

Review

Nano-Enhanced Phase Change Materials for Thermal Energy Storage: A Bibliometric Analysis

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Abstract: The high latent heat thermal energy storage (LHTES) potential of phase change materials (PCMs) has long promised a step-change in the energy density for thermal storage applications. However, the uptake of PCM systems has been limited due to their relatively slow charging response, limited life, and economic considerations. Fortunately, a concerted global research effort is now underway to remove these remaining technical challenges. The bibliometric analysis of this review reveals that a major focus is now on the development of nano-enhanced phase change materials (NePCM), which have the potential to mitigate many of these technical challenges for PCM-based thermal energy storage systems. As such, our bibliometric analysis has zeroed in on research in the field of thermal energy storage using NePCMs since 1977. It was found that journal articles were the most frequently used document type, representing 79% of the records and that the pace of new work in this specific area has increased exponentially over these two decades, with China accounting for the highest number of citations and the most publications (168), followed by India and Iran. China has also played a central role in the collaboration network among the most productive countries, while Saudi Arabia and Vietnam show the highest international collaboration level.

Keywords: nano-enhanced phase change material; NePCM; latent heat thermal energy storage; LHTES; bibliometric analysis; solar energy; electronic devices; cooling



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1. Introduction

Fossil fuels as primary resources are non-renewable and have severe impacts on the environment, such as the emission of greenhouse gases and global warming. On the other hand, energy demands rapidly grow, while generating conventional energy sources is much lower than their depletion. Hence, renewable energy sources have drawn extensive attention as potential alternatives [1]. Renewable energy with lower costs can impact energy supply and demand.

1.1. Thermal Energy Storage

Since the output of many renewable energy sources is unpredictable, they require energy storage systems. Solar energy is an excellent example of renewable resources coming with low negative impacts. Given that this energy is intermittent and dependent on weather conditions, efficient energy storage is essential to compensate for the inherent limitations. Thermal energy storage (TES) systems are widely studied as an effective technique to store solar energy all day and later utilise it overnight or on overcast days [2]. Recent advancements in TES systems are classified into two main parts: (i) physical storage and (ii) chemical storage. Physical storage is based on heat transfer mechanisms, while reversible chemical reactions play a significant role in chemical storage. As shown in Figure 1, thermal energy can be stored in physical storage by sensible and latent techniques [3].

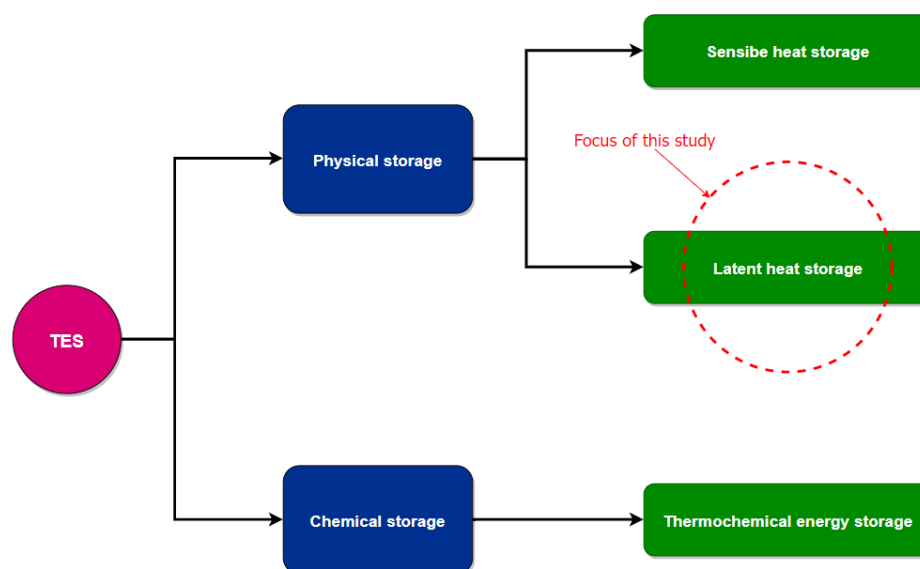


Figure 1. Classification of TESs. Adapted with permission from Ref. [3]. Copyright 2019 International Journal of Heat and Mass Transfer.

1.2. PCMs in LHTES

PCMs in LHTES units represent a compact medium to absorb and release energy [4]. The phase transition of PCMs is the key factor in charge and discharge TES systems, which occurs from the solid or liquid phase to the others [3]. Various materials are adopted for PCMs, such as organic, inorganic, or eutectics with different melting temperatures (-100 to 1000 °C). The performance of PCMs is highly dependent on the melting point. In this regard, PCMs are divided into three categories: low, middle, and high melting temperatures [2]. Huang et al. [5] assumed that the low temperature for melting temperatures is up to 120 °C, the middle for temperatures is between 120 °C and 300 °C, and the high melting temperature for temperatures is over 300 °C. Since PCMs are highly beneficial for storing thermal energy, they have a wide range of applications in solar systems, save energy in buildings, lithium-ion battery cooling, and efficient electronic cooling systems [6–12].

However, the serious challenge of PCMs is their low intrinsic thermal conductivity, increasing phase change process time, especially in solidification, since natural convection is low and conduction heat transfer is dominant [2]. Hence, various passive solutions have been proposed to tackle this issue and improve PCM functionality [11,13–15]. A simple approach is to work on the arrangement of heat transfer fluid (HTF) tubes surrounded by PCMs. Senthil [13] studied the position of HTF tubes on the melting of PCM. The inclined configuration was superior to concentric and eccentric arrangements. The following solution is HTF tubes with embedded fins to increase the contact area with PCMs and enhance the heat transfer rate [16,17]. Another method is to combine multiple PCMs with different melting temperatures to resolve the long process of phase changing [11,14,15]. Mozafari et al. [11] compared the performance of a single PCM to multiple PCMs in a heat sink. They obtained the best thermal performance when n-Eicosane and RT44 were combined. Further, the operational time was accelerated by 3.3–12%. Another method is the nano encapsulated phase change material (NEPCM), which can be adopted in base fluids [2,18,19]. Eventually, one of the most efficient techniques to overcome the remaining challenge is nano-enhanced phase change materials (NePCMs), achieved by adding nanoparticles with high thermal conductivity into PCMs [2,20].

Although a large number of NePCM articles have been published in recent years, no bibliometric study has been reported. The present study provides an overview of the application of NePCMs in LHTES systems. In addition, it aims to review publications on nanostructure additives into PCMs systematically and identify the scientific research direction, productive authors, sources, and countries in this field using bibliometric analysis.

The study is synthesised into four sections in this paper. Section 2 presents the overview of NePCMs in LHTES. The literature findings using bibliometric analysis are introduced in Section 3. A full bibliographic analysis is presented in Section 4, aiming to explore the literature based on different bibliometrics. Finally, conclusions are drawn in Section 5. By identifying the research direction, active researchers, leading sources, and productive countries, the findings in this paper are beneficial for the research communities seeking literary sources, insight into research trends and focus on NEPCM as well as international research collaboration opportunities.

2. Overview of NePCMs

Nanotechnology has paved the way to produce particles with higher thermal conductivity in nanoscales, including metal, metal oxide, single-walled carbon nanotube (SWCNT), multi-walled carbon nanotube (MWCNT), graphene, and graphite [21]. The addition of these highly thermal conductive nanoparticles in PCMs improves heat transfer performance. However, the thermal conductivity of NePCMs is affected by factors such as the size, shape, and type of particles, temperature, surfactant, and particle concentration, as shown in Figure 2 [21].

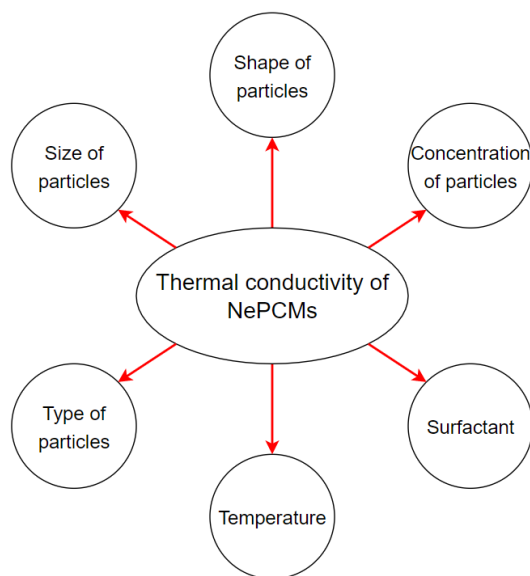


Figure 2. Influential factors affecting NePCMs' thermal conductivity. Adapted with permission from Ref. [21]. Copyright 2019 Journal of Energy Storage.

The use of nanostructures with high thermal conductivity in PCMs enhances the functionality of LHTES significantly [22]. A few contributions were reported using nanoparticles to enhance the thermal conductivity of PCMs before 2005 [23,24]. Later, a significant number of publications embraced nanotechnology to improve the performance of LHTES systems. In 2005, Elgafy and Lafdi [25] examined the effect of nanofibers in paraffin wax and enhanced thermal conductivity remarkably in a highly-cited study. As a result, increasing the carbon additives reduced the solidification time and enhanced the output power. Then, in a leading study, Khodadadi and Hosseinizadeh [20] analysed the potential of NePCMs to improve TES performance. Water PCM, enhanced with copper nanoparticles, demonstrated a higher heat release rate than conventional PCM due to increasing the thermal conductivity and decreasing the latent heat of fusion. Recently, Yazdanifard et al. [26] innovatively combined NePCMs with nanofluids to filter radiation and store solar energy in a photovoltaic thermal system. A wide range of nano additives, such as Al_2O_3 , ZnO , CuO , Cu , SiO_2 , and MWCNT, have been analysed in previous studies [27–30].

3. Methodology

Due to the significance of energy supply in the world, a large number of publications have focused on using nanoparticles in LHTES units to improve the performance of thermal storage. Bibliometrics is classified under information science to manage knowledge and monitor information. While the number of review papers on the content analysis of NePCM articles is considerable, there is no bibliometric analysis in this field. However, this method has been widely used in different fields. For instance, Calderón et al. [31] adopted a bibliometric analysis to identify the trend of TES research over the last twenty years. Later, Saikia et al. [32] monitored and planned the following research trend in solar cooling using the bibliometric approach. In addition, a bibliometric analysis was conducted to understand the perspective of thermal management in lithium-ion batteries [33]. Yataganbaba et al. [34] analysed, through bibliometric methods, the trend of encapsulation of PCMs between 1990 and 2015. The present study is a preliminary bibliometric analysis of LHTES, revealing that NePCM is an emerging topic of interest. This bibliometric study will lead researchers and predict a future trend in the field of NePCMs.

Bibliometrics is a statistical method that illustrates an overview of a specific research field's trend and introduces leading publications, publishers, countries, institutions, and researchers in such research areas [35,36]. Web of Science (WoS) Core Collection is a proper source of high-quality data for bibliometric analyses [37]. In engineering research fields, the Scopus database includes a higher number of publications than WoS [37,38]. The present methodology aims to combine the collected data extracted from both rich databases and remove all duplicates to include all publications about the integration of NePCMs in TESs.

To conduct the research process, different keywords have been selected to search relevant publications on the two websites, such as “phase change material” AND “nanoparticle”, or “phase change material” AND “nano-particle”, or “PCM” AND “particle”, or “nano enhanced phase change material”, or “nano-enhanced phase change material”, or “nepcm”, or “ne-pcm”, AND NOT “nano encapsulated”, AND (LIMIT-TO (language, “English”)) in titles, abstracts, keywords, topics. The search is limited to publications published in English, while there is no specific time span. With the queries, 926 and 807 publications are found in Scopus and WoS, respectively. Looking closely at the titles and abstracts of the collected data results in further refinement. Eventually, exported files are merged, and duplications are removed. The total number of relevant publications in this field is equal to 864. The present bibliometric analysis is carried out using VOSviewer [39] and R package Bibliometrix [40]. The following sections present bibliometric results about relevant authors, sources, institutions, worldwide networks, distribution of publications per year, and other information.

4. Results and Discussion

4.1. Main Information

Due to the improvement of LHTES by NePCMs, most of the publications have focused on this field. As shown in Figure 3, a bulk of publications (79%) collected from the WoS and Scopus databases have been published as journal papers. Furthermore, 12% and 6% of publications are distributed as conference papers and review papers, respectively. Proceedings papers and book chapters have slight portions of 2% and 1%, respectively.

The starting year of the NePCM papers is 1977, and the total document number is 864. However, this research field has become popular since 2005. Hence, Figure 4 shows the annual growth rate of publications between 2005 and 2021, and a few contributions are not shown only in this figure. While an overall increasing trend of 20.34% can be seen in this time span, the number of publications has significantly increased since 2015. It shows that NePCM is a hot topic that has been able to attract more interest due to its effectiveness. For instance, the number of publications reached its peak at 181 in 2021.

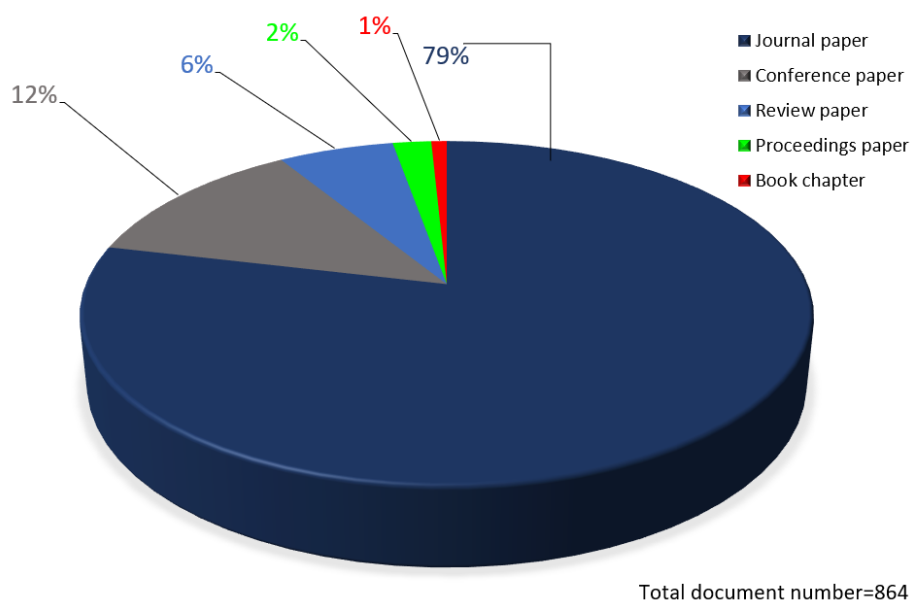


Figure 3. Distribution of publications.

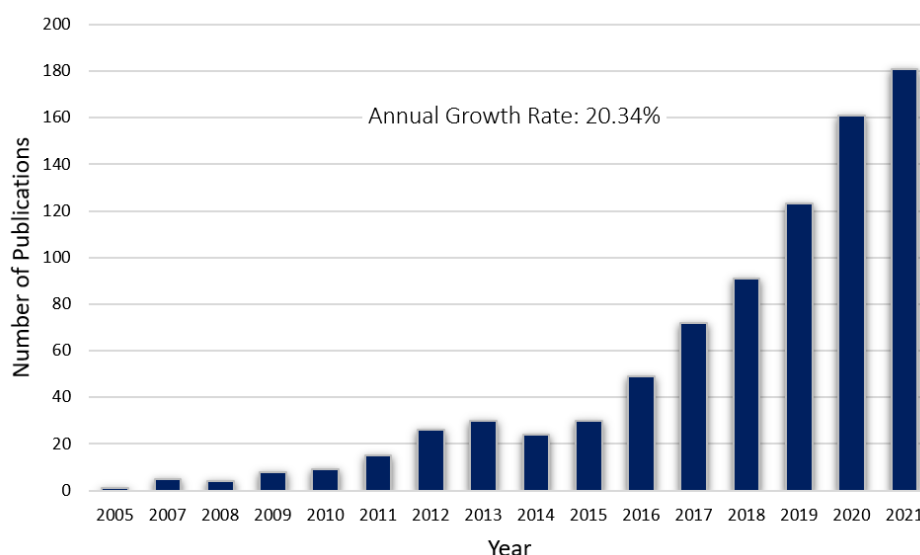


Figure 4. Number of all publications per year.

In this analysis, the collaboration through joint publications between countries is identified by the authors’ affiliations. Bibliographic networks are created to provide the reader with a visual analysis of bibliometrics pertaining to international collaboration. Figure 5 illustrates the relationship between countries publishing more than 15 relevant publications, excluding other countries. In addition, the size of the circles and country names is weighted based on the number of published articles in the NePCM research field. As can be seen, China is the most productive country in this research field (168), followed by India (130), Iran (113), and the United States (67). Saudi Arabia and Iran published more remarkable multiple-country publications (18 and 15, respectively) in this research field. Moreover, the thickness of the lines between countries represents interaction strength, and the colours show different clusters. As the first country with the most significant interactions, Saudi Arabia collaborated more with institutions in Vietnam, Egypt, India, the United States, and Malaysia. Therefore, these countries are shown in one cluster in blue. Moreover, the second cluster in red is formed by Iran, Canada, Turkey, Vietnam, Spain, and France. The third group in green includes China, the United Kingdom, Pakistan, UAE, Morocco, Taiwan, and Singapore. Therefore, these countries are shown in one cluster in

blue. Similarly, the second cluster in red is formed by Iran, Canada, Turkey, Vietnam, Spain, and France. The third group in green includes China, the United Kingdom, Pakistan, UAE, Morocco, Taiwan, and Singapore.

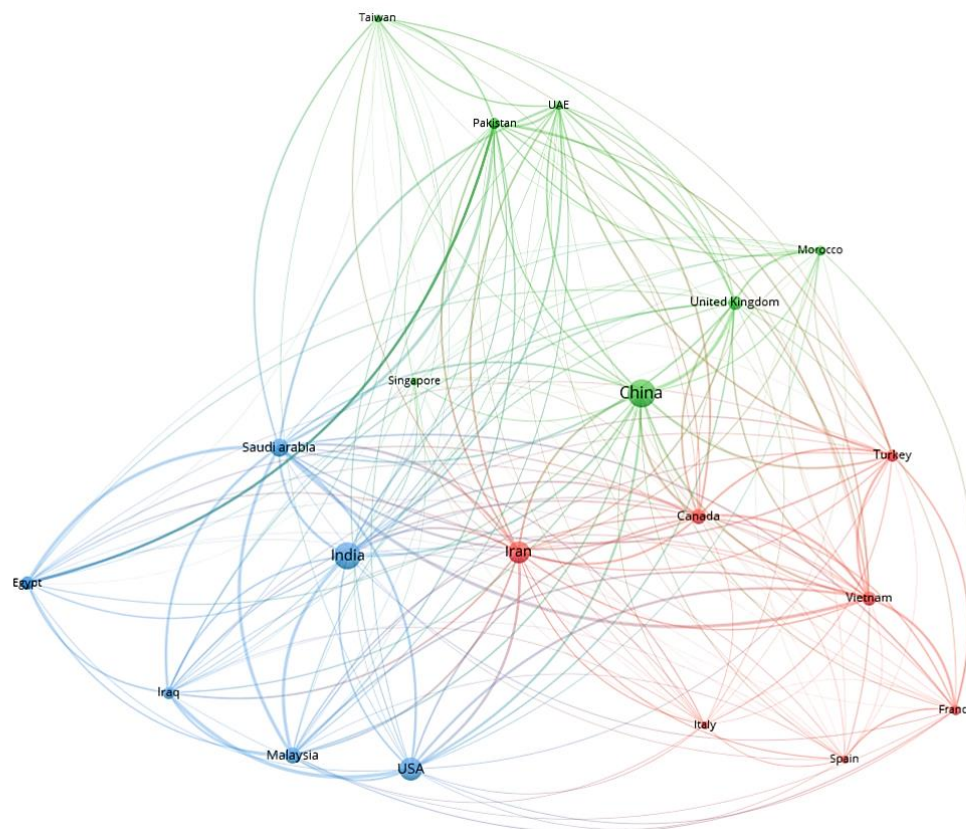


Figure 5. Collaboration between countries.

4.2. Analysis of Keywords

To shed more light on the main idea and research methodology, Table 1 shows 10 authors' keywords with an occurrence over 35. "Phase change material", with 296 occurrences, is the most frequent keyword chosen by authors, followed by "nanoparticles" and "thermal energy storage" with the frequency of 160 and 146, respectively. It is consistent with the main purpose of the current bibliometric study (i.e., the application of NePCMs in TES systems). All collected publications have focused on nanotechnology to improve the performance of LHTES units.

Table 1. Wordcloud of author's keywords with over 35 occurrences.

Terms	Frequency
Phase change material	296
Nanoparticles	160
Thermal energy storage	146
Thermal conductivity	119
PCM	90
Solidification	83
Melting	78
Nanoparticle	78
Nanofluid	41
NEPCM	36

For further evaluation, Figure 6 shows a treemap of the 30 most occurred words in research abstracts with the aim of introducing research gaps and trends to researchers. Treemaps consist of a series of rectangles with different sizes proportional to the frequencies of the words used in abstracts. As shown, “thermal”, “PCM”, and “heat” have been widely used in the abstracts of this research field with the frequency of 2759, 2184, and 1964, respectively. As shown in the figure, every three words with similar frequencies are shown vertically or horizontally next to each other. The second criterion is colour adopted to distinguish the difference in each group of words. As evident, “Thermal” is in blue, while “PCM” and “Heat” are in red and grey, respectively. Then, “nanoparticles”, “phase”, and “material” are the following widespread words in scientific research on NePCMs, whereas “volume” has the minimum occurrence (380) in the figure. It also shows that some influential parameters in NePCM, such as volume fraction, thermal conductivity, and solar application, are popular in previous studies.

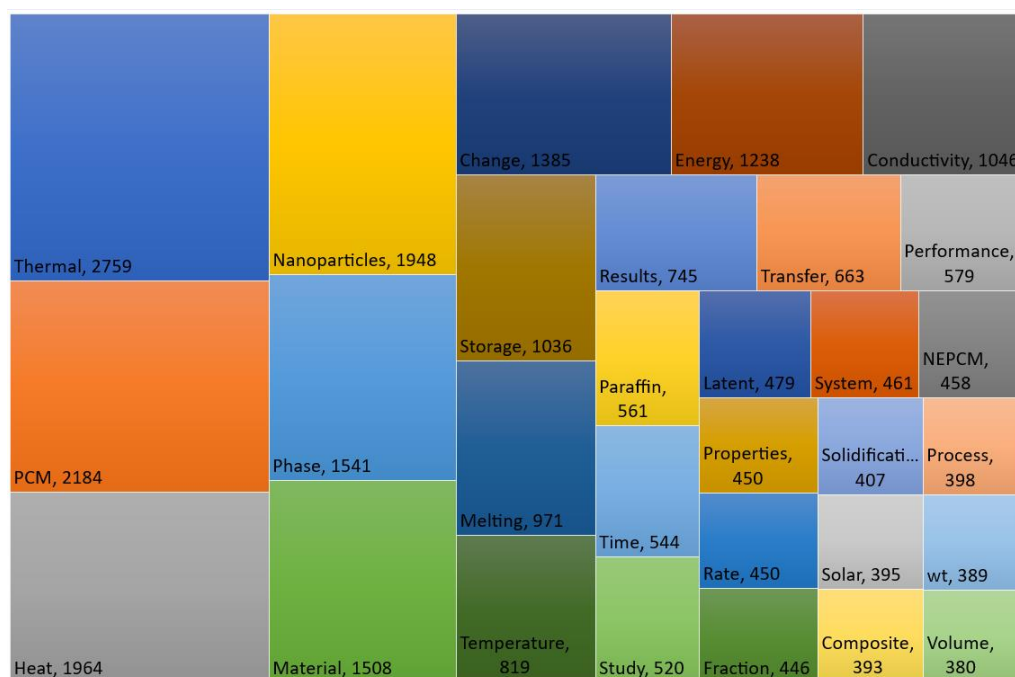


Figure 6. Treemap of 30 most frequent words in abstracts with the minimum occurrence of 380.

4.3. Productivity and Growth Rate

This section discusses the productivity and growth rate of countries and sources. Figure 7 illustrates the productivity of 10 countries with over 17 articles in the NePCM research field. China holds the highest number of articles (168), followed by India and Iran with 130 and 113, respectively. Later, the United States has shared 67 articles, and the other countries’ publications are significantly lower than these four productive countries, which is consistent with Figure 5.

The scatter of publications in a given field can be defined by Bradford’s law. In the present study, it is adopted to identify the leading publishers in the field of NePCM in TES units. Based on Bradford’s law [41], journals published in a research field can be divided into three zones, while each zone includes approximately one-third of all publications. Zone 1 has a few journals, whereas Zone 2 includes more sources, and Zone 3 has the bulk of sources. In the present bibliometric analysis, 248 sources collected from WoS and Scopus are divided into three clusters based on Bradford’s law, including Cluster 1 with 8, Cluster 2 with 33, and Cluster 3 with 207 sources. One-third of the 864 publications in NePCMs have been published by 8 sources, as shown in Figure 8. “*Journal of Energy Storage*” holds the highest contribution with 78 articles, and then two journals of, “*International*

Journal of Heat and Mass Transfer and *Applied Thermal Engineering* have published 55 and 43 publications, respectively.

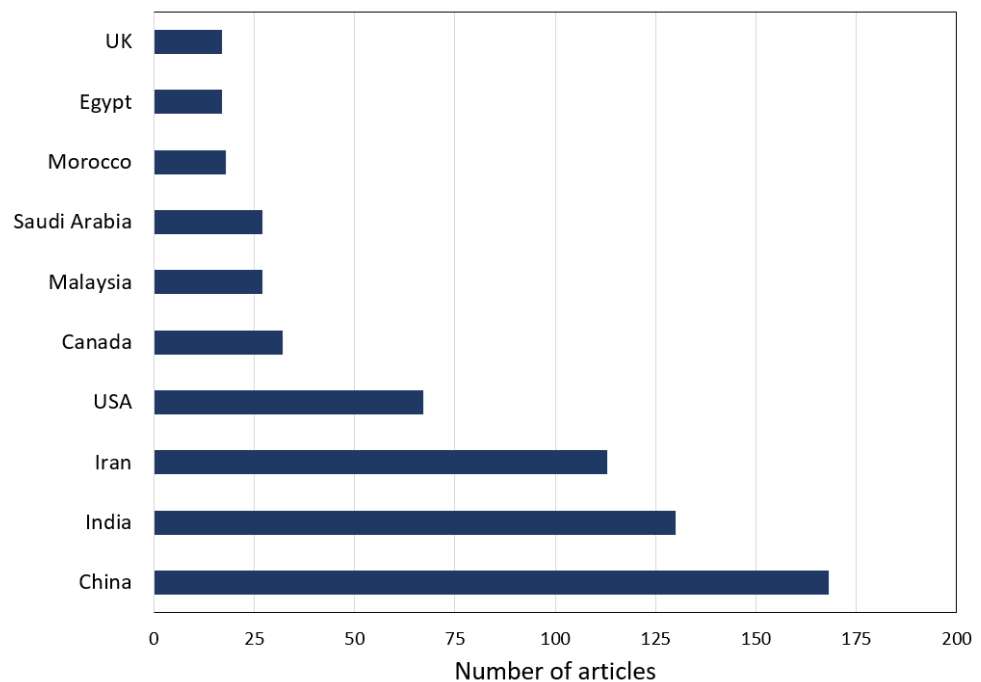


Figure 7. Productive countries.

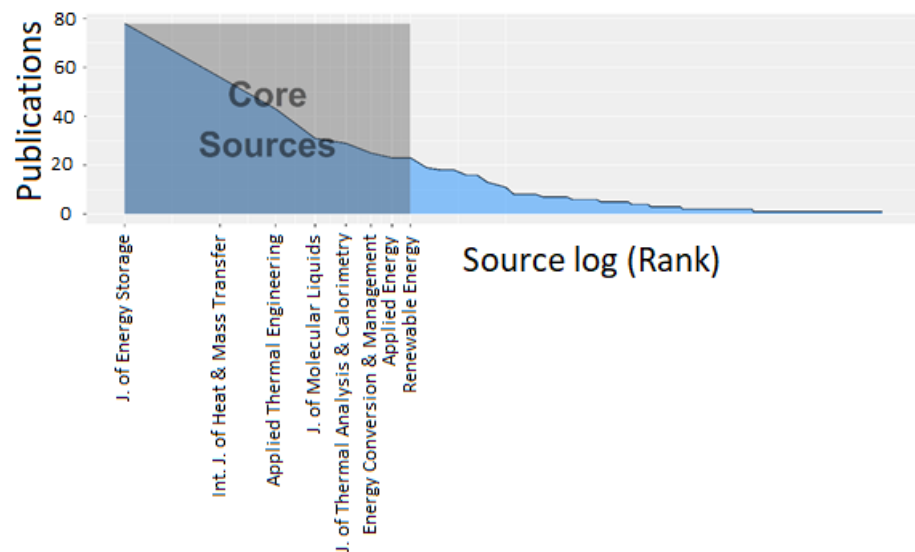


Figure 8. Bradford's Law of Scattering.

From another perspective, Figure 9 compares the cumulative evolution of ten productive sources per year since 2012. It is highly beneficial for researchers since the figure shows which sources have attracted a higher number of publications in the last 10 years. In recent years, *Journal of Energy Storage* has seen the largest publication in NePCM papers, followed by *International Journal of Heat and Mass Transfer* and *Applied Thermal Engineering*. However, *International Journal of Heat and Mass Transfer* published more articles over the years until 2020. The number of published articles in *Journal of Energy Storage* has steeply increased since 2019. In addition, a closer look indicates that NePCM has become a hot topic, and all journals have experienced significant growth.

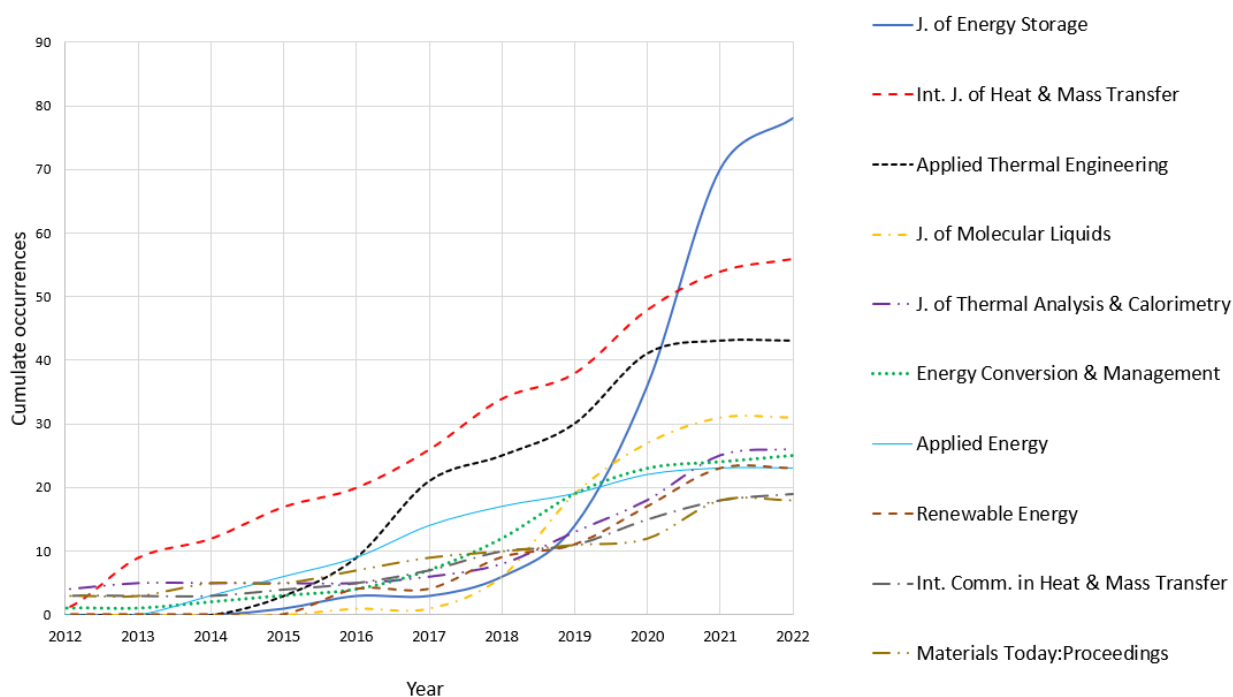


Figure 9. Cumulative evolution of sources in the last 10 years.

4.4. Authorship and Countries Evolution

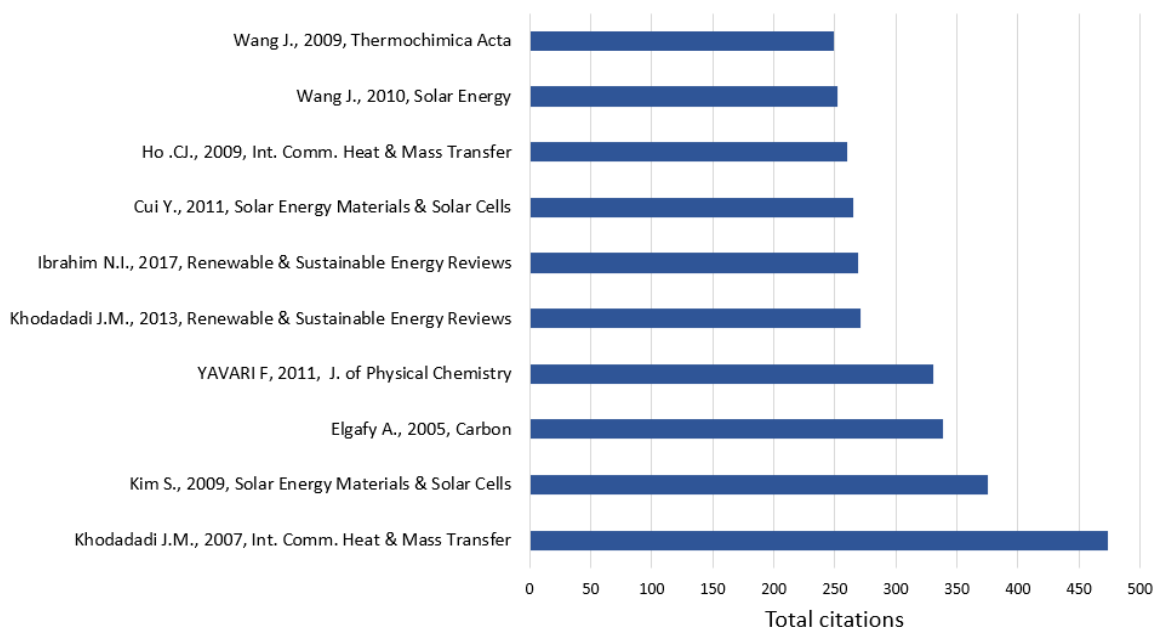
In this study, the scientific authorship output is analysed based on the collected database from WoS and Scopus using several measurements, including H-index, G-index, M-index, the total citations, and the number of publications. H-index measures the number of publications with a citation number greater than or equal to H [42]. However, G-index applies a higher weight to publications, attracting more citations [43]. Unlike H-index, M-index considers the starting year of authors and is expressed as a ratio of the H-index to years publishing [42].

Table 2 compares the research output of the 10 top authors in NePCM with some measurements. The top-one author is Mohsen Sheikholeslami from Babol Noshirvani University of Technology, who records outstanding progress with 33 NePCM articles and holds the highest bibliometric measurements (H-index = 19, G-index = 33, and M-index = 2.714). Shafee A., Ganji D.D., and Ghalambaz M. are the other productive authors with a high number of papers and indexes. The publications of Sheikholeslami M. and Khodadadi J.M. in the field of NePCM have attracted 2039 and 1404 total citations, respectively. The total citations of the other authors are less than 1000 in this field. Moreover, the H-index of all the top 10 authors is higher than 6, and the minimum citation is 189. China and Iran have 3 authors individually among the 10 top authors in this research field.

Furthermore, Figure 10 presents the most highly-cited relevant publications with a minimum of 249 total citations. The main significance of a publication's citations is to guarantee its popularity on the research topic and indicate the scholarly impact of an article. The purpose of this figure is to identify the most cited publications and introduce these valuable references to those who are keen to study in this field. Khodadadi and Hosseinizadeh's article [20] attracted the highest citation of 474. In this numerical and experimental study, they revealed early findings confirming the superiority of NEPCM for TES applications. The second most-cited publication belongs to Kim and Drzal [44]. They experimentally studied increasing the thermal conductivity of paraffin wax by exfoliated graphite nanoplatelets.

Table 2. Top 10 authors in the NePCM field.

Author	Affiliation	N. of Papers	Index			Citations
			H	G	M	
Sheikholeslami M.	Babol Noshirvani University of Technology, Iran	33	19	33	2.7	2039
Shafee A.	Duy Tan University, Vietnam	20	13	20	2.6	776
Ganji D.D.	Babol Noshirvani University of Technology, Iran	19	17	19	2.4	809
Ghalambaz M.	Ton Duc Thang University, Vietnam	19	10	19	1.7	623
Khodadadi J.M.	Auburn University, USA	13	12	13	0.7	1404
Wang J.	Hebei University of Technology, China	13	9	13	0.6	929
Fan L.W.	Zhejiang University, China	13	8	13	0.8	281
Mehryan S.A.M.	Islamic Azad University, Iran	13	6	13	2	189
Kalaiselvam S.	Anna University, India	12	12	12	1.1	586
Zhang X.	University of Science and Technology Beijing, China	12	6	12	0.5	390

**Figure 10.** Ten high-cited publications in the NePCM field are Khodadadi and Hosseinizadeh [20], Kim and Drzal [44], Elgafy and Lafdi [25], Yavari et al. [45], Khodadadi et al. [22], Ibrahim et al. [46], Cui et al. [47], Ho and Gao [48], Wang et al. [49], and Wang et al. [50].

Besides the country's productivity shown in Figure 7, Figure 11 provides evidence and information about the number of citations attracted by each country. These two factors reveal the leading countries with impactful roles in a specific research field in the world. From the perspective of the most cited countries, China holds the highest cited rank (6184) in the NePCM field in the world. Then, the United States and Iran have attracted the second and third ranks of global citations, with 4158 and 3184, respectively. India accounts for more than 2859 citations, while the citation number of other countries is below 808. Hence, the total number of citations from the top four countries is 2.3 times greater than all the citations from other countries.

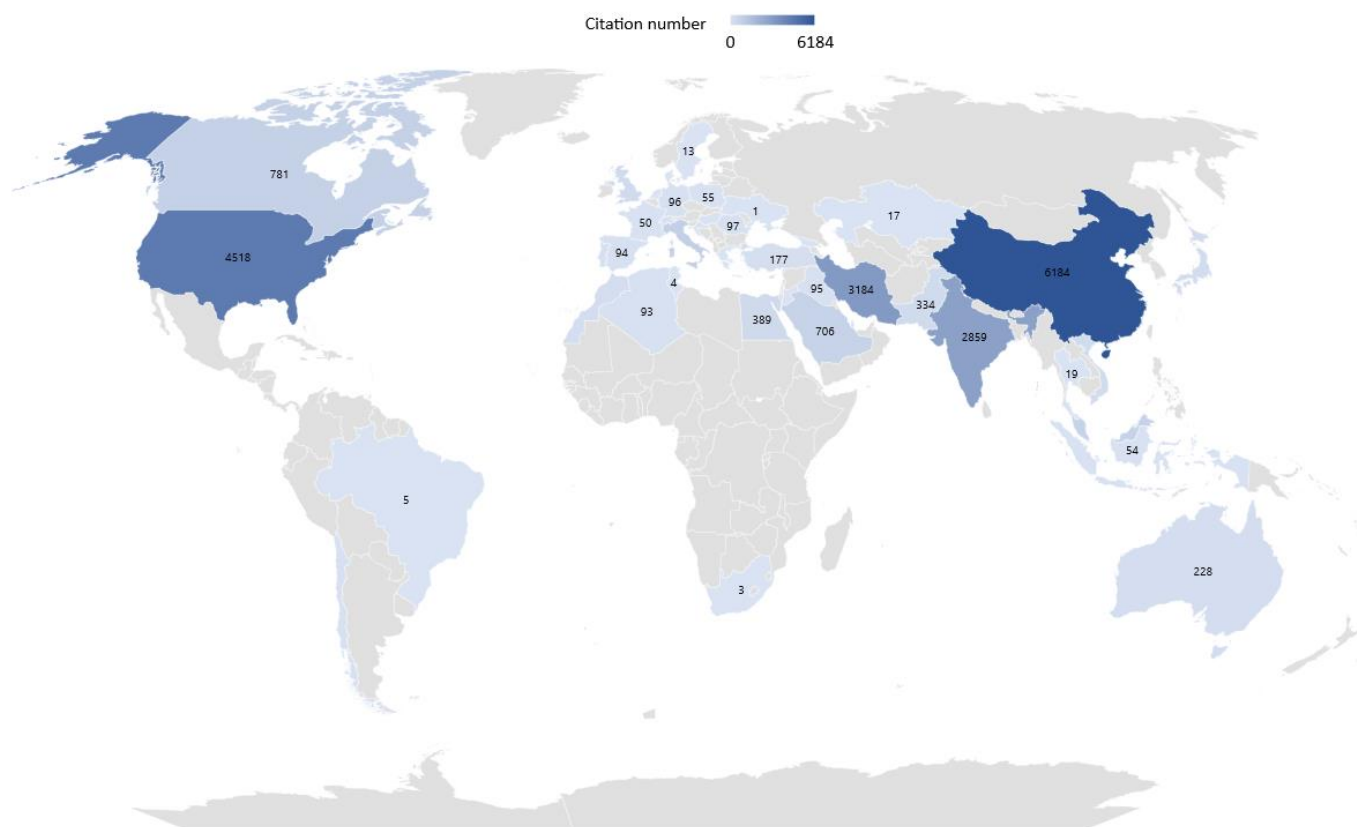


Figure 11. Most cited countries for research in TES using NePCM.

5. Conclusions

This paper presents the evolution of the LHTES study with the application of NePCM through the statistical approach for the first time. An overview of the NePCM literature review in LHTES in TES units was initially provided. Then, a bibliometric analysis was adopted to characterise the application of NePCM in thermal energy storage based on the Scopus and WoS databases.

Despite different techniques to compensate for the inherently low thermal conductivity of PCMS, the effective method is the dispersion of nanoparticles in PCMs. However, it can be further improved by some parameters, such as the size and shape of particles, particle concentration, and particle type. The bibliometric study revealed that the literature on NePCM in LHTES has exponentially grown over the past 16 years. Journal articles were the most frequently used document type, consisting of 79% of the records. Moreover, 12% and 6.1% of publications were distributed as conference papers and review papers, respectively. The analysis showed that the coupling of NePCM with LHTES is a hot topic that has been able to attract more and more interest due to its proven heat transfer enhancement. Exponential growth in the publication output is observed, and a peak record of 181 publications was attained for 2021. The annual growth rate of production was 20.34%.

China was the most important contributor to the research in NePCM in thermal energy storage with the most publications (168), followed by India (130) and Iran (113), respectively. The United States recorded 67 publications in this research field. In terms of multiple-country publications, Saudi Arabia and Iran published 18 and 15 publications, respectively, in this research field. Moreover, as the first country with the most significant interactions, Saudi Arabia collaborated more with institutions in Vietnam, Egypt, India, the United States, and Malaysia.

Based on the bibliometric analysis, 248 sources collected from Scopus and WoS are divided into three clusters. Clusters 1, with 8 sources, included 305 publications in NePCM,

where “*Journal of Energy Storage*” held the highest contribution with 78 articles, followed by “*International Journal of Heat and Mass Transfer*” which accounted for 55, and then “*Applied Thermal Engineering*” with a record of 43 publications. Therefore, in recent years, NePCM has become a hot topic in the aforementioned journals based on the significant growth statistics.

In terms of the occurrence of words in the literature, “Phase change material”, “Nanoparticles”, and “Thermal energy storage” were the most frequent keywords. However, “Thermal”, “PCM”, and “Heat” were frequently used in the previous studies with occurrences of 2759, 2184, and 1964, respectively.

“*Journal of Energy Storage*”, “*International Journal of Heat and Mass Transfer*”, and “*Applied Thermal Engineering*” were the leading players in the field of NePCM. While the “*International Journal of Heat and Mass Transfer*” published more articles over the years until 2020, the number of published articles in the “*Journal of Energy Storage*” steeply increased in the last four years. The rapid advances on the scientific frontiers of NePCM and LHTES resulted in ever-increasing citations. From the perspective of the most cited countries, China held the highly-cited rank (6184). Then, the United States and Iran have attracted the second and third ranks of global citations, with 4158 and 3184, respectively. The top four countries attracted 2.3 times more citations than the other countries.

The leading publications, publishers, countries, and researchers were successfully identified. Mohsen Sheikholeslami recorded outstanding progress with 33 NePCM articles and the highest bibliometric measurements (H-index = 19, G-index = 33, and M-index = 2.714). Most importantly, the lack of research in specific regions and areas was recognised to allow for possible collaboration opportunities between the research communities. In addition, it was observed that researchers’ interest has rapidly increased in this field due to the importance of LHTES in using renewable energy. It is expected that China will remain the most productive country, and “*Journal of Energy Storage*” will have the greatest production growth in the near future. Mohsen Sheikholeslami’s publications, which attracted the highest number of total citations, can be suggested as valuable references to those who are keen to study in this field. Moreover, it can be concluded that the maturity of this technology is moderate as there are still drawbacks associated with problems, such as corrosion, phase separation, and supercooling. These drawbacks require further attention, and therefore there is still a place to continue performing research in the TES field using NePCM.

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Nomenclature

Acronyms

FEM	Finite element method
FVM	Finite volume method
HTF	Heat transfer fluid
LHTES	Latent heat thermal energy storage
NePCM	Nano-enhanced phase change material
NEPCM	Nano encapsulated phase change material
PCM	Phase change material
TES	Thermal energy storage

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