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Phase Change Materials in Residential Building Walls: A Systematic Investigation and Evidence-Informed Decision Framework for 3E Assessment

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ABSTRACT
Phase change materials (PCMs) have been widely investigated as a passive thermal energy storage strategy for improving the energy performance of residential walls. However, their economic and environmental implications are less consistently addressed, limiting the integrated assessment of PCM design alternatives. This study investigates passive PCM applications in residential walls through an energy, economic, and environmental (3E) perspective and develops an evidence-informed decision framework for their design and assessment. A PRISMA-guided literature search covering 2015–2025 was conducted using Web of Science and Scopus, resulting in 55 eligible studies. All included studies assessed energy performance, whereas 31 focused exclusively on the energy dimension and only 10 addressed all three 3E dimensions. The findings indicate that PCM performance depends strongly on climate, phase-change temperature, thickness, position within the wall, and building characteristics. Economic outcomes are additionally influenced by PCM cost, local energy prices, and assessment boundaries, while environmental evaluations remain largely focused on operational carbon reduction, with comprehensive life-cycle assessments still limited. Based on the recurring patterns identified across the included studies and the detailed comparison of the 10 studies addressing all three dimensions, an evidence-informed decision framework was developed. The framework links application context and PCM design parameters with sequential energy screening, parallel economic and environmental assessment, and integrated 3E decision-making. The findings also underline the need for standardized indicators, long-term field validation, and multi-criteria decision-support approaches capable of comparing context-specific PCM alternatives across the three performance dimensions.
Keywords: phase change material (PCM), residential building walls, energy performance, economic performance, environmental performance, decision framework.

1. INTRODUCTION
The building sector, which accounts for a significant share of global energy demand and carbon emissions, is one of the priority areas for sustainable energy transition. According to current data, buildings account for approximately 30% of global energy demand, and about 70% of this demand comes from the residential sector (IEA, 2023; UNEP, 2022). As energy use in residential buildings is strongly associated with space and water heating, solutions aimed at improving energy performance have become particularly important for this building group (IEA, 2021; Eurostat, 2023). Therefore, developing passive and energy-efficient approaches

that can be applied to both new buildings, and the existing housing stock has become a key topic of current research.

The building envelope plays a critical role in building energy performance. Envelope characteristics, which directly affect heat transfer between the interior and exterior environments, play a significant role in determining heating and cooling requirements (Sadineni et al., 2011; Yang et al., 2022). The thermal properties of materials used in walls, which constitute a large part of the building envelope, can directly affect the control of heat flow within the building and the associated energy requirements. Therefore, in addition to traditional thermal insulation and thermal mass solutions, phase change material applications aimed at increasing the thermal energy storage capacity of walls are increasingly being researched (Sadineni et al., 2011).

Phase change materials (PCMs) are thermal energy storage materials that store heat in the form of latent heat during phase transformation and release it again under suitable temperature conditions. Widely used in building applications, solid-liquid PCMs can increase the thermal storage capacity of building elements and limit fluctuations in indoor temperatures thanks to their ability to store high amounts of energy over a narrow temperature range (Zhou et al., 2012). However, the emergence of this contribution depends on the phase change temperature being compatible with the building's operating and comfort temperatures. These features have made PCMs a significant option for improving the passive thermal performance of building envelopes (Kuznik et al., 2011; Soares et al., 2013).

In PCM applications, performance is not determined solely by the material's own properties. Phase-change temperature, PCM layer thickness, PCM position within the wall section, and climatic conditions all have a combined effect (Arıcı et al., 2020). Studies conducted in different climate zones show that the same PCM solution does not provide the same level of energy savings under different conditions. In particular, the appropriate phase change temperature can vary depending on the dominance of heating and cooling requirements (Marin et al., 2016; Saffari et al., 2017). Therefore, rather than discussing a single optimum PCM solution for residential walls, it is more meaningful to consider material selection and placement within the wall in conjunction with local climate and building conditions.

However, the reduction in energy consumption alone is not sufficient to explain the success of PCM applications at the building scale. The energy savings achieved should be evaluated together with economic indicators such as initial cost, energy cost savings, and payback period, because the economic feasibility of PCM applications can vary significantly depending on climate, material costs, and local energy prices (Mi et al., 2016). Similarly, basing environmental performance solely on energy savings during the use phase may overlook the production, integration into the building component, and end-of-life impacts of the PCM (Struhala & Ostrý, 2022). Therefore, considering energy, economic, and environmental performance together allows PCM solutions to be evaluated from a more holistic sustainability perspective.

With the expansion of the literature on PCMs in structural applications, review studies with different scopes and purposes have also been published. Lamrani et al. (2021) evaluated the energy and thermal performance results in experimental and numerical studies by examining PCM applications integrated into walls during the period 2011–2020 and noted that economic feasibility and environmental impacts remained relatively limited in the literature. Zhao et al. (2024) extended the scope of the study beyond the walls, addressing different building envelope components such as the roof, floor, ceiling, and windows.

More recently, Khdair et al. (2025) evaluated PCM applications within a 3E framework integrating energy, economic, and environmental dimensions across different building elements and climatic conditions. While these studies offer a broad framework regarding PCM technology, systematic comparison of the relationships between design variables and 3E performance in passive applications specific to residential walls, and the transformation of these findings into a structured decision-making process to guide design decisions, have been limited.

This study systematically examines passive PCM applications used in residential walls for the period 2015–2025 and evaluates the relationships between design characteristics and energy, economic, and environmental performance. Studies selected from the Web of Science and Scopus databases using the PRISMA approach were classified according to their research methods, modeling and simulation tools used, analysis approaches, and the performance dimensions they addressed. Studies that consider all three 3E dimensions together have compared them in more detail in terms of climatic conditions, PCM type, phase change temperature, thickness, and location within the wall. The study's unique contribution lies in not merely using these systematic findings to describe the existing literature but transforming them into an evidence-backed decision framework for passive PCM design and integrated 3E assessment in residential walls. Accordingly, the main research questions of the study have been determined as follows:

- **RQ1:** How have passive PCM applications used in residential walls between 2015 and 2025 been discussed in literature in terms of design characteristics and energy, economic and environmental (3E) performance?
- **RQ2:** How have design variables such as PCM type, phase change temperature, PCM thickness, location within the wall, and climatic conditions been addressed in residential wall applications?
- **RQ3:** Which methods and indicators were used to evaluate the energy and thermal performance of PCM applications, and how did this performance differ depending on the design variables?
- **RQ4:** To what extent and with what approaches has economic and environmental performance been evaluated in comparison with the energy dimension in the literature?
- **RQ5:** What research trends, methodological limitations, and research gaps stand out in the current literature regarding the use of passive PCM in residential walls?
- **RQ6:** How can the findings from the studies reviewed be translated into an evidence-backed decision framework for the design and evaluation of 3E performance of passive PCM applications in residential walls?

2. METHODOLOGY

The methodological process of this study consists of the following stages: defining research questions, systematically identifying and selecting studies, data extraction and classification, general and detailed analyses, and synthesizing the findings to transform them into a decision framework. 55 studies selected in accordance with the PRISMA approach were examined in terms of their methodological characteristics and the energy, economic, and environmental performance dimensions they addressed. Among these studies, ten that addressed all three 3E dimensions together were further evaluated to allow for a more detailed comparison of the relationships between PCM design variables and performance outcomes. The common findings from the general and detailed analyses were then used to develop an evidence-backed decision framework for passive PCM design and integrated 3E assessment in residential walls. The methodological flow of the study is summarized in Figure 1.

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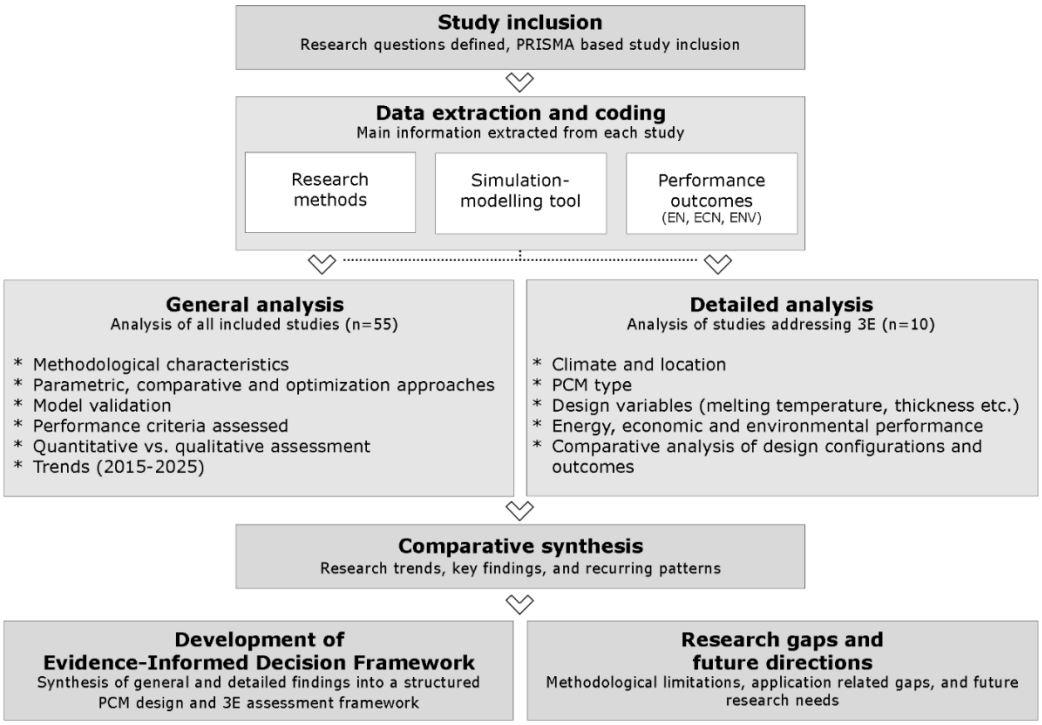


Figure 1. Methodological workflow of study selection, analysis, synthesis, and framework development.

2.1. PRISMA-Based Literature Search and Study Selection

The identification and selection of studies were carried out in accordance with the PRISMA guidelines (Page et al., 2021), and the selection process is summarized in the PRISMA flowchart presented in Figure 2. A literature search was conducted in the Web of Science (WoS) and Scopus databases to identify studies on passive phase change materials (PCMs) used in residential walls. In both databases, terms related to PCM, wall application, climate conditions, and energy/thermal performance were combined within the same basic Boolean search structure. In WoS, Topic Search (TS) was used, while in Scopus, the TITLE-ABS-KEY field, which includes the title, abstract, and keywords, was used. The search fields used, the basic query structure, and the number of records obtained according to the databases are presented in Table 1.

Table 1. Database-specific search strategy and number of retrieved records.

Database	Search field	Search query	Records
Web of Science	Topic Search (TS)	("phase change material" OR PCM) AND (wall* OR facade*) AND (climate OR climatic OR weather) AND (energy OR thermal OR performance)	654
Scopus	TITLE-ABS-KEY		546

Search results were narrowed down using criteria such as publication year, document type, and language, in line with the scope of the review. Only research articles accepted for publication between 2015 and 2025 were considered. All studies evaluated were published in English.

The initial scan yielded a total of 1,200 records, 654 from WoS and 546 from Scopus. After combining the records from the two databases, 380 duplicate records were removed, and 820 unique records were advanced to the screening stage. 271 records were eliminated as being outside the scope of the title review, and the remaining 549 studies were examined at the

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abstract level. After eliminating another 229 records during the abstract review, 320 studies were selected for full-text evaluation.

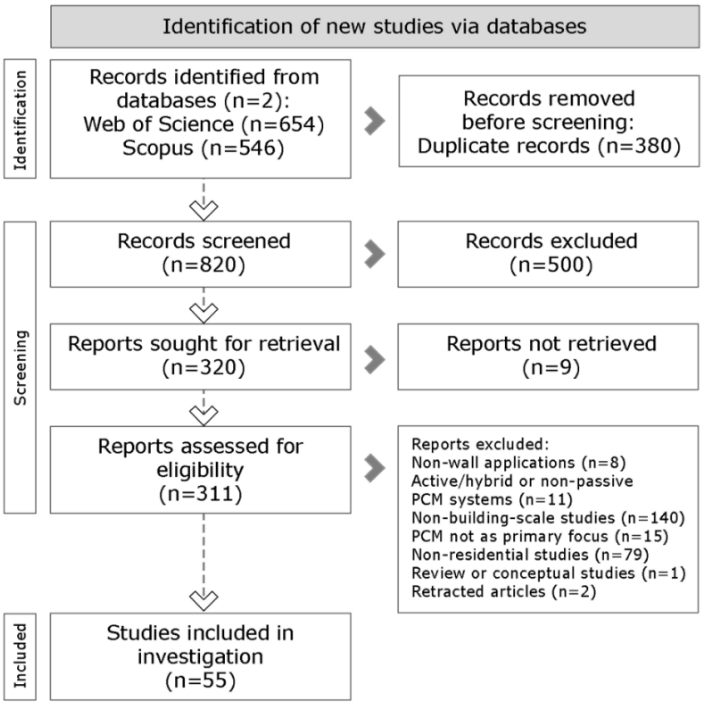


Figure 2. PRISMA flow diagram of the literature identification, screening, eligibility assessment, and inclusion process.

Of the 320 studies targeted for full text access, 9 were inaccessible, and the remaining 311 were assessed for eligibility. As a result of applying predefined exclusion criteria, 256 studies were excluded, and 55 studies were included in the final review. The exclusion criteria used in the eligibility assessment are presented below:

- Non-wall applications (n=8): Studies where PCM was used on structural components other than walls, and wall applications were not evaluated.
- Active, hybrid, or non-passive PCM systems (n=11): Studies where PCM is used as part of an active, mechanical, or controlled system, and the effect of passive application cannot be evaluated separately.
- Non-building-scale studies (n=140): Studies that do not involve a building-scale application or performance evaluation; instead, they remain solely at the scale of materials, components, or small test setups.
- PCM not as a primary focus (n=15): Studies in which PCM is not one of the key research variables or whose effect cannot be isolated from other strategies.
- Non-residential studies (n=79): Studies focusing on building types other than residential.
- Review or conceptual studies (n=1): Review or conceptual studies that do not involve original experimental or quantitative research.
- Retracted articles (n=2): Studies that have been withdrawn from publication.

The 55 studies ultimately included were classified according to energy (EN), economic (ECN), and environmental (ENV) performance dimensions. Of these, 10 studies that addressed all three performance dimensions were further evaluated to provide a more detailed and comparative examination of the relationships between PCM design characteristics and 3E results.

2.2. Data Extraction and Analysis

The 55 studies included as a result of the PRISMA process were examined using a data extraction framework created in line with the research questions. For each study, information was compiled regarding the research method, modeling and simulation tools used, analysis approach, validation method, and energy, economic, and environmental performance. Methodological evaluation considered numerical modeling and simulation, experimental or field-based applications, parametric and comparative analyses, optimization approaches, and model validation methods. In cases where more than one method or analysis approach could be used in the same study, the relevant categories were not treated as mutually exclusive classes.

Performance results are classified under a three-dimensional 3E structure: energy (EN), economic (ECN), and environmental (ENV). The energy dimension considers energy consumption and savings, heating and cooling requirements, temperature variations, and thermal comfort; the economic dimension considers initial and system costs, energy cost savings, payback period, and life cycle-based economic indicators; and the environmental dimension considers CO_2 or CO_2-equivalent emissions, embodied effects, recyclability, and life cycle-based indicators. Whether the economic and environmental assessments are conducted quantitatively or qualitatively is also included in the classification. This classification was applied to all 55 studies. Ten studies that addressed all three dimensions—energy, economic, and environmental—were selected for detailed comparative analysis. These studies were compared in terms of study area and climate conditions, PCM type or material, phase change temperature, thickness, location within the wall, and reported 3E performance results. Thus, common relationships between PCM design characteristics and energy, economic, and environmental performance, as well as differences between the studies, were identified.

2.3. Development of the Evidence-Informed Decision Framework

The findings obtained were used in developing a structured decision framework for the design of passive PCM applications in residential walls and the evaluation of their 3E performance. In constructing this framework, general methodological and performance trends identified from 55 studies were considered together with common findings from a detailed comparative analysis of 10 studies that addressed 3E.

The fundamental design variables of the framework are defined through climate and building conditions, PCM type, phase change temperature, thickness, and location within the wall—variables that have been repeatedly correlated with PCM performance in the studies examined. These variables are organized within a decision structure where the application context and PCM design configuration are first defined, followed by an assessment of energy and thermal performance as the initial technical feasibility stage. Configurations that do not provide a significant benefit in terms of energy or thermal efficiency are to be redesigned; solutions demonstrating sufficient performance are to be evaluated in parallel from both economic and environmental perspectives.

The results obtained from economic and environmental assessments were then transferred to an integrated 3E assessment along with energy performance. At this stage, the aim is to consider the balance between energy/thermal performance, economic feasibility, and

environmental impact, rather than maximizing a single performance dimension. The assessment process is structured to allow the PCM configuration to be interpreted as a suitable, conditionally suitable, or unsuitable solution, and to allow a return to the design phase if necessary.

Since the indicators, system boundaries, climate conditions, and economic assumptions used in the studies examined differed significantly, fixed numerical threshold values were not defined in the framework. Instead, a comparative and iterative decision logic was adopted that could be adapted to different building and climate conditions. Thus, the proposed framework was developed to support the combined evaluation of the energy, economic, and environmental consequences of context-specific PCM alternatives, rather than defining a specific PCM product or a single optimum solution.

3. RESULTS

This section first evaluates the general characteristics, methodological approaches, and performance dimensions addressed in the studies included in the review. Then, studies that consider energy, economic, and environmental performance together are compared in detail in terms of PCM design features and 3E results. The findings from the general and detailed analyses are then used in developing a proposed decision framework for passive PCM design and integrated 3E assessment in residential walls. Finally, the main limitations, research gaps, and future areas of study in the current literature are discussed.

3.1. General Characteristics of the Reviewed Studies

The studies examined were evaluated in terms of their general characteristics, research methods, and analytical approaches, as well as the energy, economic, and environmental performance dimensions they addressed.

3.1.1. Research Scope and Methodological Approaches

The studies included in the review utilized different research and analysis approaches to evaluate the performance of PCM in residential walls. Methodological characteristics were addressed under three headings: research approach, analysis method, and model validation/complementary analyses. In cases where more than one method was used together in a study, the relevant categories were not considered mutually exclusive classes.

(i) Research approach:

The dominant approach in literature is numerical modeling and building energy simulation. Of the 55 studies examined, 51 (92.7%) utilized numerical modeling and/or energy-thermal performance simulations at the building or structural element scale. These studies mostly compared building models with and without PCM, examining outputs such as annual or seasonal energy consumption, heating and cooling loads, indoor temperature, and thermal comfort (Saffari et al., 2017; Ramakrishnan et al., 2017; Nghana & Tariku, 2016; Soares et al., 2017; Abden et al., 2022; Park et al., 2021; Vukadinović et al., 2020; Dardouri et al., 2023; Refahi et al., 2023; Tian et al., 2025; Zhou et al., 2025).

EnergyPlus stands out as the most widely used software. EnergyPlus was reported in 34 studies (61.8%), while EnergyPlus-based DesignBuilder was reported in 18 studies (32.7%). TRNSYS and COMSOL Multiphysics were used in three studies each (5.5%), while other tools such as ESP-r and EDSL Tas were encountered to a lesser extent. Considering that EnergyPlus and DesignBuilder can be reported together in the same study, these percentages are not mutually exclusive categories. Saffari et al. (2017), Ramakrishnan et al. (2017), Abden et al. (2022), Park et al. (2021), Dardouri et al. (2023), and Jaradat et al. (2024) are examples of studies using EnergyPlus and/or DesignBuilder; while TRNSYS Al-Saadi and Zhai (2015),

Hamdani et al. (2021), and Stamatiadou et al. COMSOL Multiphysics was used by Aketouane et al. (2018), Liu et al. (2023) and Meng et al. (2023) respectively.

In addition to quantitative studies, 15 studies (27.3%) included a component based directly on experimental, laboratory, or field measurements. In these studies, the thermophysical properties of PCM or PCM-containing structural elements were determined under laboratory conditions; temperature, energy consumption, and other thermal variables were measured in prototype, test structure, or real-scale applications (Nghana & Tariku, 2016; Kim et al., 2017; Shaik et al., 2022; Saylam Canım & Maçka Kalfa, 2023; Dewi et al., 2026; Bayraktar & Köse, 2025). In some studies, experimental and quantitative methods were carried out together; measurement data were used in model validation or in transferring experimentally determined material properties to simulation.

(ii) Analysis method:
Parametric analysis, comparative evaluation, and optimization approaches are prominent in the investigation of PCM performance. In parametric studies, the effects of variables such as phase change temperature, PCM thickness, location within the wall, and PCM quantity on energy and thermal performance have been investigated (Saffari et al., 2017; Soares et al., 2017; Hamidi et al., 2021; Refahi et al., 2023; Liu et al., 2023). In some studies, insulation thickness, wall layering, window characteristics, and other building parameters have also been added to these variables (Ramakrishnan et al., 2017; Abden et al., 2022; Dardouri et al., 2023; Jaradat et al., 2024).

In comparative analyses, different PCM types, phase change temperatures, thicknesses, and wall locations were compared in solutions with and without PCM (Soares et al., 2017; Godoy-Vaca et al., 2021; Vedrtnam et al., 2025). Testing the same PCM application in different climate zones or different wall systems is also a common approach (Saffari et al., 2017; Hamidi et al., 2021; M'hamdi et al., 2022; Jaradat et al., 2024).

Optimization studies have focused on determining appropriate PCM properties and application configurations according to specific energy or thermal performance targets. Phase change temperature, thickness, and location within the wall constitute the basic optimization variables, while some studies have also used multi-objective optimization or multi-criteria decision-making methods (Saffari et al., 2017; Mukhamet et al., 2021; Refahi et al., 2023; Dardouri et al., 2023; Jaradat et al., 2024; Vedrtnam et al., 2025). These studies reveal that PCM performance cannot be reduced to a single variable; material properties, structural components, and climatic conditions must be considered together.

(iii) *Model validation/complementary analyses:*
To test the reliability of numerical models, validation or calibration was performed in 16 studies (29.1%) using experimental measurements, field data, benchmark tests, or reference data from the literature. In some studies, model outputs were directly compared with experimental temperature measurements, while in others, experimentally determined PCM or building material properties were transferred to the numerical model (Nghana & Tariku, 2016; Kim et al., 2017; Mousavi et al., 2022; Liu et al., 2023; Saylam Canım & Maçka Kalfa, 2023). Parametric scans, sensitivity analyses, and comparison of different scenarios were used as complementary methods to examine the effect of design variables on the results.

In addition to energy and thermal performance, some studies have also included economic and environmental indicators in their analysis. Economic assessments have used indicators such as initial or system cost, energy cost savings, payback period, and life cycle; while environmental assessments have used CO_2 emissions, carbon reduction, embedded energy,

and other environmental metrics. In some multi-criteria or multi-objective studies, these indicators have been considered together with energy performance within the same evaluation structure (Mukhamet et al., 2021; Jaradat et al., 2024; Vedrtnam et al., 2025). Overall, it is observed that the majority of the 55 studies are based on numerical modeling and simulation (92.7%), while direct experimental approaches (27.3%) and model validation/calibration (29.1%) are more limited. However, the combined use of parametric analysis, comparative evaluation, and optimization methods shows that PCM performance is considered not only at the material level but also as a multivariate design problem related to climate, building, and wall properties.

3.1.2. Performance Criteria Addressed in Literature

The 55 studies included were classified according to whether they addressed the energy (EN), economic (ECN), and environmental (ENV) performance dimensions. While energy performance was a common assessment dimension across all studies, the scope and assessment method of economic and environmental performance differed significantly among the studies. Therefore, the classification considered not only whether the relevant performance dimension was included in the study, but also whether the economic and environmental assessments were conducted quantitatively or qualitatively.

Table 2 shows that energy performance is clearly dominant in literature. While the energy dimension was assessed in all 55 studies examined, 31 studies focused solely on energy performance. Economic performance was addressed in 21 studies; 17 of these involved quantitative assessments, and 4 involved qualitative assessments. Environmental performance was examined in 13 studies; 11 included quantitative assessments, and 2 included qualitative assessments. A total of 10 studies were identified that addressed all three dimensions: energy, economic, and environmental. This distribution reveals that economic and especially environmental assessments remain more limited compared to energy analyses.

Table 2. Grouping of the reviewed studies according to the 3E dimensions*.

Studies	EN	ECN	ENV	n
Al-Saadi et al. (2015), Bouguerra et al. (2015), Auzeby et al. (2016), Nghana et al. (2016), Kim et al. (2017), Ramakrishnan et al. (2017), Saffari et al. (2017), Stamatiadou et al. (2017), Aketouane et al. (2018), Berardi & Soudian (2018), Lee et al. (2018), Köse Murathan & Manioğlu (2020), Vukadinović et al. (2020), Godoy-Vaca et al. (2021), Hamdani et al. (2021), Hamidi et al. (2021), Louanate et al. (2021), Park et al. (2021), Ebadati et al. (2023), Hammid et al. (2023), Liu et al. (2023), Saylam Canım & Maçka Kalfa (2023), Hamooleh et al. (2024), Hepple et al. (2024), Köse Murathan & Manioğlu (2024), Lahoud et al. (2024), Wang et al. (2024), Yari et al. (2024), Tian et al. (2025), Vedrtnam et al. (2025), Xia et al. (2025)	●	–	–	31
Soares et al. (2017), Paranjothi et al. (2021), Salihi et al. (2022), Meng et al. (2023), Refahi et al. (2023), Stasi et al. (2024), Zhou et al. (2025)	●	●	–	7
Bimaganbetova et al. (2020), Al-Absi et al. (2021), Schmerse et al. (2020), Wang et al. (2025)	●	○	–	4
Dardouri et al. (2023), Tunçbilek et al. (2025)	●	–	●	2
Bayraktar et al. (2025)	●	–	○	1
Mukhamet et al. (2021), Abden et al. (2022), Acuña-Díaz et al. (2022), M'hamdi et al. (2022), Mousavi et al. (2022), Shaik et al. (2022), Yang et al. (2023), Jaradat et al. (2024), Sun et al. (2024)	●	●	●	9
Dewi et al. (2026)**	●	●	○	1
Total				55

*Symbols: Quantitative (●), qualitative (○), not assessed (–)
** This study was published online in May 2025 and was featured in the 2026 issue of the journal. Therefore, it is included in this study.

The limited number of studies that consider 3E dimensions together indicates that the performance of PCM applications is mostly evaluated through energy savings. Studies that include economic and environmental dimensions show significant differences in the scope of

evaluation and the indicators used. Therefore, 10 studies that consider 3E performance dimensions together were comparatively evaluated in Section 3.2 to examine in more detail the relationships between PCM design features and energy, economic, and environmental outcomes. The distribution of the studies examined by year and the prominent research topics reveal how the research focus on PCM applications has diversified over time (Table 3). While studies in the early years focused more on basic thermal performance, model validation, and energy savings, in later periods, design variables such as phase change temperature, PCM thickness, location within the wall, and climate dependence were addressed in more detail. After 2020, comparative climate analyses, sensitivity studies, and multi-criteria approaches became more visible; from 2022 onwards, the number of studies evaluating economic and environmental performance together with the energy dimension increased. In the 2023–2025 period, more diverse research directions such as multi-objective optimization, machine learning, field applications, bio-based PCMs, and climate adaptation came to the fore.

Table 3. Research trends in passive PCM applications in residential walls (2015–2025).

Research trends	Year	No. of studies	Main focus	Representative topics
Early development	2015	2	Basic thermal performance	*Model validation *Melting temperature *PCM position
	2016	2	Thermal comfort and overheating	*Thermal comfort *Overheating *Field validation
Parameter optimization	2017	5	Parametric optimization	*Phase-change temperature *PCM thickness *Peak load *Climate dependency
	2018	3	Building integration and retrofit	*Building retrofit *Building typology *Window-to-wall ratio *Wall integration
Diversification and practical applications	2020	4	Cross-climate comparison	*Cross-climate comparison *Configuration optimization *Multi-component applications
	2021	8	Methodological diversification	*Multi-criteria decision making *Sensitivity analysis *Double-layer PCM *Orientation/season strategies
Expansion of integrated 3E assessment	2022	6	Integrated 3E assessment and feasibility	*Economic analysis *Life-cycle assessment *Payback period *Carbon reduction *Thermo-economic evaluation
Advanced and expanded research	2023	8	Multi-objective optimization	*Multi-objective optimization *Machine learning *Composite PCM *Advanced design configurations
	2024	9	Application diversification	*BIM-simulation workflows *Different building typologies *Building retrofit *PCM vs. insulation comparison
	2025	8	Climate adaptation and real-world validation	*Machine Learning/Genetic Algorithm optimization *Field experiments *Bio-based PCM *Climate adaptation *Rural/prefabricated housing
Note: No study published in 2019 met the inclusion criteria; therefore, 2019 is not shown in the table.				

When evaluated over the years, it is observed that energy and thermal performance remained the primary research axis in PCM studies throughout the entire study period. However, in subsequent years, the scope of research expanded beyond simply determining energy savings

to include the combined assessment of climate sensitivity, multivariate optimization, economic feasibility, and environmental impacts. Particularly in recent years, the use of multi-objective optimization, machine learning, and field experiments indicates that PCM design is increasingly treated as a context-specific and multivariate problem. However, as shown in Table 2, the fact that economic and environmental assessments are still more limited compared to energy performance shows that this methodological diversification is not reflected to the same extent in the integrated 3E assessment.

3.2. Detailed Analysis of Studies Addressing the 3E Framework

10 studies that addressed all three dimensions of energy, economic, and environmental performance were comparatively evaluated to examine the 3E performance of PCM applications in more detail. These studies were examined in terms of design characteristics such as study area and climate conditions, PCM type, phase change temperature (T_m), thickness, and location within the wall, as well as reported energy, economic, and environmental outcomes. The key characteristics of the studies and the main findings within the scope of 3E are summarized in Table 4. The studies examined reveal that the performance of PCM wall applications cannot be reduced to a single material property. While climate conditions, phase-change temperature, PCM thickness, and location within the wall together shape energy and thermal performance, economic and environmental outcomes are also affected by the evaluation method used and system limitations. Although energy performance constitutes the main evaluation dimension in all 10 studies, the way economic and environmental outcomes are calculated varies significantly among the studies. In some studies, these results are directly related to the PCM wall application, while in others, PCM is considered together with insulation, roof applications, or other passive strategies. Therefore, when interpreting 3E results, it is necessary to consider not only the reported performance values but also the system contexts within which these values were generated.

Phase change temperature is one of the design variables that shows the most significant correlation with climatic conditions in 3E studies. Mukhamet et al. (2021) reported that the highest energy savings in eight cities with tropical savanna climates were generally achieved with PCMs in the 25–27 °C range. While M'hamdi et al. (2022) used 25 °C Bio-PCM in different North African climates, Jaradat et al. (2024) identified 23 °C BioPCM® M91/Q23 as the most suitable option among materials they compared in the 21–29 °C range. Sun et al. (2024) showed that PCMs in the 18–22 °C range yielded more suitable results in Lhasa and Harbin, while higher phase change temperatures were more suitable in Guangzhou. These differences indicate that a single optimum value for phase change temperature cannot be defined independently of climate; the appropriate temperature range should be considered together with the local climate and the building's heating and cooling regime.

The position of the PCM within the wall section can also significantly affect the results. Mukhamet et al. (2021), Jaradat et al. (2024), and Sun et al. (2024) reported higher energy performance in placements closer to the interior. In contrast, Shaik et al. (2022) compared different positions of PCM within brick and determined that placement closer to the exterior could provide higher energy and cost savings in certain climate-material combinations. Yang et al. (2023) reported that facade orientation also altered this relationship; in the Shenzhen example, the highest energy sensitivity to increasing PCM thickness was observed on the east facade. Therefore, the position of the PCM within the wall is not a fixed parameter to be optimized in isolation, but rather a context-specific design variable that should be considered in conjunction with climate, orientation, and wall layering.

While increasing PCM thickness improves energy performance in most cases, this relationship appears to be non-linear. Abden et al. (2022) achieved energy consumption reductions of

20.3%, 36.2%, and 43.6% in Darwin, Alice Springs, and Sydney, respectively, by increasing the FSPCM thickness to 30 mm. Jaradat et al. (2024) identified 37.1 mm BioPCM panels as the optimum thickness among the options they evaluated, while Sun et al. (2024) compared thicknesses of 15, 35, and 55 mm and showed that energy savings increased with increasing thickness, but the marginal gain provided by each additional thickness decreased. These findings indicate that PCM thickness should be evaluated not only in terms of maximum energy savings, but also in conjunction with the cost of the additional benefit provided.

In terms of economic performance, studies show a wide range in both the indicators used and the results obtained. Some studies consider only the initial or material cost, while others use more comprehensive indicators such as payback period, life cycle cost, net present value, benefit-cost ratio, and internal rate of return. Acuña-Díaz et al. (2022) reported that the payback period, calculated as 14.3 years for basic PCM implementation, decreased to 9.3 years with investment support and to 8.3 years in the low-cost PCM scenario. M'hamdi et al. (2022) calculated payback periods ranging from approximately 7–43 years for different climates and wall types; Jaradat et al. (2024) found approximately 4 years for Amman, while Sun et al. (2024) found values ranging from approximately 9.6–10.2 years in three different Chinese cities. This wide distribution indicates that economic feasibility depends not only on energy savings but also on other factors. The study reveals that PCM cost is strongly dependent on energy prices, climate, and application conditions. Another factor that makes comparing economic results difficult is that the studies do not use the same system limits. For example, the payback periods of 2.2–7.5 years reported by Abden et al. (2022) refer not to PCM alone, but to optimized combinations of PCM and EPS insulation. Similarly, the payback periods of 3.4–5.9 years given in Mousavi et al. (2022) are calculated for final configurations involving multiple passive strategies rather than the application of PCM alone. Therefore, when comparing economic performance between different studies, it should be clearly distinguished whether the relevant indicator belongs directly to PCM wall application or to a broader building improvement package.

The most common approach in environmental performance assessments is to translate the reduction in energy consumption into operational CO_2 or CO_2-equivalent emission reductions. M'hamdi et al. (2022) reported CO_2 reductions of up to approximately 707 kg per year, while Jaradat et al. (2024) calculated a greenhouse gas emission reduction of approximately 2382 kg CO_2e/year for Amman. Sun et al. (2024) reported CO_2 reductions of between 3.8% and 4.9% in different climates, while Acuña-Díaz et al. (2022) reported a carbon footprint reduction of approximately 7%. However, environmental assessment is not limited to operational emissions. Mukhamet et al. (2021) included embedded energy and recyclability as decision criteria, while Dewi et al. (2026) qualitatively discussed the environmental characteristics of bio-based and renewable materials. Nevertheless, comprehensive life cycle assessments encompassing production, encapsulation, transportation, and end-of-life are limited in the 3E literature.

Taken together, these 10 studies demonstrate that high energy performance alone is insufficient to define a suitable solution in PCM wall applications. The impact of design decisions such as phase change temperature, thickness, and location within the wall varies depending on climate and building conditions, while economic outcomes are sensitive to PCM cost, energy prices, and system limitations; and environmental outcomes are sensitive to the scope of the evaluation used. Furthermore, the differences in the indicators used and system limitations among the studies limit the direct quantitative comparison of the 3E results. Therefore, evaluating PCM alternatives requires an integrated decision-making process that considers the design context and energy, economic, and environmental outcomes together, rather than the optimization of a single performance indicator.

Table 4. PCM design characteristics and reported 3E performance of the 10 studies addressing all three dimensions.

Study	Location / Climate	PCM type / material	PCM design parameters	Energy performance	Economic performance	Environmental performance
Mukhamet et al. (2021)	Bangkok, Bamako, Brasília, Bangalore, Kolkata, Surabaya, Maputo, Dar es Salaam; tropical savanna (Aw)	Commercial organic, salt-hydrate and bio-based PCMs	T_m: 21–31 °C; generally optimum 25–27 °C. Thickness: 20 mm. Position: near interior surface of external walls; PCM also used in roof	Peak annual energy savings 5021–8392 kWh, corresponding to 5.42–43.0% reduction; highest in Brasília (42.95%)	Initial material cost incorporated into MCDM; no explicit LCC or separately calculated payback	Recyclability and embodied energy included as environmental criteria; no building-level LCA or operational CO_2 calculation
Abden et al. (2022)	Darwin, Alice Springs, Sydney, Australia; tropical savanna, hot semi-arid, humid subtropical	Form-stable RT-26 paraffin supported by diatomite and incorporated into gypsum board	T_m: approx. 18–30 °C investigated. Thickness: 10–30 mm. Position: inner surface of exterior walls; wall, ceiling and combined configurations	At 30 mm, maximum energy reductions of 20.3%, 36.2% and 43.6% in Darwin, Alice Springs and Sydney	Optimized PCM+EPS retrofit: 10-year savings AU$167.0, 162.3 and 39.7/m²; payback 2.2–7.5 years	Optimized combined retrofit: CO_2-eq savings 380.5, 380.9 and 171.7 kg/m²; environmental cost savings AU$9.7, 9.7 and 4.4/m²
Acuña-Díaz et al. (2022)	Alice Springs, Australia; hot-arid desert (BWh)	PCM based on previously validated material data	T_m: 26 °C. Thickness: 30 mm. Position: toward interior, directly above conventional wall insulation	Cooling load reduced by up to 7%; winter heating demand by approx. 5.5%	Base payback 14.3 years; grant scenario 9.3 years; low-cost PCM scenario 8.3 years; IRR 14.2%	Approx. 7% reduction in carbon footprint
M'hamdi et al. (2022)	Benguerir, Tunis, Aswan; sub-arid (BSh), Mediterranean (Csa), arid (BWh)	Four PCM mortars evaluated; Bio PCM selected	T_m: 25 °C. Thickness: 15 mm. Position: interior side of external wall, replacing internal cement mortar	Average annual saving 251.82 kWh/year; total energy reduction 2.57–10.5%; cooling saving up to 7.3%, heating up to 10.7%	Payback approximately 7–43 years depending on envelope/climate	Operational CO_2 saving up to approximately 707 kg/year
Mousavi et al. (2022)	Monterrey, Mexico; semi-arid	Infinite R / commercial PCM25	T_m: 21, 25, 29 °C; 25 °C selected. Thickness: 12 mm. Position: external walls and roof	PCM25 yielded about 18% annual energy saving; temperature difference up to 3.4 °C in summer and 1 °C in winter	PCM cost about USD 80/m²; reported 3.4–5.9 year paybacks correspond to final combined passive configurations	CO_2 reductions of approx. 1578–3004 kg CO_2e/year correspond to combined passive configurations rather than PCM alone
Shaik et al. (2022)	Jaipur and New Delhi, India; hot-arid and composite	OM18, OM21, OM29 organic PCMs; FS29 and FS30 form-stable PCMs	T_m: 10–34 °C depending on PCM. Thickness: 30 mm single layer or 15+15 mm. Position: outer, middle, inner and combined positions within burnt-clay bricks	OM29 with outer-side configuration showed strongest overall performance	Annual energy-cost saving approx. USD 2079–2095/year; OM29 payback about 11.2 years; OM21 produced the shortest payback in some comparisons	Carbon mitigation approx. 87.80–88.42 t CO_2/year
Yang et al. (2023)	Shenzhen, China; hot summer and warm winter	Industrial paraffin	T_m: 26 °C. Thickness: 0–35 mm. Position: east, west, south and north walls; PCM also in roof and floor	East-wall thickness had greatest wall-level sensitivity; optimized Pareto solutions reduced BOEC to 39.74–47.11 kWh/m²	50-year life-cycle economic benefit around 452.21 CNY/m² for optimized design	Life-cycle carbon reduction increased by approx. 10.75 kg CO_2e/m²
Jaradat et al. (2024)	Amman, Irbid, Aqaba, Oradea; moderate, Mediterranean, hot-dry and cold-wet climates	BioPCM® M91/Q23, InfiniteR, WinCo Enerciel; BioPCM optimum	T_m: 21–29 °C; optimum 23 °C. Thickness: 11.2–37.1 mm; optimum 37.1 mm. Position: interior, middle, exterior; interior side best	Total energy reduction 20.14% Amman, 19.78% Irbid, 7.50% Aqaba, 5.64% Oradea	Amman: additional cost approx. USD 4557, annual saving approx. USD 1150, payback about 4 years	Amman: GHG reduction approx. 2382.31 kg CO_2e/year
Sun et al. (2024)	Lhasa, Harbin, Guangzhou, China; cold/dry, extremely cold, warm/humid	PCM20 reference plus PCM12–PCM32 variants	T_m: 10–34 °C ranges; optimum climate-dependent. Thickness: 15, 35, 55 mm. Position: inner/outer wall surface; inner generally better	15 mm PCM20 reduced annual energy use by approx. 12.1%; 55 mm produced about 24.9% Lhasa and 24.7% Guangzhou reductions	Simple payback 10.21 years Lhasa, 9.58 Harbin, 9.72 Guangzhou	CO_2 reduction 4.8%, 3.8%, 4.9%, respectively
Dewi et al. (2026)	Ciawi, West Java, Indonesia; tropical highland, cool-humid	Coconut-oil-based bio-PCM	T_m: 21–25 °C. Amount/configuration: about 180 L CO-PCM in bamboo wall panels; tubes approx. 8 cm diameter. Position: bamboo wall panels, east/west façades compared	Daytime peak indoor temperature reduced by approx. 1 °C; panel-temperature difference up to 1.71 °C; improved night-time stability	Additional PCM-system cost approx. USD 1572.59, or USD 44.27/m²	Renewable/bio-based/biodegradable characteristics discussed qualitatively; no quantified LCA or carbon calculation

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3.3. Proposed Evidence-Informed Framework for PCM Wall Design and 3E Assessment

The findings of the detailed 3E analysis reveal that PCM selection cannot be considered a single-stage decision based solely on material properties or energy saving potential. Climate and building conditions, phase change temperature, thickness, and location within the wall affect energy performance; while economic and environmental consequences vary depending on costs, energy prices, scope of assessment, and system limitations. Based on these relationships, an evidence-supported incremental decision framework has been developed for the design and integrated 3E assessment of passive PCM wall applications (Figure 3). The framework is based on a synthesis of common patterns obtained from the overall findings of 55 studies included and a detailed comparative analysis of 10 studies that addressed all 3E dimensions together.

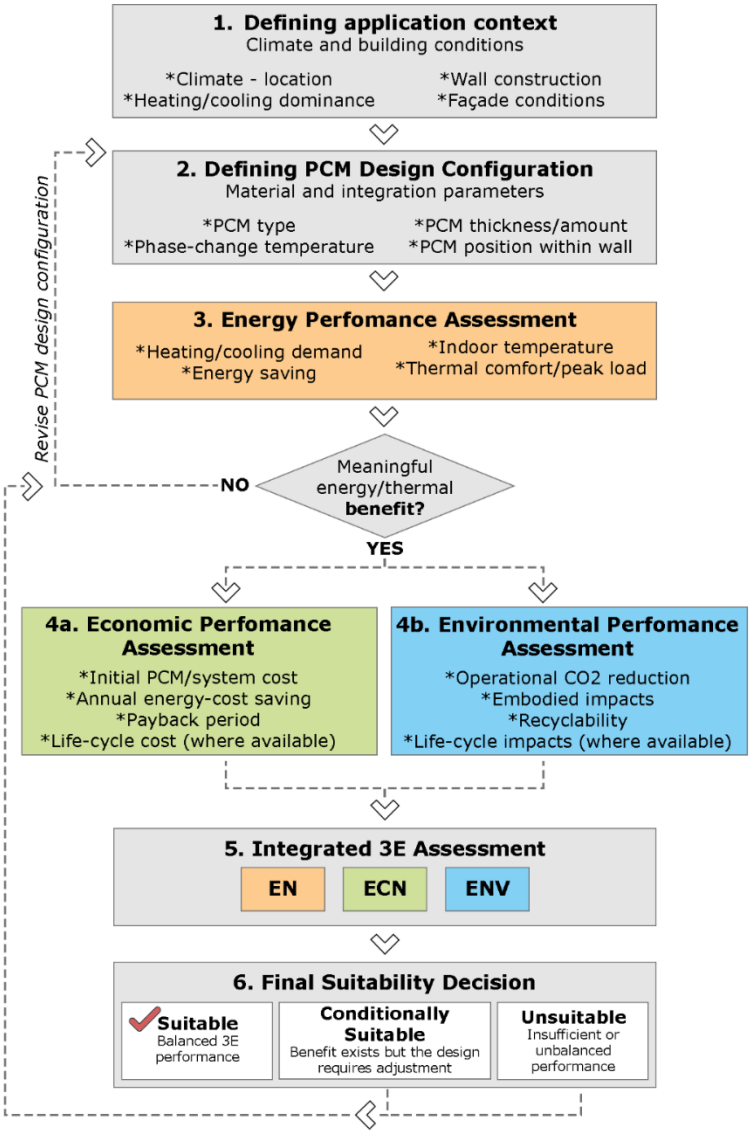


Figure 3. Evidence-informed decision framework for passive PCM wall design and integrated energy, economic, and environmental (3E) assessment.

The framework begins with defining the application context. Climate and location, the dominance of heating or cooling requirements, wall construction, and facade orientation are key conditions considered at this stage. Once this context is defined, the design configuration, consisting of PCM type, phase change temperature, thickness, and position within the wall, is determined. Thus, PCM selection is treated not as a fixed solution independent of context, but as a design decision shaped by the building and climate conditions.

The initial performance check of the selected configuration is carried out using energy and thermal indicators. Heating and cooling requirements, energy savings, indoor temperature, thermal comfort, and peak load are key indicators that can be considered at this stage. If a significant energy or thermal benefit is not obtained, the PCM type, phase change temperature, thickness, or location within the wall is re-evaluated, and the design cycle is repeated. Solutions that provide sufficient technical performance are then transferred to the next evaluation stage.

Solutions that pass the energy screening are evaluated in parallel in terms of economic and environmental performance. The economic dimension considers initial and system costs, annual energy cost savings, payback period, and, where applicable, life cycle cost; the environmental dimension considers operational CO_2 reduction, embodied environmental impacts, recyclability, and life cycle impacts. The evaluation of these two dimensions separately from, but in relation to, energy performance is based on the finding that an energy-successful solution may not automatically be the most economically or environmentally optimal option.

Energy (EN), economic (ECN), and environmental (ENV) outcomes are ultimately combined under an integrated 3E assessment. The aim here is not to maximize a single performance metric, but to consider the balance between technical benefit, economic feasibility, and environmental impact. As a result of this assessment, the PCM configuration is classified as suitable, conditionally suitable, or unsuitable. For conditionally suitable or unsuitable solutions, feedback is directed to the PCM design configuration, allowing for a reassessment of alternatives.

Since the performance indicators, system limits, climate conditions, and economic assumptions used in the studies examined differed significantly, fixed numerical threshold values were not defined in the framework. Instead, a comparative and iterative decision logic was adopted that could be adapted to different building and climate conditions. Therefore, rather than defining a specific PCM product or a universal optimum configuration, the proposed framework offers a structured process for jointly evaluating the energy, economic, and environmental consequences of context-specific PCM alternatives.

3.4. Research Gaps and Future Directions

One of the main limitations of the current 3E literature is the unbalanced treatment of energy, economic, and environmental performance. Energy remains the dominant assessment dimension, while economic and especially environmental aspects are addressed less consistently. Economic evaluations also differ substantially in terms of indicators and system boundaries. Some studies consider only PCM-related costs, whereas others evaluate PCM together with insulation or other passive strategies, making direct comparison of PCM-specific economic benefits difficult. Similarly, environmental assessments are largely based on operational CO_2 or CO_2-equivalent reductions, while impacts associated with production, encapsulation, transportation, maintenance, replacement, and end-of-life are rarely included. These methodological differences limit both the comparability of studies and the interpretation of the overall sustainability performance of PCM applications.

Another major limitation is the strong reliance on numerical modeling and simulation. Although simulation enables rapid comparison of different climates and design scenarios, long-term validation under real building conditions remains limited. For example, M'hamdi et al. (2022), Jaradat et al. (2024), and Sun et al. (2024) mainly rely on numerical analyses, whereas Dewi et al. (2026) conducted full-scale measurements but limited the monitoring period to two consecutive 24-hour cycles. Longer-term field studies covering different seasons and operating conditions are therefore needed to assess not only short-term thermal behavior but also changes in PCM performance over time. Particular attention should be given to repeated phase-change cycles, encapsulation durability, maintenance requirements, replacement needs, and possible performance degradation.

The interaction among PCM design variables also remains insufficiently explored. The reviewed studies show that phase-change temperature, PCM thickness, location within the wall, façade orientation, and wall construction can all influence performance, yet these parameters are often examined individually or in limited combinations. More comprehensive multivariable and multi-objective approaches are required to evaluate their combined effects and the trade-offs among energy, economic, and environmental outcomes. Yang et al. (2023) and Jaradat et al. (2024) provide examples of more integrated approaches in this respect.

The applicability of PCM solutions is also highly context dependent. Building typology, wall construction, climate, material costs, energy prices, and financial incentives vary substantially among studies. M'hamdi et al. (2022) demonstrated the influence of wall systems on PCM performance, while Acuña-Díaz et al. (2022) showed that economic feasibility can change considerably depending on PCM cost and investment support. Therefore, PCM solutions should not be transferred directly between buildings or climatic regions without reassessment under local design and economic conditions.

Future studies should address these limitations by adopting clearer and more consistent system boundaries and performance indicators. Energy performance could be reported using measures such as $kWh/m^2 \cdot y$ or percentage savings, economic performance through initial cost, life-cycle cost, and payback period, and environmental performance through indicators such as kg CO_2e/m^2 or kg CO_2e/y. Where PCM is combined with other passive measures, the contribution of the PCM wall application should be reported separately. Integrating energy analysis with life-cycle costing and life-cycle assessment would also allow operational benefits to be evaluated together with economic and environmental impacts over the full service life.

Another important research direction is the development of decision-support approaches capable of evaluating PCM alternatives across all three 3E dimensions. Multi-criteria decision-making, weighting, sensitivity analysis, scenario analysis, and multi-objective optimization can help compare alternatives under different design priorities while accounting for climate, building characteristics, PCM type, phase-change temperature, thickness, wall position, cost, and environmental impact. Such approaches could provide a more transparent and traceable basis for selecting context-specific PCM solutions.

Bio-based and low-environmental-impact PCMs also represent a promising research area. However, their environmental advantages should not be assumed solely from their renewable or bio-based origin. Life-cycle assessments covering production, encapsulation, transportation, use, maintenance, and end-of-life are necessary to determine whether these benefits are maintained at the system level.

4. CONCLUSIONS

This study examines passive phase change materials (PCMs) used in residential walls from a 3E perspective, considering energy, economic, and environmental performance together for the period 2015–2025. Analysis of 55 studies selected using the PRISMA approach revealed that energy performance is clearly dominant in literature, while economic and especially environmental assessments remain more limited. Thirty-one of the studies examined focused solely on the energy dimension, while only ten addressed all three 3E dimensions together. This distribution indicates that the integrated sustainability performance of PCM applications has not yet become the primary assessment approach in literature.

In terms of energy and thermal performance, PCMs hold significant potential for reducing heating and cooling requirements and limiting indoor temperature fluctuations in residential walls. However, this performance is not dependent on a single material property. Interactions between phase change temperature, PCM thickness, location within the wall, facade orientation, wall construction, and climatic conditions significantly alter the results. Therefore, it is not possible to speak of a universal optimum PCM configuration that can be transferred to different building and climatic conditions.

Similarly, high energy savings do not directly define the most economically or environmentally optimal solution. Economic feasibility varies significantly depending on PCM cost, local energy prices, climate conditions, and the limitations of the system used in the assessment. Environmental assessments, on the other hand, largely focus on operational emission reductions due to energy savings during the use phase. The limited scope of lifecycle assessments, encompassing production, encapsulation, transportation, maintenance, refurbishment, and end-of-life, makes it difficult to determine the total environmental impact of PCM applications.

Based on these findings, this study develops an evidence-supported decision framework for the design and integrated 3E assessment of passive PCM wall applications. The proposed framework is based on defining the application context, determining the PCM design configuration, evaluating energy and thermal performance as the initial technical suitability stage, examining economic and environmental consequences in parallel, and integrating the three performance dimensions under an integrated 3E assessment. Adopting a context-specific and iterative decision logic instead of fixed numerical thresholds allows the framework to be adapted to different climate and building conditions.

Future research should prioritize the use of common performance indicators and explicit system boundaries, differentiating PCM wall-specific results from other building measures, and validating numerical models with long-term field data. Furthermore, multivariate and multi-objective approaches that consider phase change temperature, thickness, wall location, facade orientation, and building characteristics together can contribute to a more realistic assessment of trade-offs between energy, economic, and environmental performance. These findings also provide a foundation for developing multi-criteria decision support tools that can evaluate context-specific PCM alternatives under energy, economic, and environmental metrics.

In conclusion, evaluating the potential of PCMs in residential walls solely through the lens of energy savings is insufficient. Determining a suitable PCM solution requires considering the design context along with energy/thermal performance, economic feasibility, and environmental impact. The 3E decision framework developed in this study brings these dimensions together in a single evaluation process, providing a structured foundation for a more holistic and contextually sensitive comparison of PCM wall alternatives.

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