported a numerical energy-saving value. Long-term cycling, future-climate performance, economic assumptions, and life-cycle impacts were not encoded as sufficiently standardized quantitative outcomes for defensible frequency estimates. They are therefore identified as qualitative comparability gaps rather than assigned legacy percentages (Di Bari et al., 2020; Frahat et al., 2023; Stasi et al., 2024; Laasri et al., 2024).

Table 8. Evidence gaps and their consequences

Gap	Evidence signal	Consequence	Priority research response
Direct Libyan field evidence	No Libya-based full-scale field study; one regional simulation explicitly included Tripoli	Low confidence in national transferability and design thresholds	Coordinated multi-city Libyan test-cell and pilot-building programme
Simulation dominance	53 numerical studies (58.9%)	Model assumptions may overstate performance or conceal operational constraints	Calibrated hybrid studies with uncertainty and sensitivity analysis
Measured validation deficit	27 studies (30.0%) used experimental or measured-data validation	Limited confidence in whole-building predictive accuracy	Material-to-building validation hierarchy with explicit error metrics
Wall concentration	66 studies (73.3%) examined walls or façades	Roofs, glazing, floors, and coordinated envelope strategies remain less mature	Comparative component and whole-envelope field studies
Incomplete PCM identification	16 studies (17.8%) were not specified or were other/unclear	Weak reproducibility and uncertain material transferability	Minimum thermophysical, formulation, and encapsulation reporting standard
Sparse quantitative outcomes	Energy saving: 34 (37.8%); indoor temperature: 30 (33.3%); peak load: 13 (14.4%)	Selective reporting and weak cross-study comparability	Core outcome set with absolute values, denominators, comfort, and cycling status

Gap	Evidence signal	Consequence	Priority research response
Short-duration evidence	Component and test-room studies often cover limited seasons or operating periods	Unknown annual performance, degradation, and rare-event response	Multi-season monitoring, heat-wave tests, and repeated-cycle assessment
Future-climate assessment	Future weather and heat-wave scenarios were not consistently evaluated	Risk of PCM mismatch and maladaptation as temperatures rise	Weather morphing, multi-scenario testing, and transition-range robustness
Economic and life-cycle comparability	Cost, tariff, carbon, service-life, and end-of-life assumptions were heterogeneous	Payback and environmental claims cannot be transferred reliably to Libya	Local cost and carbon datasets with sensitivity and cradle-to-grave analysis

Note: Percentages use N = 90 unique studies. Qualitative gaps are intentionally reported without frequency estimates where the certified database does not contain a standardized countable field.

8.8 Study limitations

This review is limited by the quality and completeness of information reported in the primary studies. Harmonization reduces terminology inconsistency but cannot recover missing thermophysical properties, unreported operating assumptions, or absent uncertainty analysis.

The fixed recent publication window captures current research but excludes older foundational studies from the primary quantitative synthesis. Foundational evidence should be incorporated selectively during journal-specific reference polishing.

The descriptive percentages map the structure of the literature but do not measure effect size. Multiple-response variables exceed 100% by design, and no pooled energy-saving estimate was calculated because study heterogeneity would make such a value potentially misleading.

The synthesis depended on the bibliographic and methodological detail reported in the source publications; consequently, incomplete reporting in individual studies may have limited the precision of some classifications and cross-study comparisons.

9. Conclusions

This systematic review synthesized a deduplicated evidence base of 90 unique studies on PCM integration in building envelopes. The literature grew rapidly in 2024–2025 and was strongly oriented toward hot-arid/desert and Mediterranean climates. Organic PCMs, wall applications, and numerical simulation dominated the evidence base. Quantitative outcomes remained unevenly reported, and direct measured validation was available in only 30.0% of studies. The central conclusion is that PCM performance is climate- and system-dependent: a product cannot be judged independently of transition temperature, integration location, regeneration potential, building operation, and validation quality. For Libya, available evidence supports carefully designed pilot implementation but not uncritical transfer of savings reported elsewhere. A national research programme should prioritize multi-city field validation, roof–wall integration, night-time regeneration, future-climate resilience, material aging, local economics, and transparent reporting. The proposed climate-responsive framework provides a structured path from climate diagnosis to post-occupancy verification.

10. Recommendations

10.1 Research recommendations

The gap matrix is translated below into eight linked research priorities. They are intended as an implementation sequence rather than independent topics: standardized local observations create the baseline for climate matching; validated assemblies enable calibrated models; and comparable technical, economic, environmental, and occupant outcomes support eventual design guidance.

- 1: Establish a Libyan PCM benchmark programme. Construct standardized test cells and monitored pilot buildings in at least northern coastal, semi-arid inland, and southern desert locations. Use common reference assemblies, sensor accuracy, sampling intervals, control schedules, and open reporting templates. The principal output should be a shared national benchmark dataset against which future materials and models can be tested (Hamidi et al., 2021; Al-Yasiri & Szabó, 2023b; Gonçalves et al., 2024).
- 2: Develop climate- and component-specific transition maps. Relate measured wall, roof, floor, and glazing-layer temperatures—not outdoor air temperature alone—to city, orientation, insulation position, occupancy, and ventilation. The output should be probabilistic transition-temperature and regeneration maps that identify robust operating

intervals rather than a single nominal melting point (Hamidi et al., 2021; Salihi et al., 2022; Dardouri et al., 2023; Jaradat et al., 2024).

- 3: Move from nominal properties to product-level durability and safety. Measure retained latent capacity, transition range, conductivity, leakage, phase segregation, subcooling, corrosion, and fire behaviour after representative thermal aging and cycling. Testing should evaluate the complete construction product—including shell, support, binder, and interfaces—so that the output is a service-life performance specification rather than a one-time DSC result (Meng et al., 2020; Shi et al., 2023; Medjahed et al., 2024; Laasri et al., 2024).
- 4: Strengthen calibration, validation, and uncertainty analysis. Calibrate models against heat flux, layer and surface temperatures, indoor operative conditions, energy use, and phase-state indicators. Report error metrics and sensitivity to hysteresis, natural convection, contact resistance, material uncertainty, schedules, and weather. The output should be an applicability domain stating where each model is—and is not—predictive (Bolteya et al., 2022; Shi et al., 2023; Gonçalves et al., 2024; Nsaif et al., 2024).
- 5: Integrate PCM with passive and active controls. Evaluate night ventilation, shading, cool roofs, insulation, demand-response control, photovoltaics, and HVAC coordination as coupled strategies. Studies should quantify whether control improves solidification and reduces peak demand without creating humidity, comfort, or seasonal penalties. The output should be a climate-specific charging and discharging control sequence (Faraj et al., 2021; Piselli et al., 2020; Salihi et al., 2024; Hadded et al., 2025).
- 6: Adopt a standardized core outcome and reporting set. Report absolute and relative heating, cooling, peak-load, temperature, comfort, and cycling outcomes with a clearly defined denominator, baseline, analysis period, weather file, schedules, PCM quantity, position, transition interval, conductivity, timestep, validation error, and uncertainty. This should produce machine-readable datasets suitable for replication and future meta-analysis (Mechouet et al., 2020; Stasi et al., 2024; Jaradat et al., 2024; Hadded et al., 2025).
- 7: Expand Libya-specific techno-economic and life-cycle assessment. Use local product, transport, installation, maintenance, tariff, discount-rate, electricity-mix, service-life, replacement, and end-of-life assumptions. Scenario analysis should show when PCM remains beneficial under price, subsidy, degradation, and climate uncertainty. The output should be transparent cost and carbon thresholds for pilot and policy decisions (Di Bari et al., 2020; Acuña-Díaz et al., 2022; Frahat et al., 2023; Hadded et al., 2025).
- 8: Address occupants, delivery capacity, and regulatory adoption. Investigate perceived comfort, user control, installation quality, maintenance capability, fire approval, supply-chain availability, and acceptance among designers, contractors, facility managers, and owners. The output should be buildable details, inspection protocols, training needs, and evidence thresholds for future Libyan guidance—not only optimized simulation parameters (Faraj et al., 2021; Stasi et al., 2024; Hadded et al., 2025).

A staged delivery pathway is recommended. The near term should prioritize shared weather files, material characterization, reference assemblies, and test cells; the medium term should deliver multi-city pilot buildings and calibrated models; and the longer term should establish open performance databases, verified economic and environmental thresholds, certification procedures, and climate-zone design guidance. Advancement between stages should depend on predefined evidence and safety criteria rather than publication volume alone.

10.2 Practical and policy recommendations

The review supports cautious, evidence-led action rather than immediate large-scale deployment. Stakeholders can begin standardization, baseline monitoring, material disclosure, and pilot design now, but climate-specific PCM thresholds and national performance claims should await Libyan field validation.

Designers and energy consultants. Begin with a measured thermal history of the intended envelope layer and a defined objective—annual energy reduction, occupied-period comfort, peak-load shifting, or resilience. Screen transition range, position, thickness, regeneration, insulation interaction, and controls together; compare the PCM option with conventional insulation, shading, and cool-roof alternatives; and reject solutions that do not complete useful cycling under design heat waves (Hamidi et al., 2021; Dardouri et al., 2023; Jaradat et al., 2024).

Manufacturers and suppliers. Provide product-level data for melting and solidification intervals, hysteresis, usable latent heat, conductivity, density, fire behaviour, leakage, corrosion, encapsulation, thermal cycling, aging, and end-of-life handling. Values should describe the delivered construction product, not only the neat PCM, and should include test methods, uncertainty, batch traceability, and performance after cycling. Modular, replaceable, and locally compatible systems would reduce implementation

risk in Libya (Meng et al., 2020; Shi et al., 2023; Medjahed et al., 2024; Laasri et al., 2024).

Policymakers, utilities, and public clients. Fund monitored demonstrations rather than prescriptive product mandates. Procurement should require a calibrated baseline, open monitoring data, safety documentation, local cost and carbon assumptions, and post-occupancy verification. Early programmes should prioritize representative housing and public buildings in coastal, inland, and southern zones, while incentives should be conditional on verified performance and durability rather than simulated percentage savings alone (Bolteya et al., 2022; Acuña-Díaz et al., 2022; Hadded et al., 2025).

Libyan universities and research centres. Coordinate around shared weather files, reference wall and roof assemblies, sensor specifications, material protocols, data dictionaries, and repositories. A distributed benchmark programme would allow specialized laboratories to contribute material characterization, test-cell measurements, modelling, economics, and life-cycle assessment without producing incompatible isolated datasets. Partnerships with regional analogue studies can accelerate method transfer while preserving local calibration (Mechouet et al., 2020; Al-Yasiri & Szabó, 2023b; Gonçalves et al., 2024).

Researchers, journal reviewers, and standards bodies. Interpret percentage savings only when the baseline, denominator, climate, operating schedule, PCM mass and position, system boundary, validation level, and uncertainty are explicit. Require separate reporting of heating, cooling, total energy, indoor conditions, peak reduction, peak delay, and cycling status. Extreme or non-standard values should be traced to the source and definition before citation or synthesis (Mechouet et al., 2020; Stasi et al., 2024; Jaradat et al., 2024; Liu et al., 2024).

In practical terms, the immediate opportunity for Libya is not to select a universal PCM product, but to establish the measurement, disclosure, validation, and procurement infrastructure needed to distinguish robust systems from climate-mismatched ones. This infrastructure can support safe pilot deployment while building the evidence required for later codes, certification, and scaled investment.

CRediT author contribution statement

Fatma Muftah Kridan: Conceptualization; Methodology; Data curation; Formal analysis; Investigation; Visualization; Writing – original draft; Writing – review and editing.

Declaration of competing interest

The author declares that she has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The structured evidence database supporting this systematic review is available from the corresponding author on reasonable request and will be deposited in an appropriate repository upon acceptance.

Acknowledgments

The author gratefully acknowledges the academic guidance and constructive feedback received during the development of this review.

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Absolute and relative values, denominator, period, baseline, statistical uncertainty

Activation/regeneration constraints, transferability, aging and safety

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Appendix A. Minimum reporting checklist for PCM-building studies

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Bibliographic

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Building baseline

Çelik, A., Mandev, E., Ersan, O., Muratçobanoğlu, B., Ceviz, M. A., & Kara, Y. A. (2025). Thermal performance evaluation of PCM-integrated interior shading devices in building glass facades. Journal of Energy Storage, 113, 115614. https://doi.org/10.1016/j.est.2025.115614

Chan, Y., Hoke, T., Meredith, K., & Chen, X. (2025). Annual simulation of phase change materials for enhanced energy efficiency and thermal performance of buildings in southern california. Energies, 18(4), 847. https://doi.org/10.3390/en18040847

Chemical/material identification, category, transition interval, latent heat, conductivity, density, cycling history

Chen, X. N., Xu, B., Fei, Y., Gan, W. T., & Pei, G. (2023). Parameter optimization of phase change material and the combination of phase change material and cool paint according to corresponding energy consumption characteristics under various climates. Energy, 277, 127625. https://doi.org/10.1016/j.energy.2023.127625

Chen, X., Kong, X., Wang, S., Fu, X., Yu, B., Yao, K., Zhong, Y., Li, J., Xu, W., & Liu, Y. (2022). Microencapsulated phase change materials: Facile preparation and application in building energy conservation. Journal of Energy Storage, 48, 104025. https://doi.org/10.1016/j.est.2022.104025

Climate

Climate classification, weather source, key temperature and solar conditions

Component, orientation, layer position, thickness, mass/area, encapsulation, contact assumptions

Construction layers, U-values, glazing, infiltration, occupancy, HVAC and thermostat schedules

Costs, service life, discount rate, tariff, embodied and operational impacts

Dardouri, S., Tunçbilek, E., Khaldi, O., Arıcı, M., & Sghaier, J. (2023). Optimizing PCM integrated wall and roof for energy saving in building under various climatic

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Domain

Economics and environment

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Elmarghany, M. R., Radwan, A., Shouman, M. A., Khater, A. A., Salem, M. S., & Abdelrehim, O. (2022). Year-long energy analysis of building brick filled with phase change materials. Journal of Energy Storage, 50, 104605. https://doi.org/10.1016/j.est.2022.104605

Experimental scale or simulation software/version, timestep, numerical method

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Frahat, N. B., Ustaoglu, A., Gencel, O., Sarı, A., Hekimoğlu, G., Yaras, A., & del Coz Díaz, J. J. (2023). Fuel, cost, energy efficiency and CO2 emission performance of PCM integrated wood fiber composite phase change material at different climates. Scientific Reports, 13(1), 7714. https://doi.org/10.1038/s41598-023-34616-8

Gbekou, F. K., Belloum, R., Chennouf, N., Agoudjil, B., Boudenne, A., & Benzarti, K. (2024). Thermal performance of a building envelope including microencapsulated phase change materials (PCMs): A multiscale experimental and numerical investigation. Building and Environment, 253, 111294. https://doi.org/10.1016/j.buildenv.2024.111294

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