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Bibliometric Analysis Of Using Phase Change Materials For Energy Efficient Air Conditioning Systems

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ABSTRACT

This bibliometric study draws the attention to the worldwide research trends on application of Phase Change Materials (PCMs) for air-conditioning and thermal energy storage systems. The analysis indicates that the number of scientific publications has grown substantially in the past decade, which is in line with the increasing global interest in Energy-conserving and energy sustainable building technologies. The results showed that India had the highest research productivity (53 publications), followed by China (41 publications), Germany (29 publications) and Australia (24 publications) and Italy (18 publications). The results also show that there is a good synergy in science between research institutes in Asia and Europe. The most fruitful institutions found were the University of Melbourne, University of Padova, and Shanghai University of Electric Power. As for the number of citations, the study published by Sharma in Energy Conversion and Management is the most often cited paper, receiving 746 citations. Furthermore, influential researchers like Aye Lu, Brey Stefan and Mousavi Seyed Mostafa have contributed significantly in the field of this research. Thermal energy storage systems, phase change materials in air-conditioning applications, energy efficiency and sustainability, thermal comfort in buildings were the four main thematic clusters identified using keyword co-occurrence analysis in VOSviewer. Overall, the results point to the multidisciplinary character and the development of research on PCMs, which is gaining in significance in the field of building technology and sustainable energy.

1. Introduction

Climate change remains a major obstacle in spite of tremendous efforts. The HVAC (heating, ventilation, air conditioning, and refrigeration) system is one field that has continuously drawn research interest [1]. Since fossil fuels are the primary source of energy produced worldwide, the Kyoto Protocol in 1997 acknowledged the existence of global warming and led to a global commitment to reduce greenhouse gas emissions, but it did not identify anthropogenic CO_2 as the primary cause [2].

Additionally, the December 2015 Paris Agreement outlined steps to keep the average global temperature increase by 2100 to less than 2 °C over pre-industrial levels [3]. Systems for thermal energy storage (TES) are being researched extensively as a practical way to store solar energy during the day and use it at night or on

cloudy days [4]. Physical storage and chemical storage are the two primary categories into which recent developments in TES systems fall. Chemical storage relies heavily on reversible chemical reactions, whereas physical storage relies on heat transfer mechanisms. Both sensible and latent techniques can be used to store thermal energy in physical storage [5].

Combining air conditioning with thermal energy storage (TES) is a cutting-edge technology that can reduce environmental issues and increase energy efficiency. TES systems can reduce the energy demands, which fluctuate on a daily, weekly, and seasonal basis. TES can reduce demand during peak hours by producing cold energy during the nighttime or when environmental conditions are more favorable. Furthermore, when there is a delay between supply and consumption, TES aids in balancing consumption [6]. Using TES in an air conditioning system has the benefit of improving overall system efficiency and reliability, which can lead to lower operating costs and less environmental pollution. [7].

Additionally, it is mentioned as a potential substitute for tropical climates [8]. In Latent Heat Thermal Energy Storage (LHTES) units, PCMs serve as a compact medium for energy absorption and release [9]. In charge and discharge TES systems, the phase transition of PCMs—which takes place from the solid or liquid phase to the others—is crucial [5]. PCMs are made of a variety of materials, including eutectics, inorganic, and organic materials with melting points ranging from -100 to 1000 °C. The melting point has a significant impact on PCM performance. Low, middle, and high melting temperatures are the three categories into which PCMs are separated in this context [4].

The low melting temperature, according to Huang et al. [10], is up to 120 °C, the middle melting temperature is between 120 °C and 300 °C, and the high melting temperature is above 300 °C. PCMs have many uses in solar systems, energy-saving buildings, lithium-ion battery cooling, and effective electronic cooling systems because of their great advantages for thermal energy storage [11]. The ability of the phase change material (PCM) to store cold energy and then release it when needed is a crucial consideration when evaluating recent studies of TES applications with air conditioning systems [12]. This decision needs to be informed by factors like thermal amplitude, for instance, and the site where the system will be installed.

Several studies were created to assess PCM with an emphasis on its use in air conditioning systems to improve efficiency and conserve energy, resulting in more linear consumption after the use of TES eliminates the day's peak hours. There are benefits to using bibliometric analysis to forecast future trends in various fields. It is frequently used to examine the state of research, future directions, and trends in development within particular fields. One of the primary ways that scientific and technological advancements are expressed is through papers.

A quantitative analysis technique called bibliometrics uses the outward features of scientific literature as study subjects. Depending on the various ways that empirical results are displayed, it can be separated into literature statistical analysis, mathematical model analysis, system analysis, matrix analysis, network analysis, and so forth. Although several previous studies discussed thermal energy storage (TES) and phase change materials (PCMs), most of them focused mainly on experimental investigations, material properties, or general energy applications. However, limited bibliometric studies have comprehensively analyzed the global research landscape specifically related to PCM applications in air conditioning and energy-efficient building systems.

The research gap addressed in this study lies in the absence of an integrated bibliometric evaluation that simultaneously investigates:

1. publication growth trends over the last decade,
2. international research collaborations,
3. leading countries, institutions, and authors,
4. citation impact and influential publications,
5. thematic evolution and emerging research directions related to PCM-based air conditioning systems.

In addition, previous bibliometric analyses often provided descriptive statistical results without linking them to engineering applications and sustainability perspectives. Therefore, the present study contributes by combining bibliometric mapping with technical interpretation related to thermal energy storage performance, Heating, Ventilation, and Air Conditioning (HVAC) energy efficiency, and sustainable cooling technologies.

The originality of this work is further represented by:

1. Focusing specifically on PCM applications in air conditioning systems rather than general PCM research.
2. Identifying emerging themes and future research directions using keyword co-occurrence and thematic cluster analysis.
3. Providing a comprehensive overview of global scientific development in PCM-based cooling technologies during the last ten years.
4. Connecting bibliometric findings with environmental and energy-efficiency objectives in modern HVAC systems.

2. Research Objectives

The main objectives of the present study are to summarize comprehensively the thermal energy storage and application of phase change materials (PCM) studies

performed in the past decade in air conditioning and building energy systems. It aims to find out the most productive countries, organizations and authors to show national research leadership, cooperation networks and to analyze the publication trends to understand the evolution and development of this area of study. It also aims to use citation analysis from both local and international sources to look into the importance of publications and references in science.
This will enable us to identify the most significant works that have contributed to the field. The study also analyzes the transitions of research fields based on the keyword occurrences, co-occurrence networks and thematic clusters. and the analysis focuses on the emerging topics and the areas of development identified by the researchers in the corresponding studies. Finally, research will elaborate on the aims and achievements of energy storage using PCM, providing some useful recommendations and development ideas on environmentally friendly energy systems.

3. Research Methodology

The research work of the scholars is conducted through bibliometric analysis. It provides insights into the worldwide research trends, the main contributors and the thematic framework for PCMs in air conditioning and thermal storage. This methodology is divided into four steps, which are: the collection of data, the removal of data, the mapping of bibliometrics, and the interpretation. The research framework design is in the table below, Table 1, as the reference.

3.1 Data Collection

The bibliographic data were retrieved from the Scopus database, which is considered one of the largest and most reliable databases for peer-reviewed scientific literature. Scopus provides comprehensive coverage of journal articles, conference proceedings, and other scholarly publications with high indexing accuracy and citation reliability, making it highly suitable for bibliometric investigations. The following search query was employed to identify publications relevant to the use of PCMs in energy-efficient air conditioning systems:

(Using Phase Change Materials For Energy Efficient A ir Conditioning Systems) AND PUBYEAR > 2013 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp")) AND (LIMIT-TO (LANGUAGE , "English"))

The search strategy was specifically designed to ensure the relevance and quality of the retrieved documents. The use of the TITLE-ABS-KEY function restricts the search to document titles, abstracts, and author keywords, thereby increasing the direct relevance of the retrieved studies to the research topic. The publication period was limited to 2014–2024 in order to capture contemporary developments and recent technological advancements in eco-friendly thermal management and thermal energy storage systems.

Only journal articles and conference papers were included in the dataset through the document type filters DOCTYPE = ar and DOCTYPE = cp. These publication types were selected because they typically contain validated experimental, numerical, and analytical findings that contribute significantly to the advancement of scientific knowledge in the field.
To ensure consistency and reliability, only English-language publications were considered. The final dataset was exported in BibTeX format and included complete bibliographic information such as authors, titles, affiliations, abstracts, keywords, citations, and references for subsequent bibliometric analysis.

3.2 Data Refinement and Preprocessing

Following initial extraction, duplicates, unrelated subjects, and incomplete records (such as "undefined" references lacking bibliographic information) were eliminated from the dataset.

To guarantee uniformity and raise the precision of co-occurrence analysis, keywords were standardized by combining related terms like "PCM" and "Phase Change Material (PCM)". The finished dataset served as a representation of the main body of research on PCM in building and energy systems.

3.3 Bibliometric Mapping and Analysis

The bibliometric analysis was conducted using several complementary quantitative techniques to evaluate both research performance and the intellectual structure of the field. Performance analysis was employed to identify the most influential countries, institutions, authors, and publications based on publication productivity and citation impact. Citation analysis was further utilized to determine highly cited studies and seminal references that have significantly contributed to the development of PCM research in cooling and thermal management applications.
In addition, keyword co-occurrence analysis was performed using VOSviewer software to identify the major research themes, emerging topics, and conceptual relationships within the literature. Frequently occurring keywords were visualized in clustered network maps,

enabling the identification of dominant and evolving research directions.
Moreover, co-authorship and co-citation network analyses were conducted to explore patterns of scientific collaboration and knowledge dissemination among

researchers and institutions. In these visual networks, node size represents the frequency of occurrence or citation, while link strength reflects the intensity of relationships between items. These indicators provide insights into the collaborative structure and academic influence within the research field.

3.4 **Visualization and Interpretation**

VOSviewer and Bibliometrix (an R package) were used to analyze and visualize the processed data. Clusters of related research topics were identified using the network maps; these clusters were represented by various colors. The intellectual structure of PCM research and its interdisciplinary development were clearly understood thanks to this clustering structure.

4. **Results**

The dataset includes bibliometric data from 2014 to 2024 about publications that talk about using Phase Change Materials (PCMs) in air conditioning systems that save energy. These were found in Scopus.

4.1 **Main Information about the Data**

Table (1) summarizes the main characteristics of the bibliometric dataset. A total of 84 publications were retrieved from 42 scientific sources, including journal articles and conference papers published between 2014 and 2024. The annual growth rate reached 18.04%, indicating a rapidly increasing research interest in PCM-integrated air conditioning systems.

The average citation rate was 22.82 citations per document, reflecting the scientific importance of the field and the growing academic attention toward green cooling solutions technologies. Moreover, the dataset included 315 authors with an average of 3.99 co-authors per document, demonstrating the collaborative nature of PCM-related research. International co-authorship represented 32.14% of the total publications, confirming the global and interdisciplinary characteristics of research activities in thermal energy storage and energy-efficient HVAC systems.

The dataset also contained 860 Keywords Plus and 272 author keywords, indicating the diversity of research topics associated with PCM applications, including thermal energy storage, building energy performance, cooling systems, and sustainable energy technologies.

Table 1: Main Information about the Data.

Results	Description
Main Information About Data	
2014:2024	Timespan
42	Sources (Journals, Books, Etc.)
84	Documents
18.04	Annual Growth Rate %
4.48	Document Average Age
22.82	Average Citations Per Doc
721	References
Document Contents	
860	Keywords Plus (Id)
272	Author's Keywords (De)
Authors	
315	Authors
3	Authors Of Single-Authored Docs
Authors Collaboration	
3	Single-Authored Docs
3.99	Co-Authors Per Doc
32.14	International Co-Authorships %
Document Types	
53	Article
31	Conference Paper

4.2 **Annual Scientific Production**

Figure (1) illustrates the annual scientific production related to PCM applications in air conditioning systems during the period from 2014 to 2024. The publication trend demonstrates a gradual increase over time, with noticeable growth after 2020. The number of publications remained relatively limited between 2014 and 2016, reflecting the early development stage of PCM applications in cooling technologies. However, research productivity increased significantly after 2017 due to the growing global interest in energy-efficient buildings and thermal energy storage systems.

The highest publication output was recorded in 2024, indicating the increasing research attention toward PCM-based cooling technologies and their role in improving HVAC energy efficiency and reducing building energy consumption. Overall, the trend confirms that PCM-integrated air conditioning systems have become an important and rapidly expanding research area within sustainable energy and building technologies.

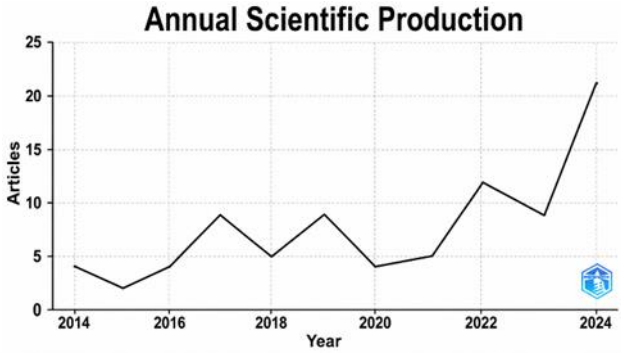
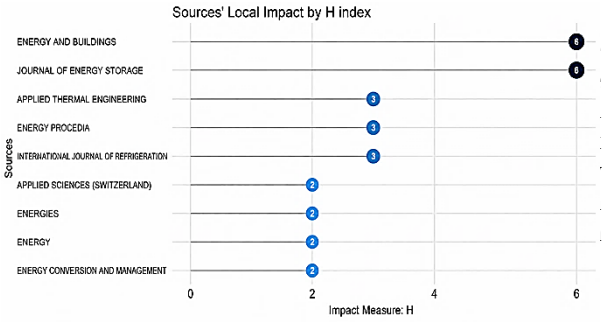


Figure 1. Annual Scientific Production

4.3 **Sources and Articles Analysis**



Other important journals included Applied Thermal Engineering, Energy Conversion and Management, Energies, and the International Journal of Refrigeration. The diversity of publication sources indicates the interdisciplinary nature of PCM research, which combines thermal engineering, building science, materials engineering, and energy management.

Table 2. Sources and Articles Data.

Articles	Sources
7	Journal Of Energy Storage
6	Energy And Buildings
3	Applied Thermal Engineering
3	Energies
3	Energy Conversion and Management
3	Energy Procedia
3	International Journal of Refrigeration
3	Materials Today: Proceedings
2	Applied Sciences (Switzerland)

*4.3.2 **Journal Impact Analysis***

Figure (2) illustrates the local impact of the major journals based on the H-index. Energy and Buildings and the Journal of Energy Storage achieved the highest H-index value of 6, indicating their strong academic influence and citation performance within the research field. Applied Thermal Engineering, Energy Procedia, and the International Journal of Refrigeration also demonstrated moderate citation impact, highlighting their important contribution to research on heat transfer and thermal management systems. Overall, the results indicate that research related to PCM applications in HVAC systems is concentrated within a limited number of highly influential journals specializing in energy storage and building energy technologies.

Figure 2. The relative scholarly influence of the primary journals

*4.3.3 **Source Production Over Time***

Figure (3) presents the publication trends of the leading journals between 2014 and 2024. The results reveal a significant increase in publication activity after 2021, particularly in the Journal of Energy Storage and Energy and Buildings. This trend reflects the increasing scientific interest in Low-carbon cooling solutions technologies and the growing importance of PCM applications in building energy efficiency. In addition, newer journals such as Applied Sciences (Switzerland) and Energies started to contribute more actively after 2020, indicating the expansion of PCM research into broader engineering and sustainability disciplines.

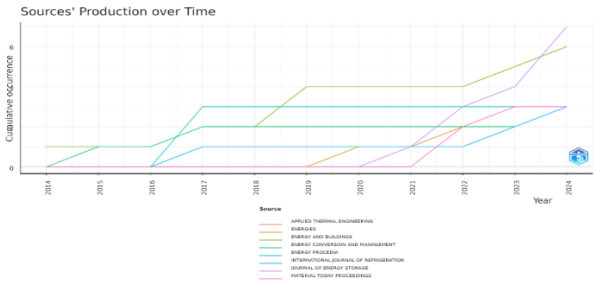


Figure 3. The cumulative publication trends of the top journals.

4.4 **Authors and Collaboration Analysis**

Figure (4) identifies the most productive authors in the field of PCM-based air conditioning systems. Several researchers, including Aye, Lu, Brey, Stefan, Mousavi, Seyedmostafa Mostafa, and Rismanchi, Behzad, contributed the highest number of publications. The results indicate that the research field is currently dominated by a relatively limited number of specialized researchers and collaborative research groups working on thermal energy storage and HVAC optimization.

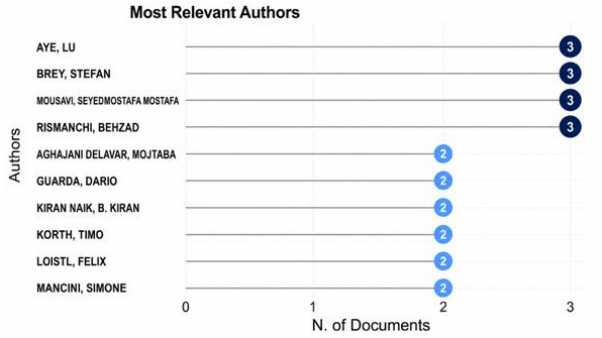


Figure 4. Most Relevant Authors.

Figure (5) further demonstrates the evolution of authors' production over time. Most leading authors showed increased publication activity after 2020, reflecting the rapid growth of scientific interest in PCM-integrated cooling systems. The citation performance also indicates that recent publications have attracted considerable academic attention, emphasizing the increasing relevance of PCM technologies in sustainable building applications.

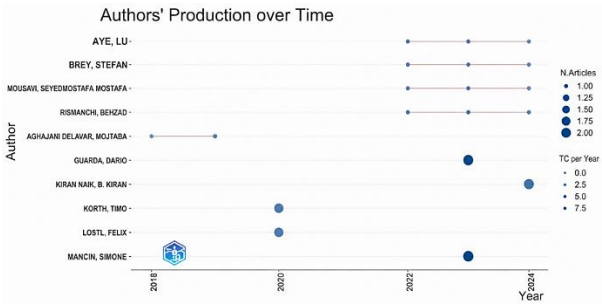


Figure 5. Authors' Production over Time.

4.5 **Institutional and Country Contributions**

Figure (6) presents the institutions with the highest research productivity in the field. The University of Melbourne (Australia) and Università degli Studi di Padova (Italy) ranked as the most productive institutions, each contributing nine publications. Other active institutions included Shanghai University of Electric Power, Shenyang Jianzhu University, and Aarupadai Veedu Institute of Technology. The results demonstrate that research on PCM applications has become internationally distributed across institutions specializing in thermal engineering, building technologies, and sustainable energy systems.

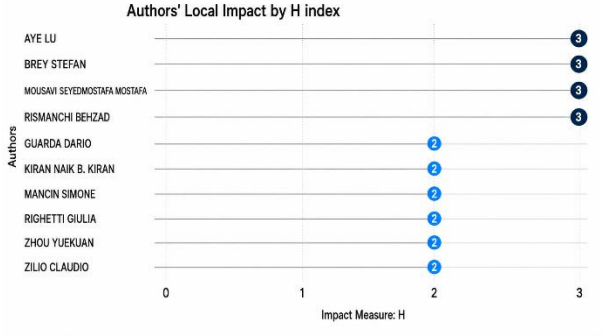


Figure 6. Authors' Local Impact by H-index.

Figure (7) illustrates the institutional production over time. Most institutions showed rapid publication growth after 2021, indicating increasing international collaboration and institutional investment in thermal energy storage technologies and energy-efficient cooling systems.

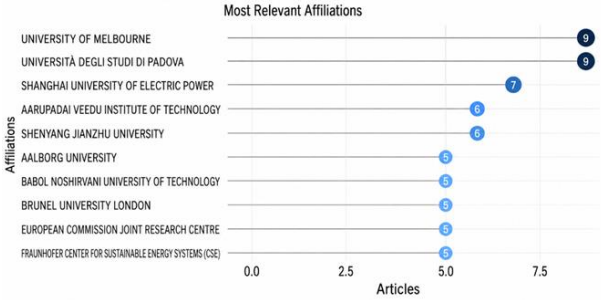


Figure 7. The Institutions with the Most Publications.

Table (3) and Figure (8) present the geographical distribution of scientific production. India ranked first with 53 publications, followed by China with 41 publications. Germany, Australia, and the United States also demonstrated strong research contributions. The dominance of India and China reflects the increasing research interest in Sustainable air conditioning technologies and renewable energy systems within rapidly developing economies. Meanwhile, Australia and several European countries demonstrated strong institutional influence and consistent research quality. The results also indicate a clear globalization of PCM-related research, with growing international collaboration among countries working on thermal management, energy efficiency, and sustainable building technologies.

Table 3. The Frequency of Publications.

Country	Freq
India	53
China	41
Germany	29
Australia	24
USA	23
Italy	20
Denmark	16
France	13
UK	12
Canada	10

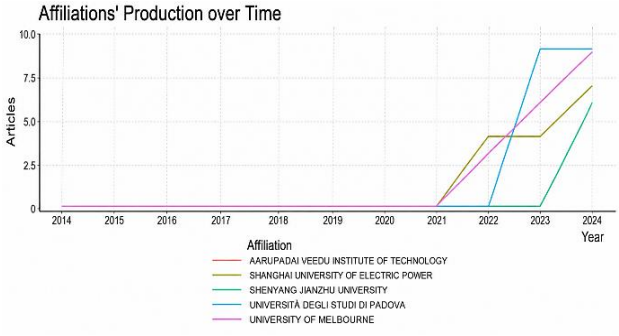


Figure 8. Affiliations' Production over Time.

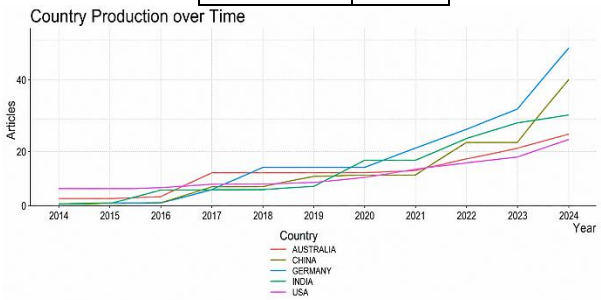


Figure 9. Country Production over Time

Table 4. The Top Ten Globally Cited Papers.

4.6 **Citation Analysis**

4.6.1 ***Globally Cited Documents***

Figure (9) and Table (4) present the most globally cited publications within the dataset. Sharma (2015), published in Energy Conversion and Management, represented the most influential paper with 746 citations and an average of 67.82 citations per year. Other highly cited studies included Fiorentini (2017), Xu (2017), and Zhou (2022), indicating the strong influence of research related to thermal energy storage, building cooling systems, and PCM integration strategies. The citation distribution demonstrates that a limited number of foundational studies significantly shaped the development of PCM research in HVAC applications. Furthermore, recent publications published after 2021 achieved high normalized citation scores, confirming the increasing scientific attention toward advanced PCM cooling technologies.

Normalized TC	TC per Year	Total Citations	DOI	Paper
2.00	67.82	746	10.1016/j.enconman.2015.01.084	Sharma, 2015, Energy Convers. Manag. [13]
3.12	12.89	116	10.1016/j.apenergy.2016.11.041	Fiorentini, 2017, Appl. Energy [14]
1.61	6.67	60	10.1016/j.egypro.2017.03.898	Xu, 2017, Energy Procedia [15]
2.91	14.50	58	10.1016/j.renene.2022.08.128	Zhou, 2022, Renew. Energy [16]
1.34	5.56	50	10.1016/j.enconman.2017.07.043	Akeiber, 2017, Energy Convers. Manag. [17]
1.96	4.17	50	10.1016/j.enbuild.2014.02.069	Bruno, 2014, Energy Build. [18]
2.99	9.20	46	10.1016/j.ijft.2020.100059	Rashad, 2021, Int. J. Thermofluids [19]
2.40	6.14	43	10.3390/APP9132726	Mousavi Ajarostaghi, 2019, Appl. Sci. [20]
2.40	6.14	43	10.5109/2321009	Byrne, 2019, Evergreen [21]
2.11	10.50	42	10.1016/j.matpr.2022.02.231	Hekimoğlu, 2022, Mater. Today: Proc. [22]

4.6.2 ***Locally Cited Documents***

Table (5) and Figure (10) illustrate the most locally cited documents within the bibliometric dataset. Mousavi (2022) achieved the highest local citation count, indicating its importance within the selected research collection. Most other locally cited papers were published during 2024, which explains the relatively low local citation counts due to the limited time available for citation accumulation. The findings suggest that PCM research in air conditioning systems is still evolving rapidly and has not yet developed a fully interconnected citation network.

Table 5. Most Local Cited Documents

Document	DOI	Year	Local Citations	Global Citations	Normalized Global Citations
Mousavi, 2022, Energy Reports [33]	10.1016/j.egyr.2022.01.032	2022	1	24	1.21
Rivera, 2024, J. Energy Storage [34]	10.1016/j.est.2024.114235	2024	0	6	1.03
Priyadarshi, 2024, Energy Convers. Manag. [35]	10.1016/j.enconman.2024.119042	2024	0	2	0.34
Santos, 2024, Processes [36]	10.3390/pr12112388	2024	0	0	0.00
Roy, 2024, J. Build. Eng. [37]	10.1016/j.jobe.2024.110250	2024	0	7	1.20
Odufuwa, 2024, J. Energy Storage [38]	10.1016/j.est.2024.112547	2024	0	10	1.72
Mousavi, 2024, Energy Build. [39]	10.1016/j.enbuild.2024.114126	2024	0	7	1.20
Lin, 2024, Int. J. Refrig. [40]	10.1016/j.ijrefrig.2024.02.010	2024	0	4	0.69
Xu, 2024, Sep. Purif. Technol. [41]	10.1016/j.seppur.2023.125888	2024	0	6	1.03
Miccoli, 2024, Energies [42]	10.3390/en17051118	2024	0	2	0.34

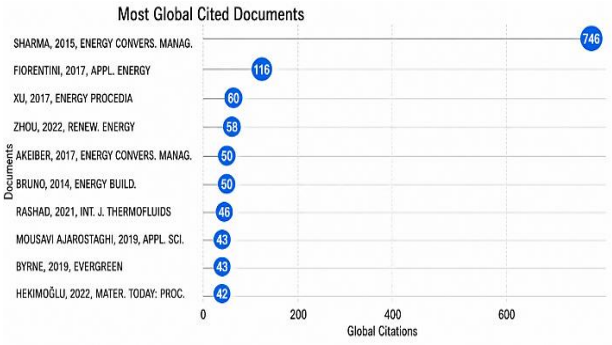


Figure 10. Most Global Cited Documents

4.6.3 ***Most Influential References***

Table (6) identifies the most frequently cited references in the reviewed literature. Sharma (2009), entitled "Review on Thermal Energy Storage with Phase Change

Materials and Applications," represented the most influential reference with five citations. Several review studies related to PCM applications in buildings, thermal energy storage, and HVAC systems were also highly cited, including works by Akeiber (2016), Al-Abidi (2012), Li (2012), and Souayfane (2016). These references established the theoretical and technical foundations of PCM research and continue to guide current developments in sustainable cooling technologies and latent heat storage systems.

Table 1: Most Commonly Cited.

Citations	Cited References
5	Sharma, Atul Kumar, Review On Thermal Energy Storage With Phase Change Materials And Applications, Renewable And Sustainable Energy Reviews, 13, 2, Pp. 318-345, (2009) [23]
4	Heat And Cold Storage With Pcm An Up To Date Introduction Into Basics And Applications, (2008)
4	PCM Enhanced Building Components, (2015)
3	Akeiber, Hussein J., A Review On Phase Change Material (Pcm) For Sustainable Passive Cooling In Building Envelopes, Renewable And Sustainable Energy Reviews, 60, Pp. 1470-1497, (2016) [24]
3	Al-Abidi, Abduljalil A., Review Of Thermal Energy Storage For Air Conditioning Systems, Renewable And Sustainable Energy Reviews, 16, 8, Pp. 5802-5819, (2012) [25]
3	Li, Gang, Review Of Cold Storage Materials For Air Conditioning Application, International Journal Of Refrigeration, 35, 8, Pp. 2053-2077, (2012) [26]
3	Nazir, Hassan, Recent Developments In Phase Change Materials For Energy Storage Applications: A Review, International Journal Of Heat And Mass Transfer, 129, Pp. 491-523, (2019) [27]
3	Souayfane, Farah, Phase Change Materials (Pcm) For Cooling Applications In Buildings: A Review, Energy And Buildings, 129, Pp. 396-431, (2016) [28]

4.7 **Keyword and Research Trend Analysis**

4.7.1 ***Most Frequent Keywords***

Figure (11) presents the most frequently occurring keywords in the dataset. The most dominant keywords were "air conditioning" and "phase change materials," indicating that the primary focus of current research is the integration of PCMs into HVAC systems to improve energy efficiency and thermal performance. Other important keywords included "heat storage," "energy efficiency," "thermal energy storage," and "cooling systems," emphasizing the strong relationship between PCM technologies and sustainable energy applications in buildings.

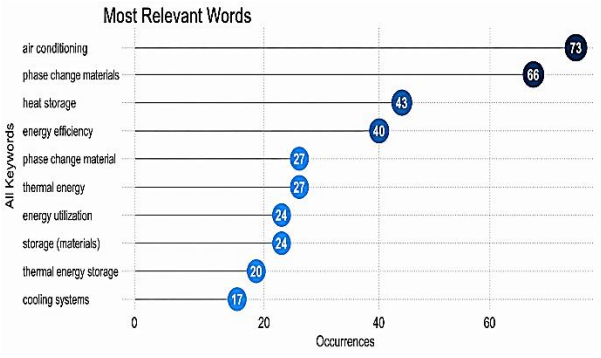


Figure 11. Most Relevant Keywords

4.7.2 ***Keyword Co-occurrence Network***

Figure (12) illustrates the keyword co-occurrence network generated using VOSviewer. The analysis identified four major thematic clusters associated with PCM research. The first cluster focused on cooling technologies and refrigeration systems, while the second cluster concentrated on thermal energy storage and latent heat management. The third cluster addressed sustainable building applications and energy conservation, whereas the fourth cluster focused on thermal comfort and energy utilization efficiency. The strong relationship between the keywords "air conditioning" and "phase change materials" confirms that current research is primarily directed toward improving HVAC performance through latent heat thermal energy storage technologies.

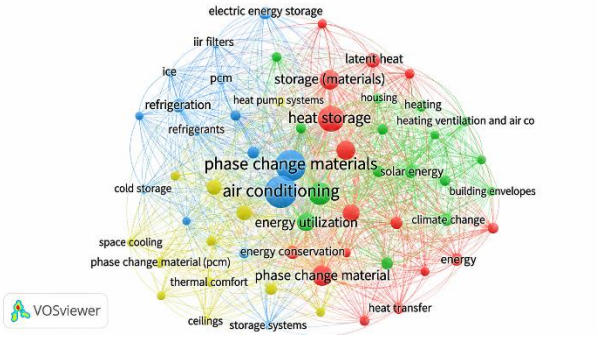


Figure 12. The keyword co-occurrence network

5. Discussion of Publication Trends and Research Development

The number of publications has noticeably increased in the past decade, indicating the global interest in achieving energy reduction and increasing the efficiency of HVAC systems by employing thermal energy storage technologies. This increase is closely linked to international environmental policies and sustainability objectives that seek to lower greenhouse gas (GHG) emissions and improve building energy efficiency. Therefore, research activities for the application of PCM for air conditioner have been increased because of the growing requirement of Low-energy cooling system, especially in hot climate countries.

The bibliometric analysis further shows that the countries with robust research infrastructure and high energy demand are predominant in the field. Investments in renewable energy technologies, sustainable buildings and smart energy systems are the main investments of the countries. Furthermore, inter-university and inter-research centers cooperation has been an important way to enhance the productivity and dissemination of scientific knowledge in the international community.

The results of the citation analysis indicate that the cited publications are mostly related to latent heat thermal energy storage, PCM thermal properties and building cooling applications. It means that PCM application in HVAC systems is a potential option for reducing peak loads and energy management. These publications have had a significant impact on the development of research into better thermal performance, storage capacity and system reliability.

The keyword co-occurrence analysis shows a progressive shift in the field of study from basic characterization of PCM materials to more practical engineering applications and designs that focus on sustainability. In recent years new and emerging topics like energy-efficient buildings, hybrid cooling systems, the integration of renewable energy and smart thermal management have become increasingly relevant. The change demonstrates that the focus of ongoing research is shifting from theoretical studies to practical implementation and environmental uses.

In addition, the analysis reveals that by storing cooling energy during off-peak hours and releasing it during peak hours, PCM-based thermal energy storage can help to reduce electricity usage during peak demand hours. This method optimizes the efficiency of air conditioning units and is crucial for the implementation of sustainable energy use in modern buildings. All in all, the results support that PCM technologies have gained significance as a research field in sustainable HVAC engineering, as they offer the potential of energy saving, environmental protection and thermal comfort improvement.

6. Practical Interpretation and Real-World Applications of the Results

The bibliometric results obtained show that the use of PCM-based thermal energy storage technologies in air conditioning systems and buildings is a proven solution gaining more and more importance. This is not only because of the academic interest in the subject, but also because of the large need in the world to develop sustainable cooling technologies that can lower the consumption of electricity and greenhouse gases.

One of the most important applications of PCMs in the real world is peak load reduction in HVAC systems. When there is low electricity demand, particularly at night, a thermal store can be used within PCM which could be released during high demand periods of the day. This load shifting approach helps to ease the strain on electrical networks and decreases the operating expenses, especially in areas with significant cooling requirements and warm weather.

The results also show rising interest in incorporating PCM in building envelopes, walls, ceilings and ventilation systems. These applications not only increase the thermal stability of the interiors, but they also help to stabilize the temperature distribution, which has a direct influence on the thermal comfort of the occupants and on reducing the need for traditional air conditioning systems. This use is particularly essential in contemporary green buildings and energy-efficient construction works.

Moreover, the keyword analysis and thematic analysis indicate that the approach of integrating PCM technologies with renewable energy systems, such as solar cooling applications, are becoming prevalent. This integration helps to achieve more sustainable energy use, as it can store surplus heat and enhance the security of renewable cooling solutions.

Citation analysis also reveals that a considerable number of significant studies are dedicated to enhancing either the thermal conductivity or melting properties of PCM, or to enhancing the charging/discharging properties of PCM. These engineering challenges are directly related to the real operational efficiency of thermal storage systems. The increasing focus of scientific research on

the enhancement of PCM properties shows that practical challenges must be addressed and then commercial and industrial applications need to be considered.

The other significant practical implication is the contribution of PCM systems to international sustainability goals and reduction of carbon emissions. By integrating PCM into HVAC systems, significant contributions can be made toward environmental protection and long-term energy conservation strategies as buildings make up a significant portion of global energy consumption.

In general, the results demonstrate a clear linkage of the current research trends with real-world applications and engineering requirements, especially in the areas of sustainable buildings, smart energy management and environmentally friendly cooling technologies.

7. Engineering Analysis of Phase Change Materials Performance in HVAC Systems

The thermophysical properties of phase change materials (PCMs) play a significant role in determining the performance of PCMs in the field of air conditioning and thermal energy storage systems from an engineering point of view. The efficiency of energy storage and retrieval processes is determined significantly by a number of key parameters that can be influenced, including the melting temperature, latent heat capacity, thermal conductivity, density, and thermal stability. It is crucial to find the right type and amount of PCM for HVAC systems, depending on the specific temperature range the system will be used in, to achieve the desired thermal management and system efficiency.

The low thermal conductivity of most PCM materials is one of the major engineering issues that are reported in the literature and can be a limiting factor for the charging and discharging rate of stored thermal energy. To address this constraint, various enhancement strategies have been proposed such as the use of fins, heat exchangers, metal foams and nano-enhanced PCMs which are all designed to enhance the heat transfer performance and system responsiveness.

In real-world HVAC systems, the main advantage of using PCM-based thermal energy storage systems is their ability to shift peak loads by storing cooling energy when it is not needed and releasing it when it is. This operation can help reduce the load on the conventional air conditioners, and increases the efficiency of the system, thus reducing the operational energy cost. Besides, incorporating PCMs into the building components like walls, ceilings, and ventilation systems produces more stable indoor environments and less temperature variation, improving the thermal comfort of buildings.

In general, the engineering evaluation of PCM performance shows that a particular balance between the properties of the material, system design and operating conditions is required for effective use of PCM. It underscores the need for ongoing research to enhance the thermal properties of PCMs and ensure their effective incorporation into sustainable HVAC systems.

8. Summary of literature studies

1. Previous research on PCM applications with HVAC and cooling systems primarily centered on enhancing the thermal storage performance of PCMs in various buildings and cooling applications and decreasing the energy consumption of these systems.
2. Most of the published studies focused on the melting process and/or the charging cycle with lesser emphasis on both melting and solidification processes simultaneously.
3. The thermophysical properties of PCM and the study of general thermal performance analysis were a focus of several studies, but no study has concentrated on the combined effect of the airflow conditions and the geometric parameters on the heat transfer characteristics.
4. As per found literature, numerical and experimental studies are typically focused on the study of a specific geometric configuration, while very few studies have been carried out to investigate the effect of variable aspect ratio (AR) of the geometry on the thermal behavior of PCM during melting and freezing cycles.
5. In spite of the use of fin in many research work for heat transfer augmentation in PCM system, many previous studies were limited to simple fin design or only investigated the influence of the fin on the heat transfer without considering other parameters like the airflow velocity or the geometry of the enclosure.
6. In addition, the effect of the air velocity, aspect ratio and fin enhancement on the transient thermal response of PCM systems is not well explored, especially under the real cooling system conditions.
7. The steady state thermal performance indicators were also highlighted by most of the previous numerical study, and only few studies were carried out to get insight into the dynamic evolution of liquid fraction/ temperature distribution and phase transition behavior during charging and discharging.

9. Research Gap

1. Comprehensive numerical study of simultaneous influence of (VAV, different aspect ratios, fin enhancement techniques) in melting and solidification of PCM in cooling applications is still lacking.
2. Detailed CFD studies were performed to quantify the impact of these parameters on transient heat transfer enhancement and the evolution of the phase transition, but limited studies were undertaken that considered the coupled effects of these parameters.
3. Further, there has been a lack of attention to the comparison of the thermal response of the PCM under a variety of operational and geometric conditions in both melting and freezing.

10. Recommendations

1. Comprehensive numerical and experimental studies are recommended in future for the performance evaluation of PCM based cooling systems with respect to combined effect of flow velocity, aspect ratio (AR) and fin configuration of the cooling systems.
2. Researchers are urged to investigate both melting and solidification processes at the same time to have a realistic understanding of the thermal behavior of a PCM during charging and discharging processes.
3. The use of advanced CFD simulation techniques to study the transient heat transfer phenomena and trajectories such as temperature distribution, liquid fraction changes, and phase transition phenomena under various working conditions should be considered.
4. The study should be followed by optimization of enclosure's geometry and fin's arrangement to maximize heat transfer rates and improve the overall thermal efficiency of PCM integrated HVAC and cooling systems.
5. Further studies are suggested on modelling simulation of the coupled effect of geometric parameters and operating conditions, especially the coupled effect of air velocity and aspect ratio on the melting and freezing performance of the PCM.
6. The reliability and applicability of simulation results under practical engineering conditions are enhanced by the experimental validation of numerical models, as this is strongly recommended.
7. The future research works should be continued for advanced and composite PCMs with better thermophysical properties to improve the energy storage capacity of the system and its performance.
8. More efforts should be made to investigate HVAC and building cooling at realistic scales to assess the viability, energy savings and sustainability benefits of PCM systems.
9. For future plans of PCM Cooling System Study, Multi-objective optimization methods and intelligent control strategies might also be combined for better thermal management and minimizing energy consumption.
10. Last but not least, it is suggested that interdisciplinary cooperation among thermal engineering researchers, material science and sustainable building technology researchers will facilitate the rapid development of PCM-based thermal energy storage system.

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