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Research papers

A bibliometrics study of phase change materials (PCMs)

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ABSTRACT

Articles on phase change materials (PCMs) were subjected to a scientometric study to determine the leading organizations, nations, journals, and topic areas over the last four decades. According to the analysis, there were significantly more publications on PCM between 2011 and 2022. In terms of total publications and total citations, China, the US, and India were discovered to be the top three nations. The country with the most citations per article was Singapore. Considering the collaboration aspect, the research revealed that Saudi Arabia exhibited the most extensive level of international collaboration. Chinese Acad Sci, Xi An Jiao Tong Univ, Univ Lleida, South China Univ Technol, and Sichuan Univ ranked first through fifth in terms of total publications. The most scientific work was produced in the Energy & Fuels topic area of PCM, while China was more active in the Web of Science topic areas. The rise in PCM publications in recent years is indicative of the field's expanding significance and interest in energy storage and sustainable energy. The importance of a multidisciplinary approach to the subject of PCM is highlighted by the high level of cooperation among nations and institutions. Examining keyword trends from 1991 to 2022 shows a growth in the use of “Thermal conductivity” beginning in 1999, a steady mention of “Latent Heat Storage” after 2010, and a consistent usage of “Energy storage” since 2005.

1. Introduction

Phase change material (PCMs) absorb and release large amounts of latent heat by their physical state, typically between a solid and a liquid state [1]. The term “latent heat” refers to the energy absorbed or released during a phase change. For PCMs, this means the energy taken in during melting or given off during solidification. Unlike “sensible heat,” where temperature changes are evident (like water warming up), latent heat involves energy changes without a corresponding temperature change in the material. Some common examples of PCMs include paraffin waxes [2], salt hydrates [2], and eutectic mixtures [3]. PCMs have various applications, including building insulation [4,5], thermal energy storage systems [6,7], textiles [8], and food packaging [9].

The capacity of PCMs to store and release thermal energy makes them a vital tool in building design and construction. These materials are exploited in buildings in three primary ways: as building envelopes [4,10,11], in building architecture [5,12], and for thermal energy storage [6]. Initially, PCMs are used in building envelopes to regulate the inside temperature. Incorporating PCMs into walls, roofs, and windows helps maintain a constant temperature and reduce energy use. PCMs, assist in managing interior temperature by storing surplus heat during the day and releasing it at night, so minimizing the demand for air conditioning. This results in not only energy savings but also a more pleasant living environment [4,10,11,13].

PCMs offer both functional and aesthetic advantages in architectural designs. PCMs can absorb and release thermal energy, making them valuable for temperature regulation [5,12]. However, beyond this functional benefit, their malleability provides a unique design opportunity. Architects can mold PCM-infused materials into diverse shapes and textures, allowing for innovative design elements that are both visually captivating and thermally efficient. This fusion of form and function creates spaces that can be responsive to environmental conditions. For example, a PCM-infused wall might adapt its appearance based on ambient temperature, introducing an interactive and dynamic design aspect. As sustainability becomes a focal point in architecture, integrating PCMs offers a solution that marries aesthetics with energy

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efficiency. Through the incorporation of these materials, architects can craft buildings that are not only energy-smart but also design-forward, demonstrating that beauty and sustainability can coexist seamlessly in the built environment.

Finally, PCMs are employed for thermal energy storage in buildings. PCMs may store surplus energy from renewable sources, such as solar panels, by adding huge thermal storage systems inside buildings. This stored energy may subsequently be used during high energy demand, lowering fossil fuel dependency and contributing to a more sustainable energy system. In addition to reducing energy consumption, using PCMs for thermal energy storage in buildings helps stabilize the power system by smoothing out changes in energy demand. [6]. In summer, the coolness of the night can be stored to offset daytime cooling needs. This reduces HVAC energy consumption, fewer greenhouse gas emissions, and cost savings. Such systems also alleviate pressure on power grids, resulting in a more resilient energy infrastructure.

In building a sustainable future, energy storage plays a pivotal role by enabling the integration of renewable energy sources like solar and wind into the grid. It helps mitigate the intermittency of these sources, ensuring a consistent power supply. Additionally, large-scale energy storage systems, such as pumped hydro storage or grid-scale batteries, can stabilize energy demand and supply, thus reducing reliance on fossil fuels and decreasing greenhouse gas emissions. A sustainable energy storage future requires a holistic approach that balances technological innovation, responsible sourcing, and effective waste management, ultimately contributing to a cleaner and more resilient energy ecosystem.

Several excellent reviews analyzed these aspects of PCMs in buildings. Cui et al. [14] examined the use of PCMs in building construction. Paraffin was shown to be the most popular PCM utilized in structures in places between 25 and 60° north and 25 and 40° south. These ranges span parts of the Northern Hemisphere and Southern Hemisphere, respectively, pinpointing specific geographical areas for the study of PCMs in building construction. The melting point of organic PCMs may range from 19 °C to 29 °C, while the heat of fusion may range from 120 kJ/kg to 280 kJ/kg. The usage of PCMs in building construction shows the capacity to reduce air temperature by up to 4.2 °C [14] and peak heat flow by over 20 % with a maximum delay of 6 h.

Incorporating PCMs into building envelopes has been demonstrated to give considerable cooling and heating advantages, resulting in enhanced thermal comfort and decreased energy usage. Suresh et al. [4] studied the influence of PCMs on building envelopes, such as walls, roofs, ceilings, and windows, as well as the incorporating techniques for energy savings and financial advantages. The study found that micro/nanoencapsulation and form stabilization are more effective incorporation approaches than macro and impregnation. The study also determined that organic PCMs as core materials and inorganic PCMs as shell materials are excellent for microencapsulation, but shape-stabilized PCMs are more effective for building applications. The study also analyzed the closeness of the PCM layer to the heat source, and it was suggested that the PCM layer be situated around the middle of the wall or brick for increased thermal energy storage capacity and on the outside wall side for enhanced cooling performance [4].

The application of PCMs in building heating systems was also examined, emphasizing the usage of PCMs in solar chimneys, heat pumps, and electric heaters [11]. According to [11], using PCMs in roofs, ceilings, and walls could reduce heating demand, improve thermal comfort, and boost solar energy usage. However, further investigation is required to maximize the performance of these applications [11].

Future research in PCMs for building envelopes should explore optimized PCM types and integration methods, considering climate-specific requirements. Focus on scalability, long-term durability, and energy efficiency is crucial, ensuring cost-effective and sustainable solutions for enhanced thermal regulation and reduced energy consumption in buildings. Enhancing phase change parameters, suggesting novel optimization objectives, engaging in multi-objective optimization, utilizing inverse problem-driven approaches, refining heat transfer model precision, and agreements between experimental investigations and numerical simulations [13]. The use of PCMs in building construction has demonstrated promising results for enhancing energy efficiency and thermal comfort, making it an important topic for further research [13].

Using PCMs in building design can increase thermal energy storage and overall building efficiency. As mentioned, PCMs can be included in building envelopes such as walls, ceilings, and façade components, as well as active systems such as heat or cold storage mechanisms. Managing temperature and humidity with PCMs reduces energy consumption and building heating and cooling loads. PCMs can indirectly influence humidity by stabilizing temperatures and reducing moisture-related fluctuations, but direct humidity management usually requires additional strategies like ventilation or dehumidification. The low heat conductivity of PCMs might be a disadvantage in building applications. Heat conductivity, or thermal conductivity, is a material's ability to conduct or transfer heat. It describes how well a substance allows heat to flow through it. Encapsulation methods, such as micro or macro encapsulation, can enhance heat transfer and remove the restrictions of direct integration. The optimal PCM position and transition temperature are environment-dependent. Xiong et al. [12] reported that more research is required to make PCMs a cost-effective, practical, and dependable technology for passive and active building applications.

Polyurethane (PU) foam is employed as a technique to encapsulate PCMs. This encapsulation occurs either indirectly, within containers, or directly, through mixing into construction materials. These methods can be broadly categorized as two modes of incorporation. This study investigates the fabrication of PCM foam composites, conventional and innovative insulations, their application issues, and their possible use in the built environment as well as the possible hurdles and research possibilities for future progress [5].

Not only can buildings benefit from PCMs, but thermal energy storage (TES) is also another primary beneficiary of PCMs. TES is required to provide energy stability and consistency in various residential and industrial processes and power generation systems for sustainable energy solutions. Due to its high thermal storage capacity, simplicity with uncomplicated heat storage mechanism, and economic practicality, PCM-based latent heat TES technology is gaining favor. PCMs may be utilized for solar-thermal storage, electro-thermal storage, waste heat storage, and thermal regulation in TES systems [7]. Latent heat refers to the energy absorbed or released during a substance's phase change, such as from solid to liquid or liquid to gas, without changing its temperature. In energy storage, latent heat is harnessed using PCMs. These PCMs can store and release significant thermal energy as they undergo phase transitions. For instance, a PCM might melt, absorbing heat when the environment is warm, and then release this stored heat as it solidifies when the environment cools. This property of capturing and releasing energy via latent heat makes PCMs invaluable for efficient thermal energy storage applications.

Cascading PCMs involves using multiple phase change materials with different melting/freezing temperatures in layers to achieve extended and controlled thermal energy storage for varying temperature ranges. The usage of multiple or cascading PCMs in latent heat thermal energy storage (LHTES) systems is analyzed regarding their thermal behavior, heat transfer uniformity, and the influence of input parameters and confinement geometry [15].

Entropy dissipation theory is vital for PCMs because it provides a framework for understanding energy storage and release during phase transitions. It helps optimize the efficiency of PCMs in applications like thermal energy storage and passive cooling by quantifying the irreversibility and guiding design to minimize energy losses and enhance performance. Using the entropy dissipation theory or the exergy approach, the optimal values of PCMs and temperature for cascaded LHTES systems may be established. Nanoparticles are used in latent heat thermal energy storage (LHTES) to enhance the thermal conductivity of PCMs. PCMs typically have low thermal conductivity, which limits their charging and discharging rates. Introducing nanoparticles improves heat transfer, reduces the time for phase transition, and boosts the system's overall energy storage and release efficiency, making LHTES systems more effective [16].

Nanoparticles can enhance or compromise performance depending on the application and implementation. Potential issues include nanoparticle agglomeration, stability concerns, and altered material properties. Proper selection and handling can mitigate these concerns [17,18].

Carbon emissions can be controlled by transitioning to renewable energy sources, enhancing energy efficiency, and employing sustainable materials and technologies. Photovoltaic thermal (PVT) systems are hybrid technologies that combine photovoltaic (PV) and solar thermal processes. These systems simultaneously produce electricity and capture heat, improving overall energy utilization from the sun. PVT systems can be integrated with thermal energy storage using molten salts. Molten salts store excess heat generated by the PVT system, allowing for energy release during non-sunlight hours. Thermo-chemical energy storage involves reversible chemical reactions to store and release heat. Both molten salts and thermo-chemical methods can enhance the efficiency and reliability of PVT systems by ensuring a continuous energy supply, even when sunlight is not available.

Nano-dispersed PCMs offer potential for various applications, but their poor performance and lack of scientific understanding prevent their broad deployment. TES based on PCMs is significant for energy efficiency, peak load reduction, low carbon emissions, and sustainable development for building thermal management. PCM-based photovoltaic thermal systems, molten salts, and thermo-chemical energy storage methods for long-term storage are other feasible options, which demand further research [6].

PCMs, crucial for heating and cold storage, are seeing expanded use in refrigeration, from air conditioning to food freezing. CTES, or Cold Thermal Energy Storage, employs these PCMs, and its study categorizes them by applications: food packaging, transportation, commercial refrigeration, and more. Notably, while ice/water PCMs are predominant in air conditioning research, water-salt, and paraffin PCMs are gaining traction for food transport and packaging. As cold storage demonstrates the potential to manage peak refrigeration loads and serve as backup during blackouts, it is garnering more appeal in retail and industrial sectors. This surge in cold storage technology is what the scientific community is focusing on.

The demand for thermal comfort has surged due to challenging climates, a growing population, and enhanced living standards, leading to heightened energy use in air conditioning. By integrating PCM technology with heating/cooling setups, significant savings can be realized. Within air conditioning contexts, PCMs boost efficiency, curtail energy expenses, and reduce CO2 emissions. Active systems, characterized by their intricate designs, require thorough optimization and financial evaluations for successful market introduction, all with the goal of fostering sustainable zero-net-energy buildings.

Besides, PCMs are used for thermal energy storage in concentrated solar power applications at high temperatures. The characterization of high-temperature PCMs is appropriate for solar systems operating between 500 °C and 700 °C, and there are twelve unique PCM candidates including organic compounds like paraffins and fatty acids, inorganic substances such as salt hydrates and metals, eutectic mixtures like salt-salt and organic combinations, and bio-based options like vegetable oils and glycerol-based solutions. Each offers distinct thermal properties suitable for various applications. The thermophysical properties of PCMs, including phase change temperature, enthalpy, specific heat capacity, reaction type, thermal stability, and corrosion behavior, are crucial for their assessment. NaF-NaCl and KCl-NaCl-Na2CO3 have been shown to have the greatest latent heat storage capacity among PCMs. There are several readily accessible and affordable PCMs for thermal energy storage systems operating between 500 °C and 700 °C [19].

Utilizing PCMs and battery thermal management systems (BTMS) may successfully preserve the performance and lifespan of batteries. Regarding BTMS and PCMs, there is a need to increase the thermal conductivity of PCMs, making organic PCMs flame-resistant, strengthening the stability of PCMs, and developing hybrid cooling systems. Thermal conductivity is another essential parameter. It defines how quickly heat can be transferred through a material. For efficient PCMs, a higher thermal conductivity is desirable as it ensures rapid heat absorption or release, leading to faster phase changes and effective temperature regulation.

High thermal conductivity in PCMs ensures rapid heat transfer, promoting efficient energy storage and release, thus enhancing the performance of systems where PCMs are integrated. Without using PCMs, achieving efficient thermal energy storage and release becomes challenging. PCMs uniquely harness latent heat during phase changes, optimizing heat management in systems where consistent temperature control is essential. Carbon materials, when used as encapsulation or structural components, can enhance containment and potentially reduce leakage in various systems due to their inherent structural strength and chemical resistance.

Using carbon materials and metals can increase thermal conductivity and reduce leakage. While using inorganic PCMs with flame-retardant qualities and adding fillers with high thermal conductivity can improve the heat transfer capabilities of PCMs for BTMS [20,21]. The use of inorganic PCMs with flame-retardant properties, the addition of high thermal conductivity fillers, the improvement of PCM encapsulation, the development of PCMs with high thermal conductivity, and the investigation of PCM-based BTMS with low operating temperatures are key issues in need of future research [21].

PCM cooling systems are preferred over air-cooling and liquid-cooling systems due to their use of passive energy; solid- liquid PCMs such as paraffin are suitable for BTMS [22]. It is possible to increase heat conductivity by including thermally conductive materials, incorporating paraffin into metal foams, or embedding metal fins into paraffin. PCM-based BTMS has low carbon emissions, making it ecologically benign; nevertheless, further study is required into the manufacturing policy and control plan for PCMs [21]. Moreover, the cost-effectiveness of PCM-based EVs relative to traditional internal combustion engines must be investigated [23].

Boosting the thermal conductivity, latent heat capacity, and melting temperature of PCMs can reduce battery temperature and enhance heat dissipation. The inclusion of carbon materials can increase thermal conductivity and decrease leakage by balancing latent and conducting heat, filling density, pore size, and mass percentage. Natural convection is the spontaneous movement of fluid, like air or water, due to temperature differences, causing density variations, leading to fluid rising or sinking without any external force or pump.

Adding metals can improve thermal conductivity and strength but limit the liquid PCM's natural convection. When metals are incorporated into PCMs, they can significantly enhance the PCM's structural strength. Metals have inherent mechanical robustness, and when combined with PCMs, they offer additional rigidity. This union aids in resisting deformation, ensuring better containment, and providing resilience during thermal cycling, thereby enhancing the overall performance and longevity of the PCM system. In low-temperature situations, combining preheating techniques and hybrid BTMS can improve battery performance [20].

Another form of phase change material is the phase change material emulsions (PCMEs), which are gaining popularity as a potential thermal storage and heat transfer medium. PCM emulsions are mixtures of PCMs dispersed in a continuous fluid, usually stabilized by surfactants, to ensure they remain mixed and don't separate. The introduction of emulsions can indeed influence the viscosity of the system. Depending on the formulation and the components involved, emulsification can potentially decrease the viscosity of the dispersed phase, making it more fluid-like and easier to pump or circulate. Subcooling refers to the cooling of a liquid below its normal freezing point, without it turning into a solid. It means the liquid is at a temperature lower than its usual solidification temperature, yet remains in its liquid state. This phenomenon can affect the performance and efficiency of systems utilizing PCMs.

While PCMEs have enhanced thermal energy storage capability, they still have limits such as instability, viscosity increases, and unwanted sub-cooling phenomena that must be addressed. Hydrodynamic mechanics of PCMs pertains to the behavior of these materials under fluid motion, influenced by factors like viscosity, density, and temperature gradients. It examines how PCMs flow, distribute, and interact under various thermal and mechanical conditions. To fully use PCMEs in various applications, it is needed to perform additional stability studies and explore their heat transmission and hydrodynamic performance, as well as the influence of formulation factors, are required. Additionally, additional research is required to comprehend the thermal and hydrodynamic mechanics of PCM droplets experiencing phase transition in flow conditions, especially during solidification, to optimize system geometries and effectively use stored energy [24]. The development of energy-saving techniques and energy-storage materials is a popular topic in the food sector. Encapsulated PCMs are phase change materials contained within micro or macro capsules, providing a barrier to separate the PCM from its surroundings. This encapsulation improves stability, prevents leakage, and allows controlled release of stored thermal energy.

The encapsulation of micro/nano encapsulated PCMs enhances their thermal conductivity and avoids contact with the surrounding matrix, allowing them to be employed as energy storage materials. Research indicates that Nano PCMs can elevate both the thermal storage capacity and thermal conductivity of heat transfer fluids. By embedding nanoparticles into phase change materials, they amplify the available surface area for heat exchange, which in turn enhances thermal conductivity. This increased conductivity accelerates heat uptake and dispersion, thereby amplifying the system's overall thermal storage efficiency where the Nano PCM is utilized [25,26]. Nano PCMs can transport and store heat with great efficiency and minimal pumping power [27]. Encapsulated PCMs are being investigated as innovative energy storage and release systems for controlling temperature-sensitive items in refrigeration equipment and intelligent food and pharmaceutical packaging [9]. Besides, the optical filtration and temperature control capabilities of encapsulated PCM slurries and dispersions make them a natural fit for photovoltaic/thermal collectors [28].

polychlorinated biphenyls PCBs are a group of organic chlorine compounds once widely used as dielectric and coolant fluids. Due to environmental and health concerns, their production was banned in many countries in the late 1970s. The textile industry utilizes PCBs for thermoregulating fabric applications. These chemicals are recognized for their potential to release latent heat during phase transitions from liquid to solid or solid to liquid, generating a transient warming or cooling effect. In garments, microencapsulated paraffin waxes and fatty acids are commonly used as PCMs. These materials are integrated into fabrics to regulate body temperature by absorbing or releasing heat during phase transitions, enhancing wearer comfort. Consequently, PCMs are excellent for usage in garments to control body temperature and enhance comfort. Incorporating PCMs into textile materials can limit the increase in microclimate temperature and loss of skin moisture, resulting in a reduction in heat stress and an improvement in thermal comfort [29]. In the textile business, researchers are investigating the incorporation of polychlorinated biphenyls PCMs into various textile materials and the properties of PCM-incorporated fibers and textiles. Coating, spinning, and laminating are ways to incorporate PCMs into textiles. Despite obstacles such as selecting the optimal PCM for a certain application and assuring material durability and stability, the textile industry's outlook for PCMs is optimistic [8].

Introducing flexible supports may lower the energy storage capacity of flexible PCMs. However, methods have been devised to optimize this trade-off, such as impregnating PCMs onto flexible porous scaffolds, encapsulating PCMs within elastic shells, and developing inherently flexible PCMs based on molecular architectures. Flexible PCMs have several uses, such as thermal management of electronic equipment, thermal treatment for people, and flexible sensors. Challenges related to developing flexible PCMs include enhancing the thermal storage capacity and cycle performance, as well as investigating novel applications and device integration [30].

In recent years, several features and uses of PCMs have been examined and investigated. However, little research has examined the trends, bibliometrics and scientometrics of PCMs or their implementation. Scientometric studies analyze scientific research patterns and trends. PCMs are a focal point due to their rising importance in sustainable energy solutions. A scientometric study on PCMs can highlight dominant research areas, leading contributors, and collaboration dynamics. This analysis not only showcases the evolution of PCM research but also pinpoints knowledge gaps and under-researched areas. By quantitatively examining PCM-related publications, stakeholders can gauge the field's momentum, direct funding efficiently, and craft informed policies. Essentially, a scientometric study offers a comprehensive roadmap, assisting researchers, policymakers, and industries in harnessing PCMs' full potential.

Bibliometrics, the statistical analysis of scientific publications, may assist in studying the evolution and effect of a particular field of research, such as PCMs. PCMs have several applications, including the storage and regulation of energy and temperature. Bibliometrics can be used to study PCMs using techniques like citation analysis, co-citation analysis, and network analysis. To measure the relevance and impact of a piece of literature, academics often undertake a citation analysis by counting the number of times other researchers in the same field have cited it. Using co-citation analysis, scientists may establish which groups of authors and publications are most interconnected. Researchers may develop graphical representations of these linkages using network analysis, which facilitates the identification of significant people and prospective areas of collaboration. Utilizing bibliometrics, researchers may learn more about the expansion of the PCM discipline, the most influential authors and institutions, and the most important study topics. This information may be used to lead future investigations better, identify cooperation chances, and assess specific studies' outcomes.

Mohammadpour et al. [31] evaluated the usage of nano-enhanced phase change materials (NePCM) for thermal energy storage in light of the bibliometrics analysis of TES. The study discovered that NePCM could solve technological issues associated with conventional PCMs, resulting in an exponential growth in research output in this field since 2005. China was discovered to have contributed the most to NePCM research in TES, followed by India and Iran. This survey recognized the top journals, publishers, nations, and researchers in this discipline. Journal of Energy Storage, International Journal of Heat and Mass Transfer, and Applied Thermal Engineering were determined to be the leading journals in this field. Corrosion, phase separation and supercooling were recognized as areas where more research is required to overcome outstanding technical obstacles. Subcooling pertains to liquids and boiling, and supercooling deals with liquids and freezing. Overall, the study indicates that NePCM has the potential to develop TES technology; nevertheless, more research is necessary to overcome outstanding problems.

In a separate study, Abdullah Naseer et al. [32] used bibliometric, network, and clustering methods to examine LHTES research trends from 2000 to 2019. The analysis showed an increase in LHTES articles between 2011 and 2019, corresponding with the enactment of energy-saving laws. China, the United States, and Germany have the most publications, but Turkey has the highest average citation per document. In addition to authorship, research topics, and leading journals, the report identifies form-stable composites and cryogenic energy storage as promising fields. This study examines the impact of government financing and foreign policy on the research outputs of regions, nations, and institutions. The Chinese Academy of Sciences produced the most publications, while Gaziosmanpasa University produced the most citations per document. “phase change materials” was the most often used author term, while “performance,” “conductivity,” and “simulation” were also popular. The top publishing journals were Applied Thermal Engineering, Applied Energy, and Energy Procedia, with Renewable Sustainable Energy Reviews having the greatest average citations per document. The study suggests that the growing interest in LHTES will result in more research and technological advancements in this promising subject.

Energy storage can be ecologically benign when it utilizes sustainable technologies that minimize environmental impact. This involves using materials and processes with low carbon emissions, minimizing resource depletion, and reducing waste generation. For instance, advanced battery technologies like lithium-ion or solid-state batteries, when produced using clean energy sources and responsibly sourced materials, can provide efficient and relatively eco-friendly energy storage solutions. Borri et al. [33] explore the significance of TES in lowering carbon emissions from buildings and present a detailed assessment and categorization of TES technologies used in the built environment. This article examines the application of TES to buildings, districts, roads, and bridges, identifying research trends and gaps in each area. In the case of TES applied to buildings, the authors note that Europe's research output has increased rapidly since 2010 due to legislation and policies promoting energy efficiency, whereas the United States' research trend primarily focuses on reducing cooling demand through optimal control techniques. Material-based research from China is the most relevant. In addition, the authors remark that latent heat thermal energy storage through passive approaches and demand-side management strategies is the primary research topic in Europe. The integration of seasonal TES, such as borehole or underground TES, is a pertinent issue at the district level; nevertheless, there is little interest in TES applied to highways and bridges, with China producing the most publications. The authors highlight research gaps, such as environmental effect assessment, economic analysis, sustainability, and social considerations.

Alptug et al. [34] address a bibliometric examination of research on the encapsulation of phase change materials as a first step towards a bigger study on the subject. The investigation investigates publishing activities, such as publication type, country, institution, author, journal, and keywords, using bibliometric techniques and knowledge visualization tools. After 2000, the number of publications on the encapsulation of phase change materials increased significantly, with China, the United States, and India being the most prolific nations. Additionally, the analysis reveals the most prolific journals and writers, as well as the most often-used keywords. The results show that bibliometric analysis is a good technique for spotting trends in study fields, and more research is advised. The study offers suggestions for future research and emphasizes the need for a deeper comprehension of bibliometric analysis. Overall, the study highlights the significance of utilizing the bibliometric analysis to chart research progress in a given domain, in this instance, the encapsulation of phase change materials.

Using the Scopus database, Cabeza et al. [35] performed a bibliometric study of research trends in thermal battery management systems from 1997 to 2019. Publications per year, leading nations and journals, and keyword network analysis were determined by analyzing the results of two inquiries. The most recent research trends in the thermal management of batteries indicate an improvement in liquid cooling via structural optimization and enhanced heat transfer in PCMs through fins, micro heat pipe arrays, and cold plates. In addition, composite PCMs for liquid cooling of batteries with thermoelectric devices are being researched, as are the electrochemical features of battery charging when PCM is utilized. However, the recognized research needs were comparing various thermal management methods and investigating thermal management of batteries other than lithium-ion batteries.

Utilizing bibliometric techniques, the application of PCMs has been widely researched in several sectors, including thermal energy storage [31], latent heat thermal energy storage [32], thermal energy storage applications in the built environment [33], thermal management of electric batteries [35]. However, there is a dearth of studies analyzing the publishing patterns and partnership maps of nations and institutions on PCMs. This research intends to address this void by measuring the cooperation maps, publications, and citations of PCM works for the first time. By examining the partnership maps, the study intends to identify the most active nations and institutions in PCM research and the manner in which they interact. In addition, the study will investigate the publishing patterns over time to discover any variations in PCM-related research interests and hot themes. The examination of citations will give insight into the influence of PCM research on the scientific community and prospective topics for further study. The usage of PCMs can introduce complexity due to their integration, optimization, and material selection in heating/cooling systems. However, they offer significant energy-saving benefits. This study will add to the knowledge of the worldwide research landscape on PCMs and give researchers and policymakers with vital information. This study may influence future research, identify possible partners, and inform governmental choices about the usage of PCMs in many industries.

2. Methodology

2.1. Phase change materials

A lot of different applications employ PCMs because of their capacity to retain and release heat. These include temperature control in electronics, heating and cooling in structures, and thermal energy storage in solar power systems. Their unique qualities allow them to contribute to sustainable energy management and pleasant temperature maintenance. PCMs can be placed in three categories organic, inorganic, and eutectic considering their structure [36], as shown in Fig. 1.

1. Organic PCMs: These are based on organic compounds, primarily hydrocarbons. Examples include paraffin waxes and fatty acids. These substances have a high heat of fusion, which means they can store significant thermal energy when they melt or freeze. Organic PCMs are generally non-toxic and non-corrosive, which makes them safe for many applications [37]. However, they can be flammable, which can limit their use in certain circumstances. Additionally, their thermal conductivity is generally low, so heat is transferred slowly. Despite these drawbacks, organic PCMs are widely used because they are relatively inexpensive and available in a broad range of melting temperatures. Organic PCMs are available over various melting

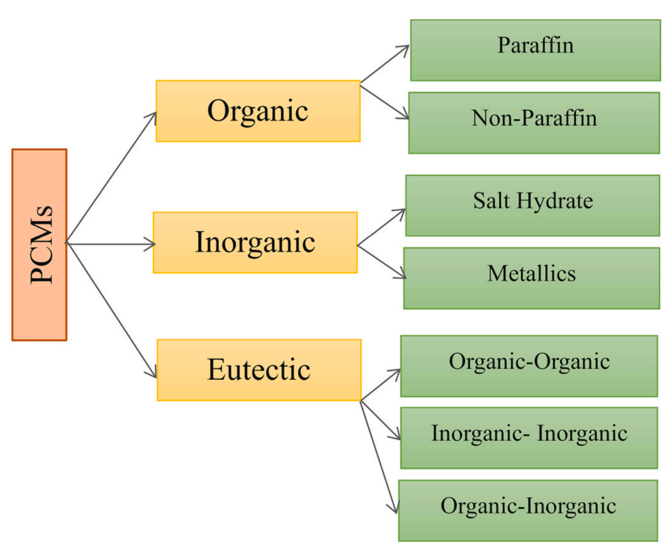

Fig. 1. PCM classifications.

Table 1
Organic PCMs and melting temperatures [38–41].

Organic PCM	Melting temperature (°C)
Paraffin wax	0–90
Lauric acid	44
Stearic acid	54
Palmitic acid	61
Acetic acid	17
Formic acid	8
Polyethlene glycol	33
Octadecane	28
Hexadecane	18
Eicosane	36.3
Heptadecane	19
Capric acid	30.1
Glycerin	17.9
Butyl stearate	19
Polyglycol E400	8
n-Pentadecane	10
Dimethyl sulfoxide	16.5
Dimethyl sabacate	21
Polyglycol E600	22
1-Dodecanol	26
1-tetradeconal	38

temperatures, making them versatile for various applications. Table 1 shows various organic PCMs and their melting temperatures.

2. Inorganic PCMs: These are based on inorganic compounds, such as salts or metals [36,42]. Inorganic PCMs can store a large amount of thermal energy due to their high heat of fusion. They also have excellent thermal conductivity, which means they can quickly absorb and release heat. However, they tend to have some limitations. For example, many inorganic PCMs go through a process called supercooling, where they cool below their freezing point before solidifying, which can be problematic in some applications. Also, inorganic PCMs can be corrosive and can have phase segregation issues, which means that different components of the PCM can separate over time.
3. Eutectic PCMs: A eutectic PCM is a mixture of two or more components that, when combined, have a lower melting point than any of the individual components [43,44]. These are essentially mixtures of organic and/or inorganic materials designed to optimize certain characteristics. Eutectic PCMs can provide a precise melting temperature, which can be beneficial in certain applications. Like other PCMs, they can store and release a large amount of thermal energy. However, the complexity of their composition can make them more expensive to produce and may limit their thermal stability over repeated cycles of melting and freezing.

2.2. Bibliometric analysis methods

The objective of this current research endeavor is to comprehensively investigate the topic of "phase change material" by employing a bibliometric methodology. This approach will enable us to quantitatively assess the existing literature, including publications and citations related to this topic. To retrieve related data to the topic, the Clarivate database was searched for the following search string on 11/17/2022:

(((**TI** = ("phase change material*")) *OR* (**AK** = ("phase change material*"))) *OR* (((((**AB** = ("phase change material*"))) *AND* ((**TI** = ("PCM")) *OR* (**AK** = ("PCM")))) *OR* (((**AB** = ("phase change material*"))) *AND* ((**TI** = ("NEPCM")) *OR* (**AK** = ("NEPCM"))))))where **TI**, **AK**, and **AB** indicate the publication title, author keywords, and publication abstract, respectively. Besides, *OR* and *AND* are the logical operators. The above strings search for publications in which the "phase change material*" is in either the title, the author keywords, or the abstract, as well as "PCM", "NEPCM", or "phase change material*" in either of the title, the author keywords, or abstract. The asterisk "*" indicates that there could be further characters after the keywords. For instance, "phase change material*" could represent each of the "phase change materials", "phase change materials", and "phase change material(s)".

The timeline for the search recorded was considered unlimited. Therefore, all the records available in the Clarivate database (WOS) were considered regardless of their publication time and were included in the analysis. The data has been made available here: https://doi.org/10.17632/dbnnjpt6f8.1.

3. Data analysis

3.1. Data scope

The explained search string and criteria in the previous section were applied, and 16,771 records were found. Overview of publication types are presented in Fig. 2, while a details of publication types can be found in Table 2. Here, TP shows the total number of publications for each item, and PR represents the percentage of each publication type among 16,771 records. As seen, "Article", "Proceedings Paper", "Review", and "Article; Proceedings Paper" constitute 77.2 %, 13.9 %, 4.4 %, and 2 % of the total publications, respectively. An "Article" is typically a comprehensive study published in journals, presenting original research, methodologies, or theories. On the other hand, an "Article; Proceedings Paper" is a contribution found in conference proceedings. It details research presented at a conference, often highlighting recent findings or developments. The first three records, which indicate the original full paper, involve 93.1 % (15620) of all records. The review articles are not considered in the present research for further analysis since they are based on other published articles and do not report original research. Thus, solely the "articles", "proceedings papers" and "article; proceedings Paper" were adopted for further analysis in the present study. Besides, the early access publications were also ignored since they have not been fully published yet. Considering these filters, finally, 15,620 records related to PCM remained for further analysis. Table 3 shows the language of the publications. Approximately 99 % of the articles are published in English, and other languages account for only 1 % of the publications.

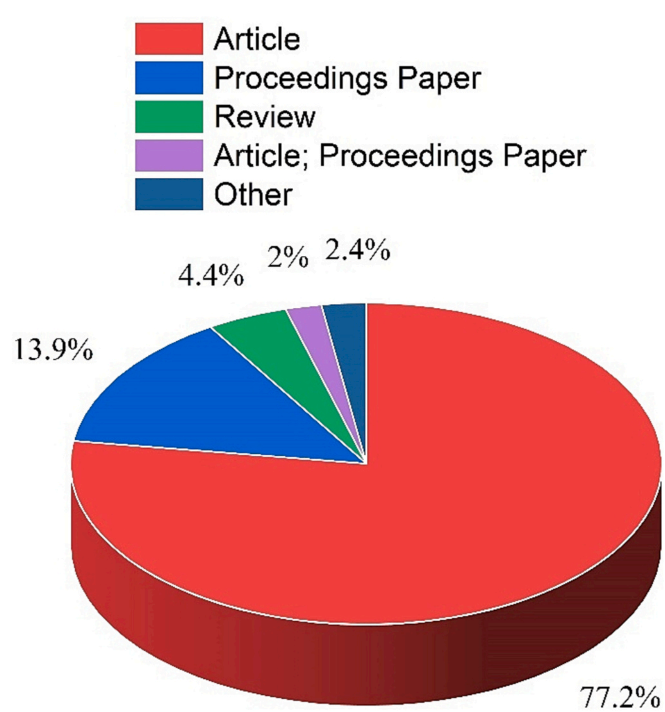

Fig. 2. Overview of 16,771 publication in PCM.

Table 2
The details of 16,771 publication records related to PCM.

Publication type	TP	PR
Article	12,955	77.2
Proceedings Paper	2333	13.9
Review	743	4.4
Article; Proceedings Paper	332	2
Article; Early Access	163	1
Article; Book Chapter	61	0.4
Meeting Abstract	58	0.3
Editorial Material	37	0.2
Correction	33	0.2
Review; Early Access	17	0.1
News Item	9	0.1
Letter	9	0.1
Editorial Material; Book Chapter	6	0
Article; Retracted Publication	3	0
Article; Data Paper	3	0
Review; Book Chapter	3	0
Book	2	0
Retraction	2	0
Book Review	1	0
Note	1	0

Note: TP = total number of publications for each item, PR = the percentage of each type of publication among 16,771 records.

Table 3
Publication's languages.

Language	TP	PR
English	15,454	98.9
Chinese	68	0.4
Japanese	21	0.1
German	16	0.1
Korean	14	0.1
French	10	0.1
Portuguese	9	0.1
Spanish	8	0.1
Polish	7	0
Turkish	4	0
Russian	3	0
Croatian	2	0
Slovene	2	0
Chinese; English	1	0
English; English	1	0

3.2. Impact factor and H index

In the field of bibliometrics, the impact factor and H-index are two commonly used metrics for evaluating the impact and influence of scholarly journals and researchers. The impact factor measures how often an article or item in a specific year is cited by dividing the number of citations received in that year by the number of articles published in the previous two years. The impact factor is published annually by the Web of Science in the Journal Citation Reports (JCR) and is used widely as an indicator of a journal's relative importance within its field.

While H-Index and Impact Factor metrics are widely recognized and employed, it is acknowledged that newer metrics, such as the Article Influence Score (AIS) and the Journal Citation Indicator (JCI), are increasingly being used in scientometrics. Article Influence Score measures a journal's prestige based on per-article citation impact. It's calculated by dividing a journal's Eigenfactor Score by the number of articles in the journal, then normalized against all journals. It reflects long-term influence of articles. The decision to employ the impact factor and H-index in this study was primarily driven by their widespread acceptance and application in assessing the influence and reach of scientific publications. Both metrics provide useful, albeit different, insights: the impact factor measures the average number of citations a journal receives, reflecting its overall influence, while the H-index assesses both the productivity and citation impact of a publication or researcher.

The H-index, or Hirsch index, measures both the productivity and impact of a particular scholar. It is calculated by identifying the publication numbers (H) that have been cited at least H times. For example, if a scholar has an H-index of 20, it means the scholar has 20 papers that have been cited at least 20 times. The H-index is a more comprehensive measure of a researcher's impact than the impact factor, as it considers both the quantity of work in terms of publication numbers and the quality of the publications by citations.

It is important to note that both the impact factor and H-index are not perfect measures and have some limitations. For example, the impact factor of a journal is heavily influenced by the citation number of highly-cited papers, which is not representative of the quality of the journal's overall content. It also favors journals that publish more articles and journals that are older. Additionally, the H-index does not consider the quality of the cited papers, the research field, or the researcher's career stage. Therefore, it is important to use these metrics in conjunction with other information, such as the papers' content and the researcher's field and career stage, to get a more accurate picture of the research impact.

Hirsch provides a detailed explanation of the metric, its calculation, and its advantages over other measures of research impact [45], which was used in the present study. A more general introduction to bibliometrics, which explains the concept of impact factor and other bibliometric indicators and their application in science and technology, can be found in [46].

3.3. Content analysis and analysis method

Bibliometrics is a technique for quantifying the literature that employs different metrics to assess the significance and influence of academic works and academics. The total number of publications mentioned by other publications is considered as an indicator of the impact and influence of that article on the subject. The impact factor (IF) and the h-index (HI), which were examined in the present study, are the most commonly used citation-based measures.

Co-authored (Collab), also called collaborative publications, are works with two or more authors. In many scientific disciplines, collaborative publications are becoming increasing prevalent because they may bring together various specialties, viewpoints, and resources to address challenging research topics. Research networking, visibility, and influence can all be significantly boosted through collaborative publications, which can also lead to better scientific achievements. The independent publications (Indep) are in contrast to the collaborative publications.

There are several sorts of collaborative publications depending on the number of authors, locations, and connections with one another. Several instances include collaboration between organizations within which the authors are affiliated. When authors from many nations collaborate, this is called an international collaboration. Collaboration among authors from several disciplines or fields is known as interdisciplinary collaboration. Collaboration in publication can offer several benefits. For instance, they can create higher-quality research since several viewpoints and domain knowledge are applied to a challenge. Authors can use their personal networks and resources to reach a larger audience, increasing research productivity and impact. Collaborations across disciplines, cultures, and borders can also be fostered by collaborative publishing.

It is crucial to remember that joint publications can also present certain difficulties, including managing timetables, maintaining communication, and allocating tasks among the writers. As some measures, like the h-index, are calculated based on the publication's number and citation times, but a publication's author count can also have an impact on how it is cited and evaluated. A publication with more authors may receive less credit for the research.

Therefore, when organizing and conducting research, carefully weigh the potential advantages and disadvantages of collaborative publications. Scientific knowledge can be advanced through collaborative publications, but it is crucial to make sure that they are managed well and that all authors receive recognition and credit for their works.

The first author indicator (AU1) is another criterion utilized in the present study. A document in which the author named first has made the most significant contributions to the research and the manuscript is referred to as a first author publication, also known as a lead author publication. Most of the time, the first author is responsible for writing, researching, and editing the work.

Being the first author of a publication is typically regarded as a noteworthy accomplishment because it shows that the individual has contributed significantly to the research and acted as the manuscript's primary writer and editor. Being the first author can help a researcher become recognized as an authority in their field and can help them advance their careers because it is frequently taken into account when assessing a researcher's productivity and effect.

Leading the research, coordinating and informing the co-authors, and supervising the editing and submission of the manuscript are all duties that come with being the first author. It also takes a great amount of time and work and a high degree of commitment to the project and the document.

It is crucial to remember that first authorship is not the only factor to consider when assessing a researcher's accomplishment; other factors include the last author, corresponding author, and senior author. Various elements, including the research group size, the financing, and the subject matter, can also influence the authorship order.

In some domains, a first-author publication strongly indicates a researcher's productivity and influence. Hence it is crucial to consider this when evaluating a researcher's productivity and impact. Though it may not accurately reflect the roles and responsibilities of the authors in a research project, it is crucial to remember that authorship order should not be the sole criterion used to assess a researcher's contributions.

The next indicator, which was used in the current research, is the corresponding author (AUC). The principal point of contact for a publication is the corresponding author, who typically is in charge of getting in touch with the journal editor, submitting edits, and approving the final version of the paper. The corresponding author is frequently in charge of organizing the manuscript's submission, handling it, and ensuring that all authors have reviewed and approved the final draft.

It entails ensuring the manuscript is accurate and comprehensive, that all authors have agreed to the submission, and that they are aware of their responsibilities. This is why being the corresponding author on a publication is regarded as carrying much responsibility. This involves ensuring that all authors have agreed upon the sequence of authorship and that all potential conflicts of interest have been declared.

Table 4
The features of the published records for each year.

Year	TP	AU	Inst	Count	TC	TC/TP	AU/TP	PR (%)
1981	1	1	1	1	27	27	1	0.01
1982	2	3	1	1	14	7	1.5	0.01
1983	1	4	1	1	0	0	4	0.01
1984	3	9	3	3	152	50.7	3	0.02
1985	1	3	1	1	2	2	3	0.01
1986	5	13	2	2	258	51.6	2.6	0.03
1987	2	8	2	2	43	21.5	4	0.01
1988	9	20	6	5	90	10	2.2	0.06
1989	6	17	4	4	288	48	2.8	0.04
1990	7	18	4	2	100	14.3	2.6	0.04
1991	19	49	11	5	1042	54.8	2.6	0.12
1992	9	14	4	3	324	36	1.6	0.06
1993	11	27	6	5	287	26.1	2.5	0.07
1994	13	32	10	6	596	45.8	2.5	0.08
1995	16	37	11	6	524	32.8	2.3	0.10
1996	28	56	10	6	1069	38.2	2	0.18
1997	29	73	14	9	1188	41	2.5	0.19
1998	24	64	31	12	1132	47.2	2.7	0.15
1999	27	71	26	14	1084	40.1	2.6	0.17
2000	30	79	29	10	1346	44.9	2.6	0.19
2001	40	127	44	16	2067	51.7	3.2	0.26
2002	52	174	62	20	3436	66.1	3.3	0.33
2003	57	143	64	24	2899	50.9	2.5	0.36
2004	79	212	90	24	5977	75.7	2.7	0.51
2005	96	273	105	24	6254	65.1	2.8	0.61
2006	127	389	133	29	7253	57.1	3.1	0.81
2007	167	525	176	35	11,098	66.5	3.1	1.07
2008	183	575	204	32	12,265	67	3.1	1.17
2009	245	816	248	45	12,464	50.9	3.3	1.57
2010	300	989	311	46	13,866	46.2	3.3	1.92
2011	369	1252	372	54	17,212	46.6	3.4	2.36
2012	480	1498	443	46	18,807	39.2	3.1	3.07
2013	539	1762	511	56	23,151	43	3.3	3.45
2014	676	2178	631	65	27,073	40	3.2	4.33
2015	779	2538	725	72	27,915	35.8	3.3	4.99
2016	902	2994	867	72	29,809	33	3.3	5.77
2017	1154	3780	1046	75	32,907	28.5	3.3	7.39
2018	1233	4120	1127	73	31,550	25.6	3.3	7.89
2019	1586	5165	1332	81	33,245	21	3.3	10.15
2020	1785	6169	1587	80	28,226	15.8	3.5	11.43
2021	2186	7611	1919	83	17,480	8	3.5	13.99
2022	2290	8103	2055	86	4823	2.1	3.5	14.66
2023	52	256	86	18	4	0.1	4.9	0.33

4. Results and discussions

4.1. Characteristics analysis of the literature reports

Table 4 presents an overview of the articles published between 1981 and 2023. AU, Inst, Count, and TC denote the number of authors, institutes, countries, and total citations, respectively, which were reported by year. Moreover, PR shows the percentage of total publications for each year compared to all years. Table 4 shows that in 2013, the number of publications was approximately 539; in 2017, this number reached 1154. The number of publications doubled during these five years. In the same period, the number of authors and institutions also doubled. In 2018, the number of publications was approximately 1233; in 2022, this number reached 2290. Thus, the number of publications doubled during the second five-year period (2018–2022).

Fig. 3 displays the number of publications over time. This figure shows six groups of five-year periods from 1981 to 2010. Group One spans 1981–1985, Group Two covers 1986–1990, Group Three ranges from 1991 to 1995, Group Four is from 1996 to 2000, Group Five includes the years 2001–2005, and Group Six encompasses 2006–2010. In each period, an increase in publications can be seen compared to the previous period. From 2011 to 2022, the number of publications increased continuously.

Paying attention to the data from 1981 to 2010, little scientific publication is available. Therefore, to better display the data, the primary productions were divided into six groups of five-year periods. As seen, in the early periods, except from 2006 to 2010, scientific publications are minimal but with an upward trend of scientific publication. In 2011, scientific publication was 2.4 %, which increased to 5 % in 2015. Later it reached 11.4 % in 2020. The maximum production occurred in 2022, with a value of 14.7 %. The noted trend might be partially influenced by the increasing number of journals and conference proceedings indexed within the Clarivate database. This factor could be contributing to the perceived increase in publications on this subject.

Table 4 indicates a clear trend of increasing publications from 1981 to 2022, accompanied by a general rise in citations up to 2022. However, in 2022, while there is an increase in the total number of publications, there's a drastic drop in citations. The sudden drop in citations for articles published in 2022 is because articles from 2022 had limited time to gather citations by year-end, particularly those published later. In comparison, older articles had longer exposure, leading to more discussions and citations.

The production of 2022 was almost three times the production of 2015. It should be noted that the current research was conducted based on available data in 2022, but a small number of future scientific publications published in 2023 were also available in the database, which was included in the analysis. Since the scientific publications of 2023 have not yet been properly published, the data reported for this year is not complete and should not be used as a basis for future judgments.

4.2. National/regional contribution analysis

Fig. 4 shows scientific publications over time by country. In this figure, the five countries that had the most scientific publications are shown. Considering that there were few scientific publications before 2000. Therefore, these productions have been integrated into one group, and since 2000 scientific publications have been displayed annually. From 1981 to 2006, there were few scientific publications, and there was almost no significant difference between countries. Since 2007, a significant difference can be seen in China's trend, which is increasing with a significant upward slope of its production. This increasing slope for China has continued until 2022. China has been the leader of scientific publications in the field of PCM from 2007 to 2022. From 2007 to 2019, the United States ranked second after China. Since 2019, India has surpassed the USA, and this country has taken second place. In 2021, China's production was almost four times that of the United States. Considering that the populations of India and China are each more than one billion, it may be expected that these two countries will have more

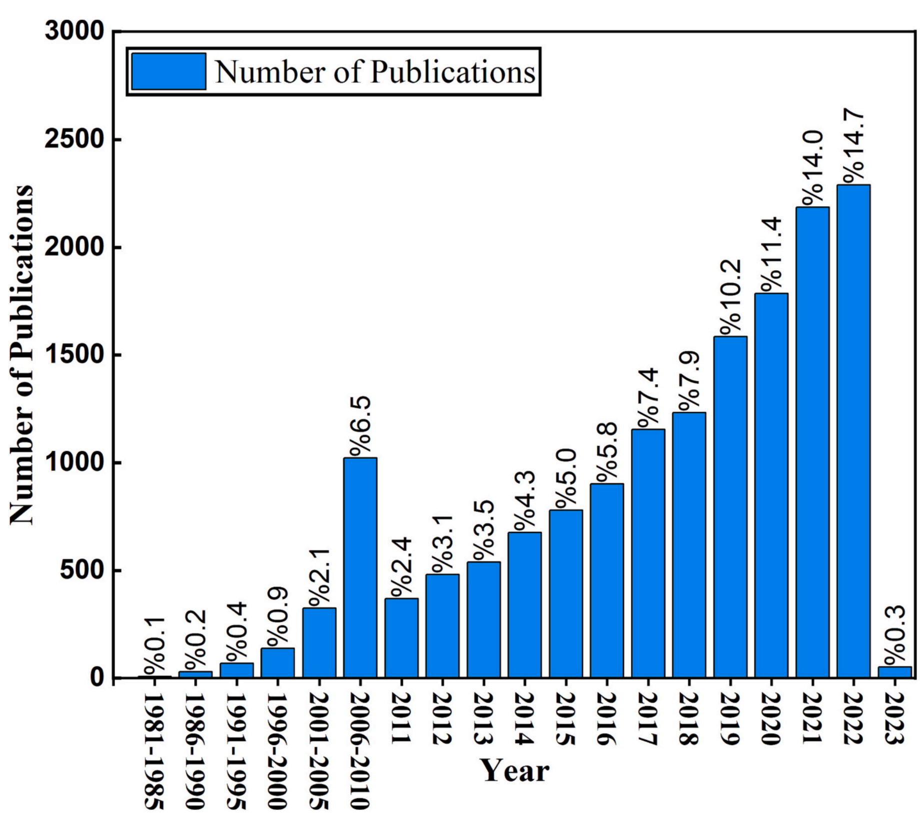

Fig. 3. Number of publications related to PCM for six groups years 1981–2010 and years 2011–2033.

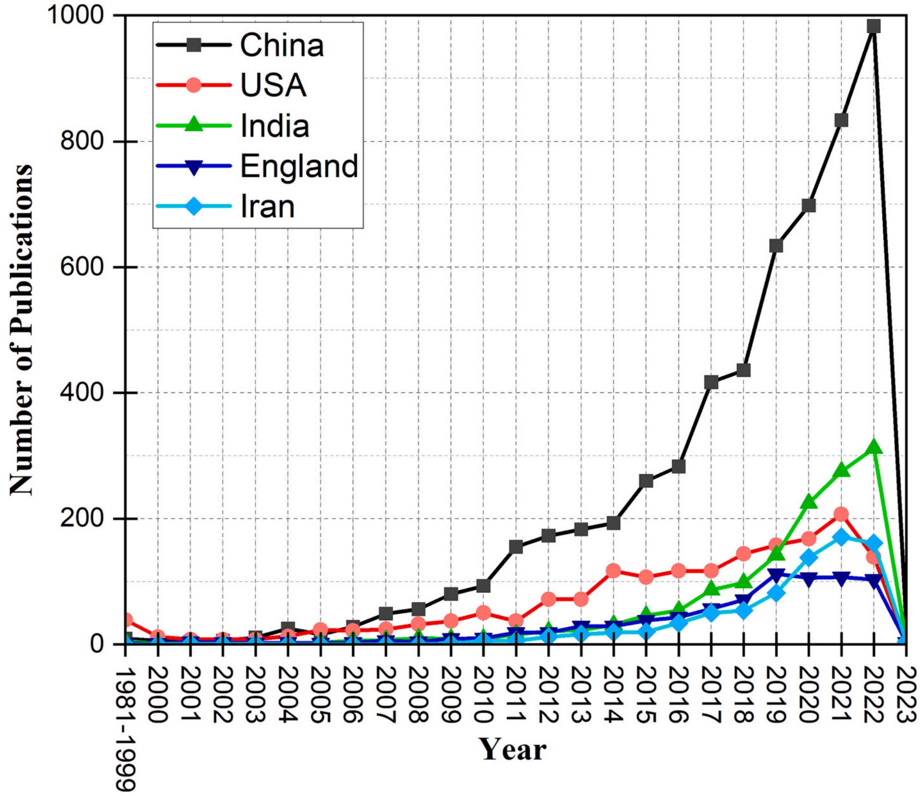

Fig. 4. Publications of top five countries over time.

scientific publications than the United States, which has a population of about 300 million.

Recently, Chinese publications on PCMs have seen a rise in recent years. This can be attributable to various factors, such as: 1- Urbanization and economic expansion: Energy storage is becoming more crucial as China's economy expands and urbanizes. There has been an increase in research and development in this field since PCMs have been recognized as a potential technology for energy storage. 2- Government funding and initiatives: The Chinese government has invested in energy storage research and development, including PCMs. As a result, more research organizations and groups are now focused on PCMs in China, which has increased the number of publications on the subject. 3- Energy storage is also necessary for renewable energy sources like solar and wind power, which is why the Chinese government has put various regulations and efforts in place to encourage its development and use. PCMs have drawn more attention in China due to being recognized as a promising technology for its use in various energy management applications. 4- Strong industrial foundation: China has emerged as a prominent participant in the global PCM industry with a strong industrial base for PCM manufacture and use. As a result, Chinese researchers and businesses are investing money in PCM research and development to raise their efficiency and lower production prices, which also helps explain the rise in publications on the subject. 5- In recent years, China has invested in research and development. As a result, there are now more research institutions and academic institutions in China, which has increased the number of publications. 6- The number of doctoral students in Chinese universities has increased each year. These students have been the major contributors to scientific publications in recent years.

Overall, the rise in publications on PCMs in China can be ascribed to several causes, including the country's expanding need for energy storage, government funding and legislation, the use of renewable energy sources, and the expansion of the PCM business in China.

The scientific publications of the top countries with more than 200 publications are presented in Table 5. Here, Collab, Indep, AU1, and AUC represent the number of collaborative publications, independent publications, the first author's name publications, and corresponding author-name publications, respectively. In addition, HI is the H-Index factor for each country.

The top three countries in terms of total publications (TP) were China, the USA, and India, respectively. As seen in Table 5, China, the USA, and India have allocated 36, 11, and 9 productions, respectively. According to Table 5, the top three countries in terms of total citations (TC) are China, the USA, and the UK. A parameter that can be important and show part of the quality of scientific publications is TC/TP, which indicates the ratio of citations to publications. Considering TC/TP, Singapore, Turkey, and the UK are the top three countries. Singapore has the highest citation rate (i.e., the highest ratio of citations to publications). This shows that Singapore is focusing on producing high-quality, impactful research rather than just increasing the quantity of publications. The next indicator, presented in Table 5, is the Collab parameter, which represents the level of cooperation of a country with other countries. The total publications (TP) of China were 5663, of which almost 20 % (1162) of China's productions were in cooperation with other countries, and almost 80 % of China's productions (4501) were independent and without cooperation with any country. According to collaborative publications (Collab) and independent publications (Indep), China is at the top of the table. Regarding collaborative publications, the three countries, China, the USA, and the UK have established the highest degree of cooperation with other countries. In terms of independent publications, the three countries, China, India, and the USA, have established the highest degree of cooperation.

In order to provide a fair judgment on the level of cooperation of a country with other countries, the Collab/TP parameter was defined. This parameter evaluates the number of collaborative publications of a country compared to that country's total number of publications. Based on this parameter, Saudi Arabia has published 91 % of its scientific publications with the cooperation of other countries and has the highest

Table 5
The statistical analysis of countries/regions with more than 200 publications in PCM.

Country	TP	TC	TC/TP	PR (%)	Collab	Indep	Collab/TP (%)	AU1	AUC	HI
China	5663	135,911	24	36	1162	4501	21	5223	5250	133
USA	1734	51,346	29.6	11	691	1043	40	1194	1275	106
India	1390	24,940	17.9	9	323	1067	23	1225	1224	69
UK	785	25,737	32.8	5	567	218	72	382	410	78
Iran	776	19,854	25.6	5	318	458	41	646	617	70
France	676	15,745	23.3	4	417	259	62	411	397	65
Germany	651	20,511	31.5	4	349	302	54	427	426	71
Spain	633	17,946	28.4	4	310	323	49	469	469	68
South Korea	528	9999	18.9	3	140	388	27	407	449	48
Italy	525	12,311	23.4	3	261	264	50	387	395	57
Turkey	524	19,784	37.8	3	179	345	34	378	431	73
Japan	511	11,305	22.1	3	192	319	38	322	394	57
Canada	480	9715	20.2	3	235	245	49	298	317	53
Australia	434	11,199	25.8	3	279	155	64	253	247	55
Saudi Arabia	407	7298	17.9	3	370	37	91	174	145	45
Egypt	259	5876	22.7	2	168	91	65	172	133	45
Malaysia	250	7997	32	2	177	73	71	172	166	50
Singapore	220	9324	42.4	1	149	71	68	135	136	50

level of cooperation among countries. China has published 21 % of its scientific publications in cooperation with other countries. As a result, it can be concluded that Saudi Arabia produces most of its publications in cooperation with other countries.

Another parameter that is effective in ranking a university is the first author's name publications (AU1) and the corresponding author name publications (AUC), which are presented in Table 5. China, India, and the USA are among the top three countries in terms of AU1 and AUC. China had 5663 publications, of which 5223 (almost 90 %) publications were AU1, and 5250 (almost 90 %) were the AUC. China ranks first among countries in the field of PCM in both parameters of AU1 and AUC. India also behaves very similarly to China, with AU1 1225 (almost 88 %) and AUC 1224 (almost 88 %). Therefore, it is concluded that India and China were the founders of the PCM movement independently, and other countries tried to participate in the PCM movement in parallel.

The last parameter examined in Table 5 is the H-Index factor (HI). The H-index for a country is defined as the maximum value of h such that the given country has published at least h papers that have each been cited at least h times. China, the USA, and the UK have the highest H-index with values of 133, 106, and 78, respectively. These three countries have high H-index values compared to the usual H-index values. According to the definition of H-Index, China has at least 133 articles that have received 133 citations. This high H-index indicates the high quality of China's publications in PCM.

Further analysis of the results in the supplementary materials showed that Russia published 140 papers related to PCMs with a total number of 1528 citations. Thus, Russia places the 25th (TP) and 45th (TC) on the table. A full list of countries and data can be found in the supplementary materials of this paper, published on Mendeley [47]. Russia has published fewer articles on phase-change materials. This disparity may be attributable to a variety of factors. Lack of money or resources for study in this field may be a contributing factor. In addition, the literature review showed that PCMs are crucial for renewable energy applications and thermal energy management. Russia probably devotes less financing to renewable energy research than the United States and China. Without sufficient financing, researchers may lack the means to undertake and publish research in this field. Russia may not place as much emphasis on renewable energy as the United States and China in terms of policy or public interest. This might result in fewer studies being conducted on this issue.

Moreover, Russia's energy infrastructure and market may not be as receptive to renewable energy as those in the United States and China. This might impede researchers' ability to perform and publish research in this field. Differences in research priorities or interests between Russia and other nations in the realm of energy and materials science might also be an influence.

A connection network, which is another name for a collaboration network, is a mean to visualize relationships between various entities (such as people, institutions, or nations) based on their communications or teamwork. It is frequently used in bibliometrics and scientometric to examine the dynamics of scientific collaborations and pinpoint influential figures and common collaboration patterns. The representation of connectivity networks can take many forms, such as a graph where the nodes stand for the actors and the edges for the interactions between them. Here, the connectivity map (the connection network) between top countries is plotted in Fig. 5, considering joint publications. Each line in the figure represents at least fifteen connections. Connections that were fewer than fifteen are not drawn in the figure. For example, the Netherlands has never had more than fifteen connections; thus, it has no connection line. Each line between two countries represents fifteen joint publications, and the thickness of each line indicates the number of joint publications. The connectivity number for Poland was low; hence, the circle indicating the country is barely visible. A thicker line indicates a stronger correlation. The size of each circle represents the total number

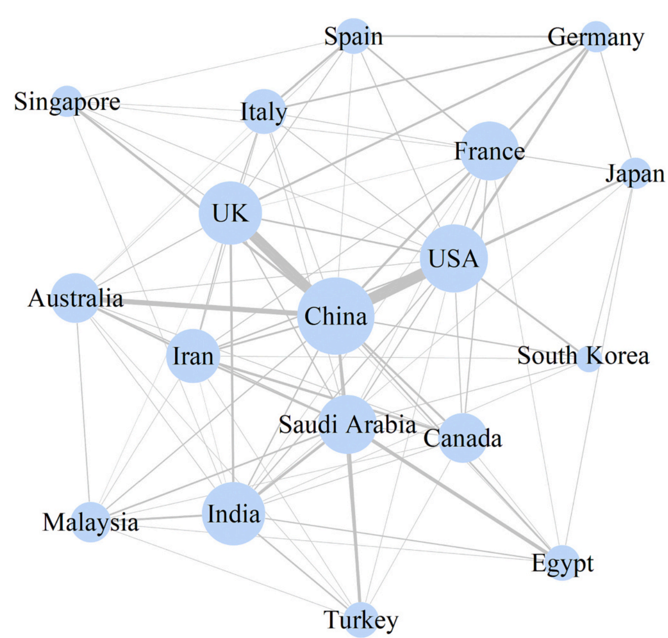

Fig. 5. Connectivity network of the top productive countries with more than 200 publications in PCM, with a threshold of 10 connectivity for connection each line.

of connections. The results show that China-USA and China-UK have the strongest relationship among all the countries, followed by China-Australia. China can be considered a hub because the most robust connections lead to China. The USA has normal relations with other countries except China.

On the other hand, the thickness of the lines that lead to Saudi Arabia is relatively thick. Saudi Arabia has established a relatively good relationship with four countries: China, Egypt, India, and Turkey. Thus, Saudi Arabia can be considered a small hub between China, Egypt, India, and Turkey countries.

4.3. Institutes contribution analysis

Fig. 6 shows scientific publications over time by institutions. In this figure, the five institutes that had the most scientific publications are shown. Considering that there were few scientific publications before 2005. Therefore, these productions have been integrated into one group. Since 2006, scientific publications have been displayed annually. Until 2011, all institutions except Chinese Acad Sci had little scientific publication, and there is little difference between the institutions. From 2007 to 2022, the Chinese Acad Sci Institute has been the leader of scientific publications in PCM. From 2011 to 2013, a significant difference can be seen in the trend of Univ Lleida, which is increasing with a sharp upward slope where the productions of Univ Lleida (TP = 25) and Chinese Acad Sci (TP = 30) institutes have become very close in 2013. In 2016, all the top five institutions, except Univ Lleida, rapidly increased their scientific publication in PCM. Univ Lleida had its highest production in 2013, and then until 2022, it had a decreasing trend with fluctuations. From 2016 to 2022, Xi An Jiao Tong Univ's production trend has been strictly upward. It should be noted that the production in 2023 is incomplete and insignificant, as discussed in Table 4. Thus, the publication data for 2023 should not be a basis for comparison and judgment.

In the present study, 6044 institutions had at least one publication in PCM. Table 6 lists the scientific publications of the top twenty institutes based on the number of productions. Here, Collab, Indep, AU1, and AUC represent the number of collaborative publications, independent publications, the first author's name publications, and corresponding author name publications, respectively. In addition, HI is the H-Index factor for each institute. The top five institutions in total publications (TP) were Chinese Acad Sci, Xi An Jiao Tong Univ, Univ Lleida, South China Univ Technol, and Sichuan Univ, respectively, which results are consistent with Fig. 6. Of these top five institutions, four are from China, and one is from Spain. These five institutions have allocated 3.3 %, 1.4 %, 1.3 %, 1.3 %, and 1.1 % of total productions, respectively. According to Table 6, the top three institutions in terms of total citations (TC) are Chinese Acad Sci (TC = 12,115), univ Lleida (TC = 8699), and Rhein Westfal Th Aachen (TC = 8005). The term "Not Available" in Table 6 are independent researchers who do not have an academic or organizational affiliation, or their organization has not been reported.

A closer look at all the investigated institutions showed that Gaziosmanpasa univ ranks second in citations, with 97 publications and 9163 citations. The number of publications in Gaziosmanpasa univ is less than the last record in Table 6 (TP = 114). Table 6 is arranged based on the number of publications. Therefore, the Gaziosmanpasa univ is not seen among the top twenty institutes due to low publications. However, the number of citations of the Gaziosmanpasa univ is so high that it ranks second in citations among all institutions. The full list of institutes can be found in supplementary data.

A parameter that can be important and show part of the quality of scientific publications is TC/TP factor or index. Rhein Westfal Th Aachen, Shanghai Jiao Tong Univ, and Univ Lleida are the first three institutes in this index. Rhein Westfal Th Aachen has received the most citations compared to its number of publications.

The Collab parameter, which represents the level of cooperation of an institute with other institutes, is presented in Table 6. According to

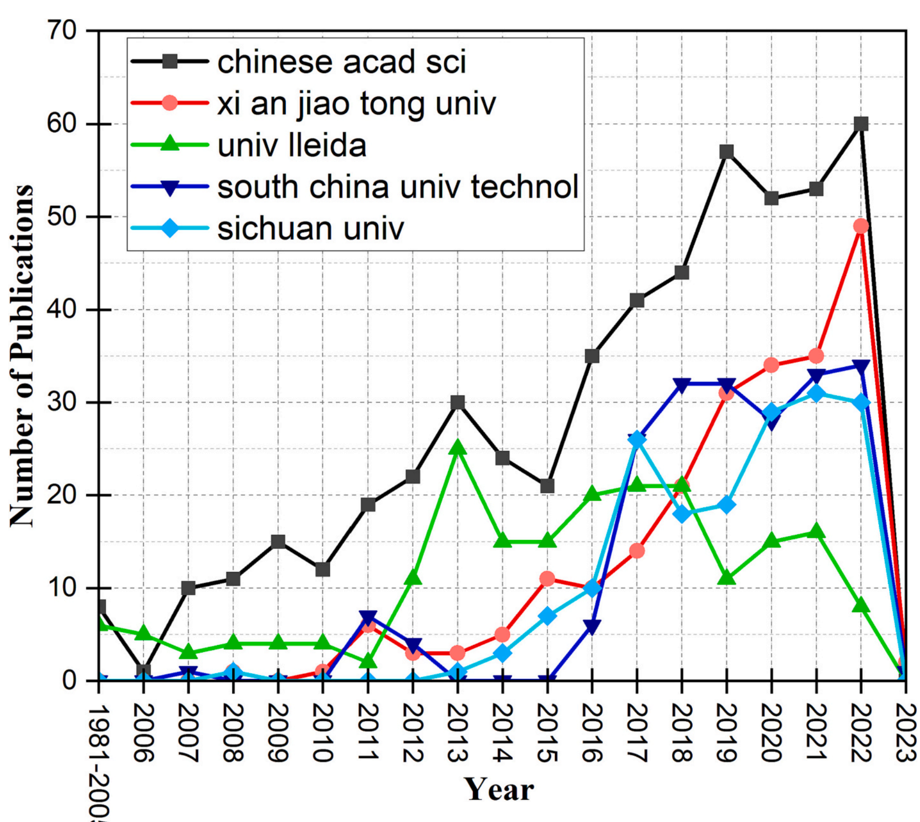

Fig. 6. Publications of top five institutes over time.

Table 6
The statistical analysis of institutes.

Institution	TP	TC	TC/TP	PR (%)	Collab	Indep	Collab/TP (%)	AU1	AUC	HI
Chinese Acad Sci	515	12,115	23.5	3.3	90	425	17	354	316	61
Xi An Jiao Tong Univ	226	6629	29.3	1.4	86	140	38	177	178	48
Univ Lleida	206	8699	42.2	1.3	110	96	53	114	120	50
South China Univ Technol	204	5667	27.8	1.3	13	191	6	155	151	45
Sichuan Univ	175	4890	27.9	1.1	7	168	4	156	148	41
Univ Chinese Acad Sci	169	3429	20.3	1.1	18	151	11	121	3	35
Islamic Azad Univ	162	4308	26.6	1	86	76	53	90	79	35
Shanghai Jiao Tong Univ	161	7027	43.6	1	57	104	35	119	129	44
Tsinghua Univ	159	6366	40	1	16	143	10	77	97	50
Rhein Westfal Th Aachen	148	8005	54.1	0.9	93	55	63	77	82	44
Guangdong Univ Technol	145	4002	27.6	0.9	28	117	19	112	110	37
Southeast Univ	141	4283	30.4	0.9	27	114	19	110	106	35
Univ Sci & Technol China	136	4511	33.2	0.9	28	108	21	93	72	42
Zhejiang Univ	131	2948	22.5	0.8	42	89	32	91	94	30
Univ Sci & Technol Beijing	126	3154	25	0.8	30	96	24	102	99	32
Univ Nottingham	117	3305	28.2	0.7	79	38	68	60	66	32
Anna Univ	117	4050	34.6	0.7	29	88	25	73	84	36
Nanyang Technol Univ	116	4726	40.7	0.7	87	29	75	64	63	35
Univ Birmingham	115	2829	24.6	0.7	86	29	75	50	56	29
Not Available	114	3776	33.1	0.7	0	114	0	0	28	33

Table 6, the top three institutions in terms of collaboration with other institutions are Univ Lleida (Collab =110), Rhein Westfal Th Aachen (Collab =93), and the Chinese Acad Sci (Collab =90), respectively. Prince Sattam Bin Abdulaziz Univ, with TP = 100, was not among the top twenty institutions in Table 6. However, this institution with Collab =99 has established greater cooperation than Rhein Westfal Th Aachen.

In terms of independent publications, the three institutions, Chinese Acad Sci, South China Univ Technol, and Sichuan Univ, have published most papers without collaboration with other institutes.

To provide a fair judgment on the level of cooperation of an institute with other institutes, the Collab/TP parameter was defined. This parameter evaluates the number of collaborative publications of an institute compared to that institute's total number of publications. Based on this parameter, Nanyang Technol Univ and Univ Birmingham have published 75 % of their scientific publications with the cooperation of other institutes. Nanyang Technol Univ and Univ Birmingham have published 75 % of their scientific publications in collaboration with other institutions and have the highest level of cooperation among institutes. These institutions have produced most of their publications in collaboration with other institutions.

Another parameter that effectively ranks the university is the first author's name publications (AU1) and the corresponding author name publications (AUC), which are presented in Table 6. Chinese Acad Sci and Xi An Jiao Tong Univ are among the top two Institutes in terms of AU1 and AUC. Chinese Acad Sci had 515 publications, of which 354 (almost 69 %) were AU1, and 316 (nearly 61 %) were the AUC. Chinese Acad Sci ranks first among institutions in the field of PCM in both parameters of AU1 and AUC. Xi An Jiao Tong Univ Sci had 226 publications, of which 177 (almost 78 %) were AU1, and 178 (nearly 79 %) were the AUC. Xi An Jiao Tong Univ ranks second among institutions in the field of PCM in both parameters of AU1 and AUC.

The last parameter examined in Table 6 is the H-Index factor (HI). The h-index for institutes is defined as the maximum value of h such that the given institute has published at least h papers that have each been cited at least h times. According to Table 6, Chinese Acad Sci is at the top with an H-index of 61. Univ Lleida and Tsinghua Univ are in second place with an H-index of 50. The Gaziosmanpasa Univ ranks second after Chinese Acad Sci with an H-index of 54. As mentioned, this institute is not among the top twenty institutes in Table 6 due to low publications.

4.4. Web of Science journals analysis

In the present study, 2385 journals had at least one publication in PCM. The twenty most productive journals in PCM are presented in Table 7. Here TP represents each journal's total publication during 1988–2023. PR shows the percentage of journal publications to the total publications in PCM. The Journal of Applied Thermal Engineering has the most publications in PCM, with 901 publications, and the Journal of Energy Storage is in second place, with 842 publications. These two journals contain 11.2 % of all publications in PCM. The journals Applied Energy, Solar Energy Materials and Solar Cells, and Energy and Buildings are in third, fourth, and fifth places, respectively. Moreover, 6719 articles have been published in the top twenty journals, which includes 43.1 % of all publications.

Table 7
Top twenty most productive journals.

Journal name	TP	PR (%)	IF
Applied Thermal Engineering	901	5.8	6.465
Journal of Energy Storage	842	5.4	8.907
Applied Energy	488	3.1	11.446
Solar Energy Materials and Solar Cells	460	2.9	7.305
Energy and Buildings	435	2.8	7.201
International Journal of Heat and Mass Transfer	417	2.7	5.431
Energy Conversion and Management	406	2.6	11.533
Solar Energy	365	2.3	7.188
Energy	359	2.3	8.857
Renewable Energy	357	2.3	8.634
International Journal of Energy Research	260	1.7	4.672
Energies	244	1.6	3.252
Journal of Thermal Analysis and Calorimetry	199	1.3	4.755
Construction and Building Materials	180	1.2	7.693
Materials Today-Proceedings	162	1	–
Thermochimica Acta	157	1	3.378
Materials	138	0.9	3.748
Chemical Engineering Journal	119	0.8	16.744
International Journal of Thermal Sciences	116	0.7	4.779
Case Studies in Thermal Engineering	114	0.7	6.268
Total	6719	43.1	–

Fig. 7 shows the scientific publication of the five journals with the most scientific publications over time. This figure shows that Applied Thermal Engineering, Journal of Energy Storage, Applied Energy, Solar Energy Materials and Solar Cells, Energy and Buildings have had the most publications in PCM. Considering that there were few scientific publications before 2000, the old data before 2000 have been integrated into one group, and since 2000 scientific publications have been displayed annually.

According to Fig. 7, the publications were insignificant, and no significant difference can be seen between the publications of journals until 2012. From 2012 to 2017, all top journals except the Journal of Energy

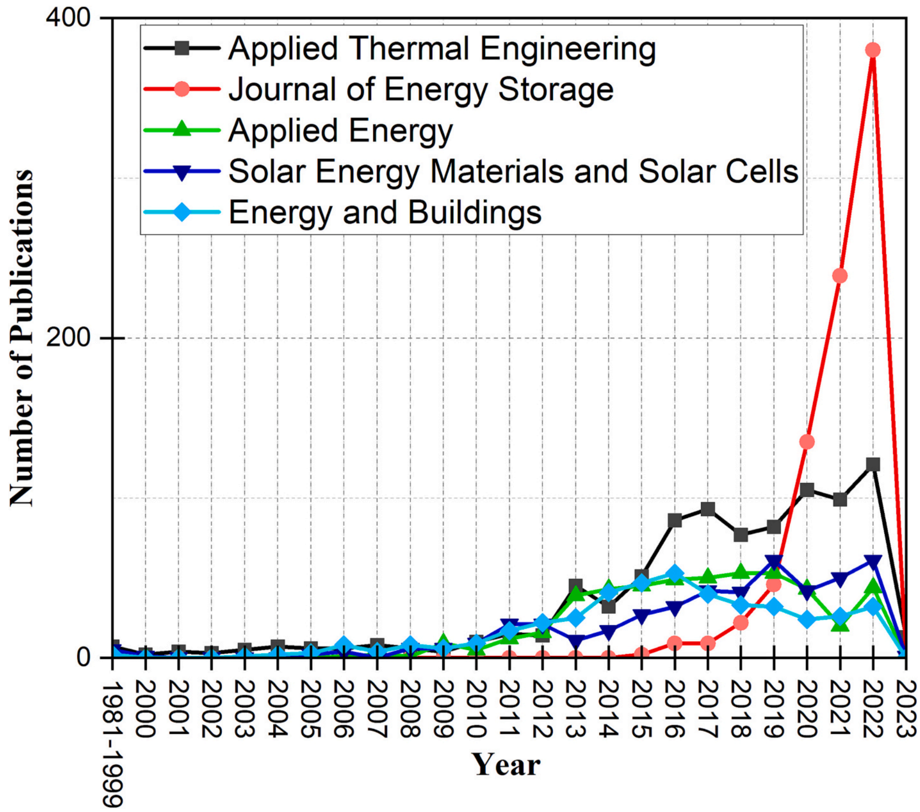

Fig. 7. Publications of top five journals over time.

Storage tried to increase their publications in PCM. From 2017 onwards, the Journal of Energy Storage dramatically increased its publications in PCM. So, the publications in this journal reached 380 in 2022. Before 2020, no journals had more than 100 publications per year in PCM. Two journals, Applied Thermal Engineering and Journal of Energy Storage, reached the mark of 100 publications in 2020. From 2015 to 2019, Applied Thermal Engineering had the most publications in PCM, and since 2019, the Journal of Energy Storage had the highest number of publications.

4.5. Web of Science research areas analysis

Web of Science core collection assigns every journal and book to at least one subject category [48]. Users can explore and evaluate research topics and trends in a particular subject with the use of the Web of Science Research Areas analysis tool. It is based on the extensive database of scholarly papers known as the Web of Science (WoS). The program identifies and categorizes papers into research fields using text-mining algorithms and manual indexing. Users can utilize this to search, browse, and explore various research fields, view the most often referenced books, authors, and institutions, and track the evolution of research trends.

Table 8 shows the top twenty subject areas with the most scientific publications. In the present study, 130 subject areas contained at least one scientific publication in PCM. The subject area of Energy & Fuels contains the most scientific publications in PCM with 6603. This subject area has approximately 42.3 % of all the publications. The subject areas of “Thermodynamics”, “Materials Science Multidisciplinary”, “Engineering, Mechanical”, and “Mechanics” are in the next ranks with 3943, 3100, 2499, and 2226 scientific publications, respectively. It should be noted that a publication may be categorized into several subject areas simultaneously.

Fig. 8 shows the evaluation of the top twenty subject areas in five group years. All subject areas contain insignificant scientific publications in the first (1981–1999) and second (2000–2005) periods. In the third period (2006–2011), an increase can be seen in all subjects, especially in the following six subjects: “Energy & Fuels”, “Thermodynamics”, “Materials Science, Multidisciplinary”, “Engineering, Mechanical”, “Mechanics”, and “Physics, Applied”. The fourth period (2012–2017) is the beginning of the prosperous period in PCM. In this period, both “Energy & Fuels” and “Thermodynamics” subject areas significantly raised and exceeded the limit of one thousand scientific publications. The trend continued in the last period (2018–2023). In the last period, only the six subject areas of “Energy & Fuels”, “Thermodynamics”, “Materials Science, Multidisciplinary”, “Engineering,

Table 8
Top twenty web of science subject areas.

Subject area	TP	PR (%)
Energy & Fuels	6603	42.3
Thermodynamics	3943	25.2
Materials Science, Multidisciplinary	3100	19.8
Engineering, Mechanical	2499	16
Mechanics	2226	14.3
Physics, Applied	2035	13
Construction & Building Technology	1313	8.4
Chemistry, Physical	1224	7.8
Engineering, Chemical	1100	7
Engineering, Civil	967	6.2
Engineering, Electrical & Electronic	962	6.2
Green & Sustainable Science & Technology	892	5.7
Nanoscience & Nanotechnology	709	4.5
Chemistry, Multidisciplinary	676	4.3
Physics, Condensed Matter	602	3.9
Optics	527	3.4
Polymer Science	428	2.7
Chemistry, Analytical	377	2.4
Engineering, Environmental	368	2.4
Engineering, Multidisciplinary	354	2.3

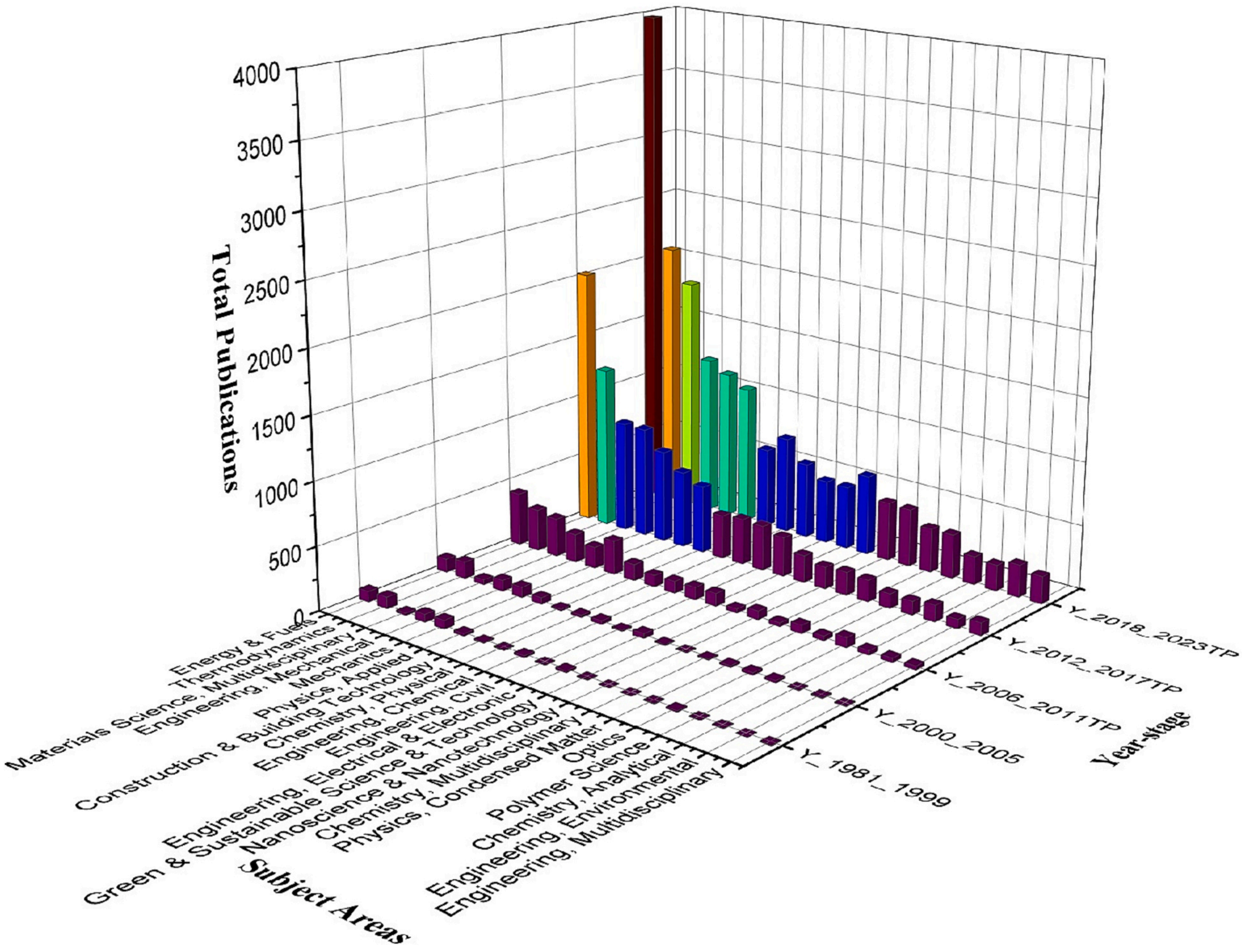

Fig. 8. Change of 20 most productive subject areas over time for four stages.

Mechanical", "Mechanics", and "Physics, Applied" had more than a thousand scientific publications. It is clear that the "Energy & Fuels" subject area is now at the top of the present period with about 4000 scientific publications.

Fig. 9 shows the relationship between subject areas. Each line in the figure represents at least six connections. Connections that were less than six were not drawn in the figure to avoid congestion. Thus, each line between two subject areas represents at least six joint publications, and the thickness of each line indicates the number of joint publications. A thicker line indicates more connections or a stronger correlation. The size of each circle stands for the connection numbers. It is interesting that "Engineering, Civil" has the smallest circle size and the lowest number of connections among all subject areas. In contrast, the three subject areas of "Thermodynamics", "Engineering, Mechanical" and "Mechanics" have a powerful relationship with each other and have formed a cluster. Each cluster member has established a strong connection (thick lines) with Energy & Fuels. Energy & Fuels can be considered a hub with a line of communication with all subject areas. The two subject areas of "Chemistry, Physical" and "Engineering, Civil" have the weakest connection (thin lines) with Energy & Fuels.

Table 9 shows eight countries with the most involved web of science subject areas. According to this table, the most involved subject areas belong to China, with 104 different subject areas. The USA, India, and France are in the next rank. China has a high and rising energy demand, which has necessitated the development of more efficient and sustainable energy storage technologies, such as those based on phase change materials. This demand may increase the importance of research and development in this field.

The top eight countries, presented in Table 5, are China, the USA, India, UK, Iran, France, Germany, and Spain. Fig. 10 depicts the subject areas of these top eight countries in PCM in the form of a radar map.

The publications of each country were examined in the top ten subject areas. All countries, except Germany, have published most of their publications in "Energy & Fuels". Most of Germany publications were in "Materials Science, Multidisciplinary" and then "Energy & Fuels". The USA's publications are almost equally distributed in the four fields of "Energy & Fuels", "Thermodynamics", "Materials Science," "Multidisciplinary", and "Engineering, Mechanical". Germany has also paid particular attention to the three subject areas: "Energy & Fuels", "Materials Science, Multidisciplinary", and "Physics, Applied". The focus of Iran has been on the two subject areas of Energy & Fuels and Thermodynamics. The five countries, China, India, UK, France, and Spain, have almost similar patterns.

4.6. Keyword analysis and trending

In this section, we aimed to provide an accurate and realistic analysis of the keywords used in the field of PCMs by conducting a keyword rooting process. This involved identifying and grouping together all the keywords that share the same root and represent a single concept.

For instance, we observed that several keywords used in the literature were related to the concept of "Phase Change Materials," including "phase change material," "PCM," "phase change materials," "phase change material (PCM)," "PCMs," and "phase-change materials." To ensure consistency and clarity in our analysis, we took the root of these keywords and referred to them collectively as "Phase Chang Materi" in our research.

By conducting keyword rooting, we were able to streamline and

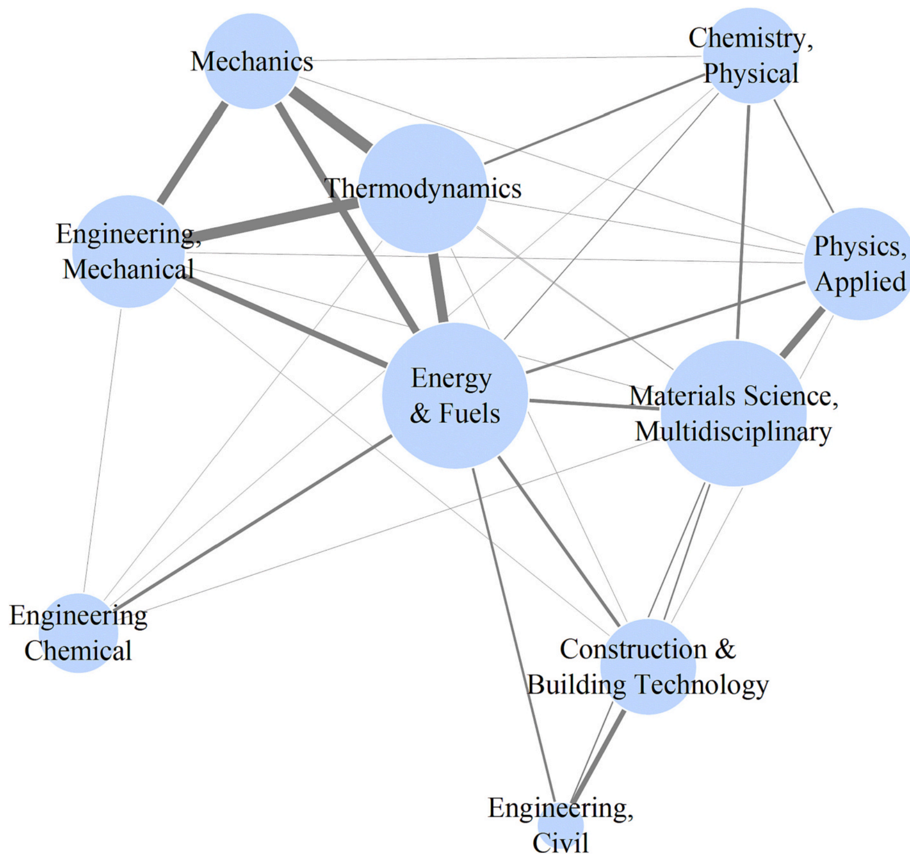

Fig. 9. Connectivity network of a web of science subject areas in PCM.

Table 9
Countries with the most involved web of science subject areas (SC).

SC	China	USA	India	France	South Korea	Germany	Spain	UK
	104	102	81	69	66	64	63	61

simplify the analysis of PCM-related keywords, making it easier to identify the most relevant and significant terms. Fig. 11 shows a graphical representation of the frequency of keywords (in their root form) in the field of PCMs. These words are typically displayed in different sizes or colors to represent their prominence in PCM.

This figure can provide insights into the most important topics and trends in the field of PCMs. The size and prominence of each keyword in the map correspond to its frequency of occurrence in the text data. This allows researchers, engineers, and other stakeholders to quickly identify the most relevant and important keywords and topics related to PCMs.

The keywords "Phase Chang Materi", "Thermal Energi Storag", "Thermal Conduct", "Latent Heat Storag", "Energi Storag", and "Thermal Properti" are frequently used because they are essential to understanding the behavior and potential applications of PCMs. By analyzing the keywords cloud map, researchers can gain a better understanding of the current state of research and development in the field of PCMs and identify potential areas for future research and innovation.

Table 10 provides a comprehensive view of the most prominent and frequently researched keywords related to PCMs. The keyword "Phase Chang Materi" which is present in 10,409 publications, accounting for 66.9 % of the total publications. The rest of documents contain this keyword in other parts of the topic such as their title or abstract. This keyword also claims 257,087 total citations and a high H-index of 167.

Next is "Thermal Energi Storag", appearing in 2276 publications or 14.6 % of the total. It has 70,414 total citations and an H-index of 112. This reflects the importance of thermal energy storage in the application of PCMs, including uses in heating and cooling systems, renewable energy, and grid energy storage.

The term "Thermal Conduct" is found in 759 publications, making up 4.9 % of the total publications, and has been cited 26,441 times. With an H-index of 85, research in this area likely explores the mechanisms of heat conduction in PCMs and methods to enhance their thermal conductivity.

"Latent Heat Storag" is a term that appears in 519 publications keywords, accounting for 3.3 % of the total. With 13,091 citations and an H-index of 60, it refers to the storage of energy in the form of latent heat, a key feature of PCMs. "Energi Storag" is present in 517 publications keywords, 3.3 % of the total, and has 14,365 citations with an H-index of 64. This term indicates the broader context of energy storage, where PCM research is a significant contributor.

"Thermal Properti" is a keyword present in 500 publications or 3.2 % of the total. It has 17,564 citations, yielding an H-index of 71. It represents research focused on understanding and optimizing the thermal properties of PCMs. The term "Latent Heat" is present in 468 publications, accounting for 3 % of the total. It has 14,028 citations and an H-index of 65. This is a key feature of PCMs and research in this area likely focuses on understanding, measuring, and optimizing the latent heat of these materials.

"Thermal Manag" appears in 404 publications, making up 2.6 % of the total. It has 15,194 citations with an H-index of 71. This term refers to the control of temperature in a system, a task at which PCMs excel due to their thermal energy storage capabilities. The term "Heat Transfer" is found in 388 publications, or 2.5 % of the total, with 8924 citations and an H-index of 52. Research in this area likely involves studying and improving how heat is transferred in the context of PCMs. "Melt" is present in 381 publications, accounting for 2.4 % of the total, with 12,407 citations and an H-index of 60. Melting is a key process for PCMs

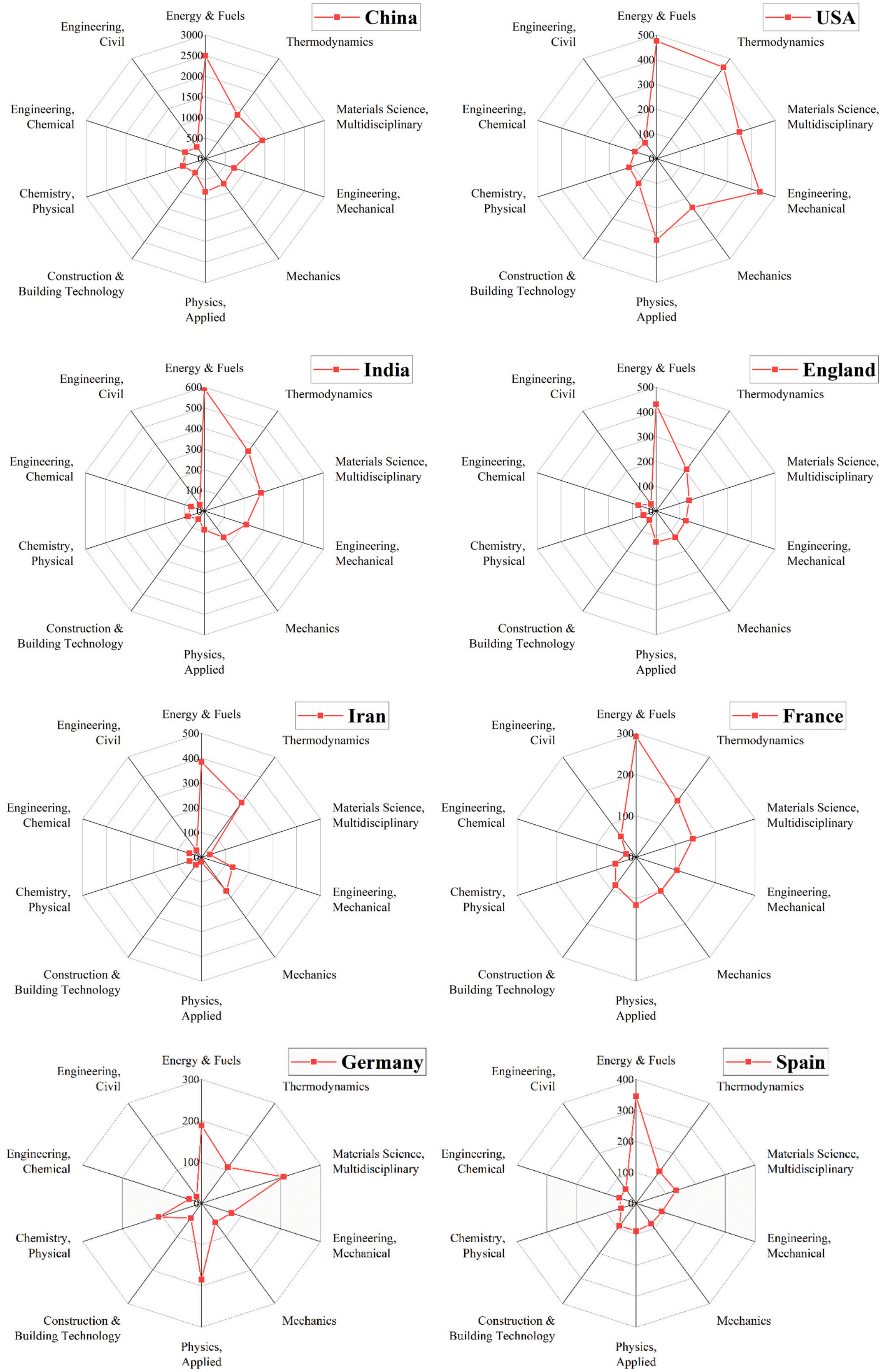

Fig. 10. Radar maps of subject areas from the top eight productive countries during 1981–2023.

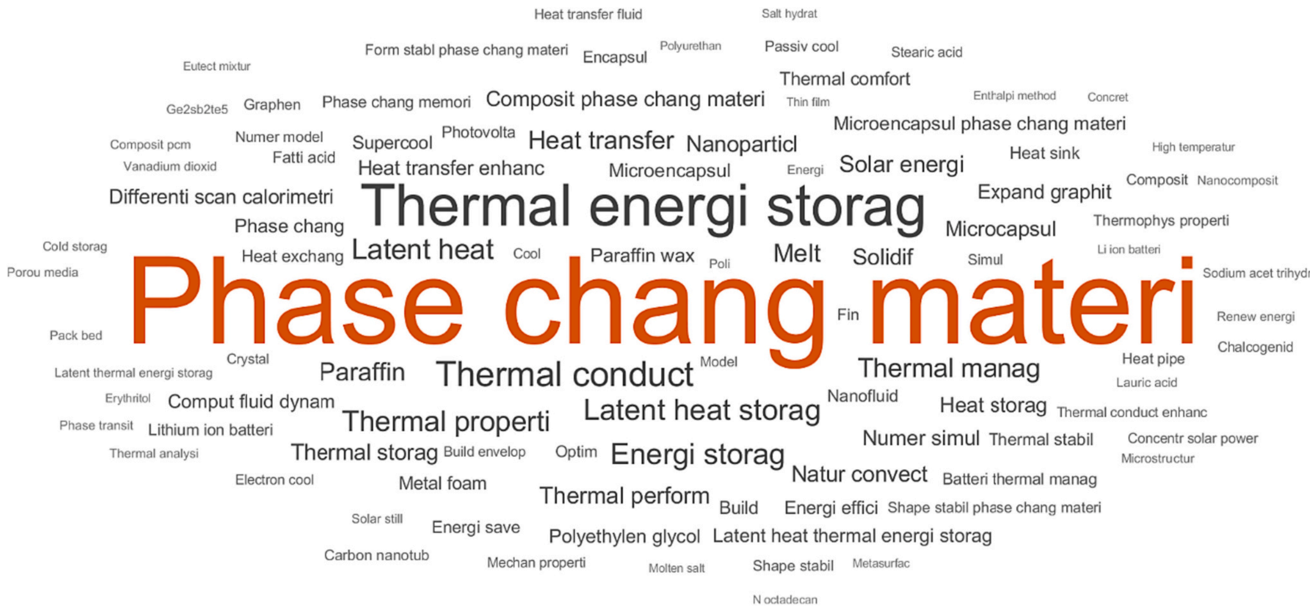

Fig. 11. Cloud map of one hundred top keywords. The keywords are in their root format.

Table 10
Top 20 root keywords in PCM.

Keyword root	TP	TP (%)	TC	HI
Phase Chang Materi	10,409	66.9	257,087	167
Thermal Energi Storag	2276	14.6	70,414	112
Thermal Conduct	759	4.9	26,441	85
Latent Heat Storag	519	3.3	13,091	60
Energi Storag	517	3.3	14,365	64
Thermal Properti	500	3.2	17,564	71
Latent Heat	468	3	14,028	65
Thermal Manag	404	2.6	15,194	71
Heat Transfer	388	2.5	8924	52
Melt	381	2.4	12,407	60
Paraffin	355	2.3	11,710	64
Solar Energi	314	2	7930	52
Thermal Perform	311	2	8573	49
Natur Convect	288	1.8	8110	50
Thermal Storag	285	1.8	7977	47
Nanoparticl	270	1.7	8776	51
Solidif	266	1.7	8072	52
Composit Phase Chang Materi	246	1.6	5740	43
Heat Storag	239	1.5	5424	44
Microcapsul	234	1.5	7766	50

during which they absorb heat and store it as latent heat. This keyword likely represents research focused on understanding and optimizing the melting process of PCMs.

The remaining keywords in Table 10 highlight more specific areas of research within the field of PCMs. “Paraffin” suggests a focus on a particular type of PCM, which is often used due to its suitable melting point and high latent heat. “Solar Energi” indicates a connection between PCM research and solar power, potentially exploring how PCMs can store solar heat for later use. “Thermal Perform” likely reflects research aimed at understanding and improving the efficiency and effectiveness of PCMs in various applications. “Natur Convect” could be related to the study of how natural convection impacts the heat transfer properties of PCMs. “Thermal Storag” further emphasizes the pivotal role of PCMs in storing thermal energy. “Nanoparticl” might point towards investigating nano-enhanced PCMs, which can have improved thermal properties. “Solidif” is another key process in PCMs, during which they release stored heat, and is likely a significant focus of research. “Composit Phase Chang Materi” suggests the study of PCMs combined with other materials to enhance their properties. “Heat Storag” reflects the broader context of heat storage in which PCM research is embedded. Finally, “Microcapsul” could suggest research into microencapsulated PCMs, which have unique advantages such as preventing leakage of the PCM during phase transitions.

Fig. 12 illustrates trends for top eight keywords from 1991 to 2022. The term “phase change materi” first appeared in 1991, experienced a peak in 1992, and then showed a steady presence throughout the remaining years. This term likely pertains to PCMs, which are substances with a high heat of fusion and are used in various applications ranging from energy storage to construction and textiles.

The term “Thermal Energi Storag” also appeared in 1991, but unlike “phase change materi,” it experienced an incline in the subsequent year. The trend for this term shows a gradual increase over the years, suggesting growing interest and applications in this area. Thermal energy storage systems are essential for managing energy demands by storing excess thermal energy for later use.

The trends for “phase change materi” and “Thermal Energi Storag” have been relatively constant over the examined period. This consistent presence highlights the ongoing significance of these terms within their respective fields. It's likely a reflection of the steady development and application of phase change materials and thermal energy storage technologies. These technologies play vital roles in numerous sectors, such as renewable energy and heating and cooling systems, contributing greatly to energy efficiency and sustainability goals.

“Thermal conduct” only began appearing in the data in 1999. This keyword has seen an upward trend, despite experiencing fluctuations, from 1999 to 2022. This increasing interest could be due to advancements in material sciences, focusing particularly on the thermal conductivity properties of various materials. Thermal conductivity is vital in many applications, including heat dissipation in electronics, energy efficiency in insulation materials, and thermal comfort in clothing.

“Latent Heat Storag” appears first in 1996. It reached its peak in 1999 and then followed a generally downward trend until around 2010. After 2010, the trend seems to stabilize, indicating a consistent research interest and application of this concept. Latent heat storage is an efficient way of storing thermal energy, especially in phase change materials. The shifts in its trend might be indicative of changing research focus, technological advancements, or variations in funding and market demand in the field of energy storage.

“Energi storag”: The term first made an appearance in 1993, and its frequency has fluctuated until 2005. This could be attributed to the

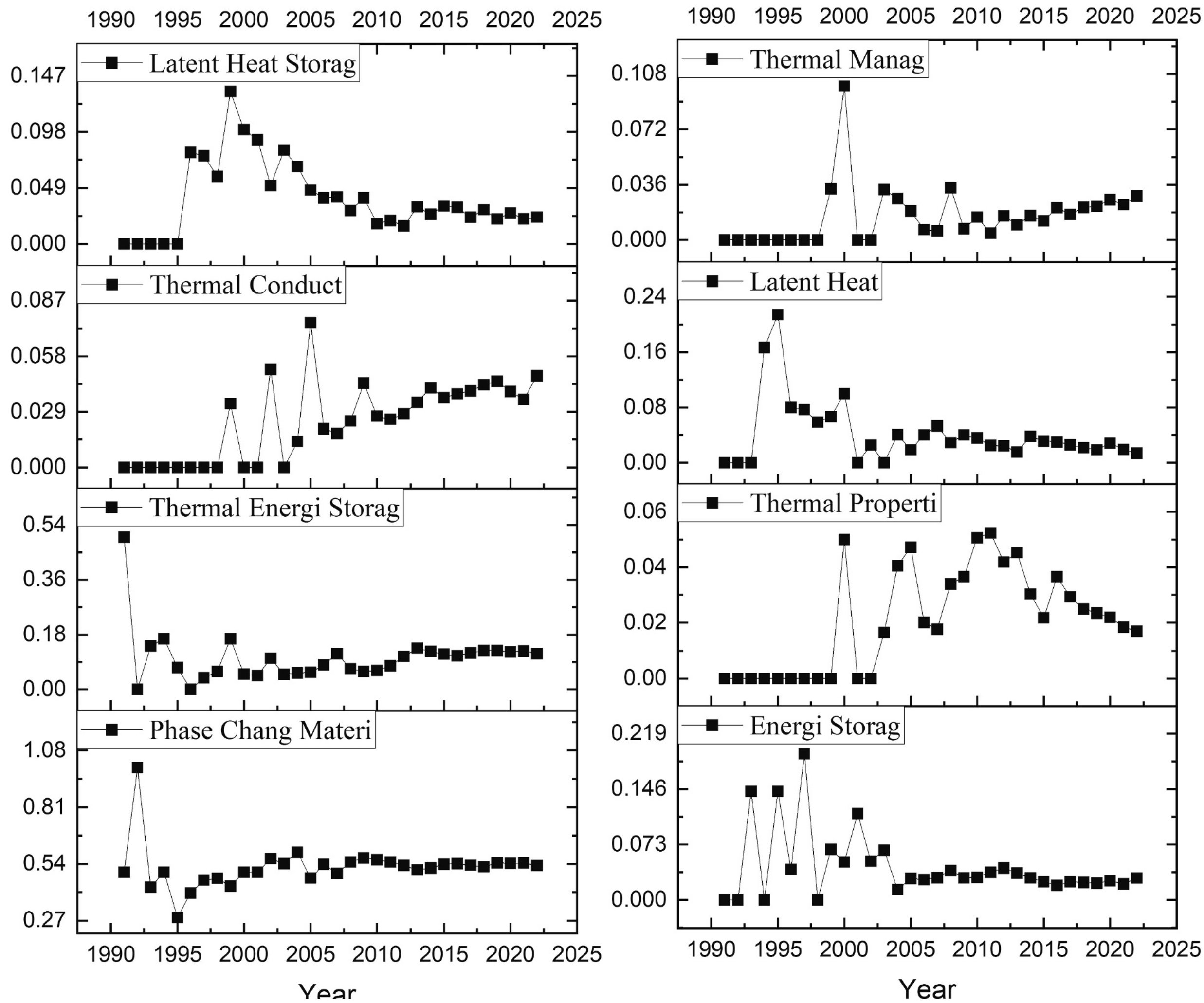

Fig. 12. The behavior of root keywords with TP greater than 400 over time.

evolving nature of the field, with different focus areas gaining prominence at other times. However, since 2005, the usage frequency of "energi storag" has stabilized, suggesting that it has become a core topic in the field of PCMs. The consistency of its presence over the past few decades underscores its ongoing significance in the study and application of PCMs.

"Thermal properti": The frequency of this term shows significant variability from 2000 to 2016, pointing towards changing research interests and the rise and fall of different trends within the field. However, its usage frequency has been declining since 2016. This could imply that studies focusing specifically on the "thermal properties" of PCMs have been less frequent in recent years, possibly due to a shift in research emphasis towards other aspects of PCMs.

"Latent heat": The trend of "latent heat" is almost similar to "latent heat storag," suggesting a strong correlation between these two terms in the literature. This is not surprising, given that latent heat storage is a primary mechanism of energy storage in PCMs. The trend of these keywords reflects the ongoing importance of understanding and optimizing the latent heat storage capacity of PCMs.

"Thermal manag": The term reached its maximum usage in 2000, suggesting a heightened interest in thermal management applications of PCMs around this time. What is more, there has been a noticeable upward trend in its usage over the past decade. This suggests that thermal management has become an increasingly critical consideration in PCM research and applications. This trend may be driven by the growing demand for effective thermal management solutions in various sectors, from electronics to building design to renewable energy systems.

4.7. *Top papers with more than 1000 citations in PCM*

Table 11 lists the top selected papers in PCM with more than 1000

Table 11
List of top selected publications (review and original papers) with more than 1000 citations in PCM.

Reference	PY	TI	TC
[42]	2009	"Review on thermal energy storage with phase change materials and applications"	3339
[49]	2003	"Review on thermal energy storage with phase change: materials, heat transfer analysis and applications"	3131
[50]	2007	"Phase-change materials for rewriteable data storage"	2574
[51]	2004	"A review on phase change energy storage: materials and applications"	2118
[52]	2010	"A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS)"	1242
[53]	2010	"Phase Change Memory"	1160
[54]	2014	"Phase change materials for thermal energy storage"	1091
[55]	2012	"Review on thermal energy storage with phase change materials (PCMs) in building applications"	1090
[56]	2011	"Materials used as PCM in thermal energy storage in buildings: A review"	1068

citations each. In the following, the key topic and outcomes of these top papers have been discussed. Sharma et al. [42] reported that PCMs are desirable materials for use in thermal energy storage systems due to their high energy storage density and isothermal nature. They focus on the most recent analysis of the thermal characteristics of PCMs and how they are used in various scenarios. These include off-peak power storage systems, waste heat recovery systems, solar water heating systems, solar air heating systems, solar cooking, solar greenhouses, and space heating and cooling applications for buildings. Additionally, the research examines melt fraction analyses of the few discovered PCMs employed in various storage system applications using diverse heat exchanger container materials [42]. Overall, PCMs have several uses in thermal energy storage systems and have the potential to be helpful for energy saving. To fully realize their potential and maximize their use, more studies are required. The benefits of PCMs for use in thermal energy storage systems are discussed in this review paper, along with an outline of the most recent research in this area [42].

In the past two decades, a group of studies has reported using solid-liquid PCMs for TES. There are 45 commercially available choices in addition to over 150 materials that have been identified as possible PCMs. The thermophysical characteristics of these materials, as well as their long-term stability and encapsulation, are also included in the paper. Theoretical aspects of heat transport, including numerous modeling methods, are also covered in this article. The use of PCMs in buildings, preserving and transporting temperature-sensitive products, and comparing water tanks to PCM tanks are also explored. Overall, the work offers a thorough analysis of TES with PCMs and is a useful reference for field scholars [49].

Another application of phase-change is in data storage as phase-change memory to be used as non-volatile electronic memory in rewriteable data storage. The special qualities of phase change memory for data storage are examined in [50]. In their crystalline form, these materials usually have atomic arrangements resembling an octahedron and noticeable lattice aberrations, and enormous vacancy concentrations. This is a result of p-orbitals' promotion of chemical bonding. The article explores using crystalline knowledge to construct phase change memory with the desired qualities. Phase change memories' optical characteristics are also examined, particularly the difference between amorphous and crystalline states. The paper also discusses the reasons behind phase change memory's quick crystallization kinetics. The article ends by posing questions that can serve as a roadmap for future research into determining phase change memories with the best qualities for data storage, such as how to reduce the power required to melt the crystalline region and how to identify PCMs that are compatible with electrical memories but incompatible with the specifications for optical storage.

With PCM, thermal energy can be stored via latent heat storage, which offers a greater capacity and a smaller temperature differential between heat storage and release. The review of Farid et al. [51] summarizes past contributions to creating new classes of PCMs for TES applications and analyzes prior works on latent heat storage. In this overview, PCM materials, encapsulation, and applications are the main topics. Numerous PCMs are ideal for various applications because they melt and solidify at a wide temperature span. Compared with hydrated salts with higher energy storage density and thermal conductivity but subject to supercooling and phase separation, paraffin wax, which is less expensive and has lower thermal conductivity, has moderate energy storage density. Encapsulating PCMs can limit their reactivity to the environment, increase heat transfer area, and regulate how much the volume of storage materials varies while phase transition takes place. This paper also reviews the various uses of the phase change thermal energy storage method, such as building heating/cooling, and satellite thermal storage. The issues with PCM materials and techniques for containing them are also covered in the study.

This review [52] discusses the evolution of latent heat TES systems with a particular emphasis on the various PCMs studied over the past three decades; reports the heat transfer and PCM-enhanced techniques to charge/discharge latent heat energy; and identifies the formulation of the phase change problem. The research conducted numerical and experimental tests to examine the geometry and configurations of PCM containers for assessing variables like the input temperature and the mass flow rate of the heat transfer fluid. The research determined that most phase change issues have been investigated at temperatures between 0 °C and 60 °C, which are appropriate for household heating applications. Enthalpy formulation has been a widely used strategy in problem formulation. Before accounting for additional convection in the melt, the phase change problem's heat transport was conceptualized using a pure conduction approach. However, the situation has since become more complex. Since there is no established standard test procedure for PCMs, comparing them and determining which applications PCMs are best suited for is challenging. Comparisons and knowledge transfer from one test to another must be made possible to ensure the same or similar standards (performance curves), such as British or EU standards.

In [53], the developments in phase-change-memory technology are reviewed. The study discusses the thermal and electrical characteristics of PCMs, emphasizing scaling and how it affects device design. The essay also discusses techniques for multi-bit operation, 3-Dimension, multi-layer high-density memory arrays, and improvements in device structure and memory cell selectors. The uses of specialized devices and innovative materials highlight the scaling features of phase-change-memory. Additionally, factors influencing phase-change-memory's dependability are examined. The paper indicates that gains in performance require sophisticated knowledge of phase transition, electrode bulk, and interface properties as phase-change-memory technology scales and integrates more sophisticated materials. As the crucial technology for a high-density memory array, the memory cell selector takes up the most layout space in the memory cell and is challenging to satisfy the needed standards. Phase change memory is now advanced to the place where it can be applied in real-world systems, so it is possible to redesign how memory and storage are used to improve energy efficiency and user applications.

The use of PCMs in TES systems is reviewed in this research [54]. Latent heat offers a higher energy density with a smaller temperature differential than sensible heat. Investigated groups of materials include polymeric materials, organic compounds, and inorganic systems. Additionally, the study highlights current initiatives to enhance the functionality and security of PCMs, such as enhancing thermal conductivity, encapsulating techniques, and shape stabilization. Future research directions are also given, as well as the broad spectrum of PCM applications in many industries. According to the study, TES with PCMs are advantageous over sensible heat storage devices and are widely used in fields including buildings, electronics, biomedicine, textiles, and automobiles. However, the PCMs' service life and stability over numerous temperature cycles determine whether utilizing them is economically feasible.

Applications of PCMs for TES in buildings have been the subject of prior research, which has been reviewed [55]. It goes over the criteria for choosing PCMs, such as the ideal phase change temperature range for comfortable indoor temperatures, as well as the essential chemical stability, fire resistance, and compatibility with existing building materials. The article also discusses several strategies for embedding PCMs into the walls, floors, and ceilings of buildings to lessen temperature variations and enhance passive solar heating and off-peak thermal storage. The importance of assessing thermal performance using metrics like thermal inertia, total equivalent temperature difference, thermal capacitance, U-value, and R-value is also emphasized in the text. Details about the terminologies can be referred to [55]. The study concludes that while PCMs have been proven effective at reducing temperature variations, more research is necessary to determine their long-term stability and safety.

The use of PCMs in TES for buildings is discussed in [56]. An overview of the prerequisites for employing this technology, the categories of materials, and the materials that are available for usage are provided in the article. The article also examines the issues that have previously been faced and potential solutions to these issues. The article concludes that although PCMs for TES in buildings have been widely studied, more research is required to find new and affordable materials and more effective solutions to technical issues like PCM subcooling, phase segregation, and material compatibility.

5. Conclusions

The publications of the last four decades on PCMs were analyzed using a scientometric analysis approach. A total of 16,771 records were found, of which 15,620 were journal and conference publications selected for analysis. After analyzing the data, the most influential organizations, countries, journals, and subject areas were identified. The connection between research areas was also mapped and studied. A systematic approach was applied to analyze keywords in the realm of PCMs. The major findings of this research can be summarized as follows:

From 1981 to 2010, there was very little scientific publication in the field of phase change materials, but this changed significantly from 2011 to 2022. The maximum production occurred in 2022, with 14.7 % of total publications. Regarding the countries, from 1981 to 2006, there were few scientific publications, and there was almost no significant difference between countries, while China was more active than others. The top three countries in terms of total publications (TP) were China, USA, and India, respectively. The top three countries in terms of total citations (TC) are China, USA, and UK. Singapore has received the most citations compared to the number of its publications. Moreover, Saudi Arabia has published 91 % of its scientific publications with the cooperation of other countries and has the highest level of cooperation among countries.

China, the USA, and the UK have the highest H-index with values of 133, 106, and 78, respectively. China and India have been the first or corresponding authors in most of their publications. As a result, India and China were among the pioneer of the PCM movement, and other countries tried to participate in the PCM movement in parallel. From the institution point of view, the top five institutions in total publications (TP) were Chinese Acad Sci, Xi An Jiao Tong Univ, Univ Lleida, South China Univ Technol, and Sichuan Univ, respectively. Rhein Westfal Th Aachen has received the most citations compared to its number of publications. The top three institutions in terms of collaboration with other institutions are Univ Lleida, Rhein Westfal Th Aachen, and the Chinese Acad Sci, respectively. Chinese Acad Sci ranks first among institutions in PCM in both parameters of AU1, AUC, and H-index. Gaziosmanpasa Univ ranks second after Chinese Acad Sci in term of H-index.

Five prestigious journals with the most scientific publication are Applied Thermal Engineering, Journal of Energy Storage, Applied Energy, Solar Energy Materials and Solar Cells, Energy and Buildings. Journal of Applied Thermal Engineering and Journal of Energy Storage contains 11.2 % of all publications in PCM.

Energy & Fuels subject area contains the most scientific publications with approximately 42.3 % publications in PCM. The subject areas of “Thermodynamics”, “Materials Science Multidisciplinary”, “Engineering, Mechanical”, and “Mechanics” rank next. The “Thermodynamics”, “Engineering, Mechanical” and “Mechanics” subject areas have a powerful relationship with each other. The subject area of Energy & Fuels is a hub and has established a strong connection with all the subject areas. China has the broadest reach across Web of Science subject areas, spanning a total of 104 distinct fields. The top eight countries with the most publications in the field of PCM have published most of their publications in “Energy & Fuels” subject area, except Germany, which has focused on “Materials Science, Multidisciplinary”.

The keywords “Phase Chang Materi,” “Thermal Energi Storag,” “Thermal Conduct,” “Latent Heat Storag,” “Energi Storag,” and “Thermal Properti” appeared frequently, indicating their importance in understanding PCMs' behavior and potential applications. The keywords “Thermal Energi Storag” and “Thermal Conduct” appeared in 2276 (14.6 %) and 759 (4.9 %) publications respectively.

The trends of the top eight keywords from 1991 to 2022 were evaluated. “Phase change materi” and “Thermal Energi Storag” showed a steady presence throughout the years. “Thermal conduct” started appearing in 1999 and showed an upward trend. “Latent Heat Storag” peaked in 1999 and then stabilized after 2010. The term “Energi storag” showed stability since 2005. The frequency of “Thermal properti” has been declining since 2016, and “Thermal manag” showed an upward trend in the past decade.

CRediT authorship contribution statement

Yinghong Qin: Conceptualization, Methodology, Formal analysis, Data curation, Writing – review & editing, Supervision, Investigation. **Mohammad Ghalambaz:** Visualization, Writing – original draft, Investigation, Formal analysis, Software, Validation, Data curation, Supervision. **Mikhail Sheremet:** Methodology, Conceptualization, Investigation, Formal analysis, Data curation, Writing – review & editing. **Mehdi Fteiti:** Investigation, Formal analysis, Writing – review & editing, Conceptualization. **Faisal Alresheedi:** Conceptualization, Investigation, Writing – review & editing.

Declaration of competing interest

The authors clarify that there is no conflict of interest for report.

Data availability

Data has been made available in the following address with DOI 10.17632/dbnnjpt6f8.1.

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