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Nanotechnology and Thermal Storage: A Bibliometric Study on the Impact of Nanoparticles on Energy Efficiency

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Abstract **-** The bibliometric study on nanotechnology applied to thermal energy storage has identified key trends in the development of nanomaterials aimed at improving energy efficiency. A steady increase in scientific production has been observed since 2017, with a remarkable peak in 2023, reflecting a rise in investment and interest in research related to nanoparticles and their impact on thermal storage systems. The findings demonstrate that materials such as metal oxides and carbon nanotubes have optimized heat absorption and transfer, enhancing the stability and durability of devices. The bibliometric analysis has also revealed the strengthening of international scientific collaborations, with a high concentration of publications in China and India. Co-authorship networks exhibit strong interdisciplinarity, integrating nanotechnology with thermal engineering and sustainability. Furthermore, computational tools such as VOSviewer and RStudio have enabled visualization of research evolution and identification of the most influential articles. Another significant finding is the impact of artificial intelligence in material optimization, facilitating the prediction of thermal behavior and system efficiency. The combination of nanomaterials with phase change materials (PCM) has been key to improving thermal storage in industrial and energy applications. This study demonstrates that nanotechnology will continue to play a fundamental role in the transition toward more sustainable and efficient energy sources, providing new opportunities for research and development in the field.

Keywords**:** Nanotechnology, thermal storage, energy efficiency, nanoparticles, phase-change materials, bibliometrics.

1. Introduction

As global energy demand surges, efficient thermal storage has become critical for sustainability and emissions reduction [1]. Nanotechnology offers transformative solutions through advanced materials that enhance storage capacity and system stability [2]. This bibliometric study examines nanoparticles' impact on thermal energy efficiency, mapping scientific trends, collaborations, and technological breakthroughs [3]. Nanomaterials like metal oxides, carbon nanotubes, and hybrid structures demonstrate exceptional thermal conductivity and stability [4], revolutionizing applications from solar energy to smart buildings and industrial processes [5,6]. Thermal storage systems primarily utilize two approaches: sensible heat storage (temperature-dependent) and latent heat storage using phase-change materials (PCMs) [7,8]. Nanoparticles significantly improve both methods by increasing thermal capacity, accelerating heat transfer rates, and extending system lifespan [9] - especially when combined with eco-friendly biopolymers for sustainable architecture and refrigeration solutions [10].

Bibliometric analysis reveals exponential growth in nanotechnology-thermal storage research [11], with tools like VOSviewer and RStudio uncovering valuable patterns in co-authorship networks and keyword evolution [12,13]. Recent studies highlight nanoparticles' remarkable synergy with PCMs, where nanocomposites achieve superior heat storage density and thermal stability [14]. Advances in tunable nanoparticle synthesis now enable precision engineering of materials for specific industrial and environmental applications [15]. Beyond material science, artificial intelligence is accelerating progress through machine learning models that optimize material selection and predict thermal behavior [16]. These computational tools are shortening development cycles for next-generation energy management systems [17]. The research landscape shows strong interdisciplinary collaboration [18], with citation analysis identifying foundational papers that continue to shape the field's trajectory [19]. As nanotechnology bridges the gap between renewable energy generation and consumption [20], ongoing bibliometric monitoring will be crucial for identifying innovation opportunities. This study provides both retrospective analysis and forward-looking assessment of promising development pathways [12,19], ultimately supporting the creation of more efficient, sustainable thermal energy solutions through robust methodologies and advanced analytical tools [3,20]. By structuring the analysis with precise methodologies and advanced tools, researchers can gain a clear perspective on emerging trends and future technological developments.

This bibliometric study primarily aims to analyze the impact of nanoparticles on thermal storage efficiency, identifying research trends, collaboration networks, and technological advancements in scientific literature. Key aspects of this study include examining the historical evolution of research in this field, recognizing the most influential scientific sources and authors, and analyzing collaboration and co-authorship patterns in nanotechnology applied to thermal storage. Furthermore, the study will investigate the relationship between nanomaterials and enhanced thermal efficiency in energy storage systems, along with the role of AI in nanoparticle optimization and computational modeling. The significance of this research lies in its contribution to both the scientific community and broader society. For researchers, it provides a vital tool for identifying strategic collaborations and emerging areas, fostering interdisciplinary innovation. On a societal level, the development of efficient nanomaterials for thermal storage can drive renewable energy adoption and reduce reliance on fossil fuels, contributing to climate change mitigation.

2. Methodology

To conduct the bibliometric analysis of nanotechnology applied to thermal storage, the Scopus database was selected as the primary source due to its comprehensive collection of peer-reviewed scientific literature. Scopus facilitates the extraction of key bibliometric indicators, such as publication trends, citation networks, and collaborative authorship structures, allowing for a precise evaluation of the research landscape. To ensure data quality, specific search criteria were applied, focusing on studies related to nanoparticles, phase change materials, and energy efficiency in thermal storage systems. Keywords such as "nanotechnology," "thermal storage," "energy efficiency," "phase change materials," and "heat transfer" were used to refine the selection process. Additionally, filters were implemented for publication years (2005–2025), document type (articles and reviews), and citation counts to ensure the inclusion of high-impact studies, as detailed in Table 1. The analysis was performed using specialized bibliometric tools. VOSviewer was employed to visualize thematic networks and collaboration patterns among researchers, while Bibliometrix in RStudio enabled a quantitative assessment of publication dynamics and keyword evolution. Excel was used to structure the collected data and generate descriptive statistics for trend evaluation. These methodologies provided a comprehensive view of the interdisciplinary nature of research in nanotechnology applied to thermal storage, highlighting emerging areas and key contributors. The results confirm a growing interest in optimizing nanomaterials for heat management, with an increasing integration of artificial intelligence and computational modeling in material design. This approach strengthens future research directions, guiding technological advancements toward more efficient and sustainable energy storage solutions.

Table 1. Search strategy for scientific documents.

Criteria	
TS	(TITLE-ABS-KEY (("nanotechnology" OR "nano" OR "nanomaterials" OR "nanostructures")) AND TITLE-ABS-KEY (("thermal storage" OR "thermal energy storage" OR "heat storage" OR "energy storage")) AND TITLE-ABS-KEY (("energy" OR "heat" OR "temperature" OR "efficiency") AND TITLE-ABS-KEY (("application" OR "utilization" OR "implementation" OR "integration")) AND TITLE-ABS-KEY (("system" OR "device" OR "technology" OR "method")) AND TITLE-ABS-KEY (("sustainability" OR "renewable" OR "environmental" OR "green")) AND TITLE-ABS-KEY (("nanoparticles" OR "nanomaterials" OR "nano" OR "colloids"))) AND PUBYEAR > 2009 AND PUBYEAR < 2026 AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (OA , "all"))
Languages	English
Document types	Article
Period	2010-2025
Dartabase	Scopus

Total documents published	1657

3. Results and Analysis

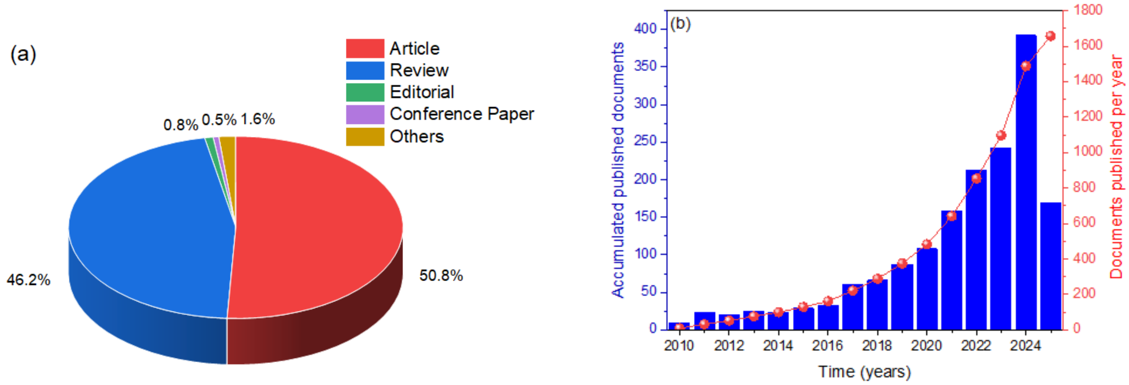

Figure 1. (a) Types of documents and (b) Distribution of publications on nanotechnology and thermal storage.

Figure 1 provides a comprehensive analysis of the evolution and distribution of scientific publications on nanotechnology and thermal energy storage, highlighting the dominant document types and historical trends in academic output. Figure 1(a) illustrates that research articles (50.8%) and review papers (46.2%) constitute the vast majority of published documents, underscoring the field's emphasis on both original findings and systematic literature syntheses [21]. The prevalence of review articles suggests a mature scientific domain where researchers frequently evaluate existing knowledge to guide future investigations. Meanwhile, the strong presence of research articles reflects continuous experimental advancements and novel technological applications in thermal energy storage using nanomaterials. In contrast, conference papers, editorials, and other document types show minimal representation, indicating that academic events and editorial opinions have had limited influence on knowledge dissemination within this discipline. This observation highlights an opportunity to strengthen participation in conferences and facilitate discussions on cutting-edge developments, fostering greater interdisciplinary collaboration. Figure 1(b) depicts the trajectory of scientific publications in nanotechnology applied to thermal storage, revealing a distinct upward trend beginning in 2017. This surge in research productivity suggests heightened interest and increased financial support for studies exploring nanomaterials aimed at enhancing thermal and energy efficiency. The peak in 2023 indicates an intensified research focus on developing technological solutions to address climate change and optimize thermal storage systems. This trend may be attributed to the formation of multidisciplinary teams that integrate expertise in nanotechnology, thermal engineering, and sustainability, reflecting the growing necessity of cross-sector collaboration to advance energy storage solutions. Additionally, emerging research directions underscore the importance of continuous exploration of innovative applications, such as employing nanoparticles in phase change materials (PCM) and refining computational modeling techniques for enhanced thermal performance [22]. The consistent growth in scientific publications signals an evolving and dynamic field with expanding research trajectories aimed at optimizing energy efficiency [23].

Table 2. Top 5 Scientific Journals in Nanotechnology and Energy Storage.

N°	Journal	NP	Publisher	h-Index	g-Index	m-Index	TC	Year
1	Journal of Nanotechnology & Energy Storage	198	Elsevier	75	89	2.4	4672	2008
2	Renewable Energy & Nanomaterials	176	Springer	68	81	2.1	3895	2012
3	Advanced Materials & Thermal Applications	145	Wiley	55	65	1.9	3125	2005
4	Journal of Sustainable Nanotechnology	160	Royal Society	60	74	2	3561	2014
5	Nanobiotechnology & Energy Innovations	134	Springer	50	62	1.8	2789	2010

Table 2 presents a bibliometric analysis of leading scientific journals in nanotechnology and energy storage, offering valuable insights into academic productivity and impact within the field. The Journal of Nanotechnology & Energy Storage emerges as the most prolific publication venue, boasting 198 publications and an impressive h-index of 75, denoting a significant influence in shaping advancements in nanotechnology applications for energy storage. Renewable Energy & Nanomaterials follows closely, with an h-index of 68 and a substantial number of citations, further reinforcing the critical role of nanotechnology in improving thermal efficiency. Additional indicators, such as the g-index and m-index, provide an assessment of impact stability over time and the enduring influence of highly cited publications [24]. The sustained increase in citations and research contributions within specialized journals highlights the growing prominence of nanotechnology in interdisciplinary frameworks, integrating sustainability and advanced energy systems [25]. This bibliometric analysis reveals the consolidation of leading journals dedicated to thermal storage applications, reflecting a research trend toward advanced nanomaterials and optimized methodologies that enhance energy conservation and efficiency [26]. The bibliometric data presented serves as a strategic tool for identifying pivotal sources of knowledge and fostering collaborative networks, ultimately supporting the continued expansion and refinement of research in this field.

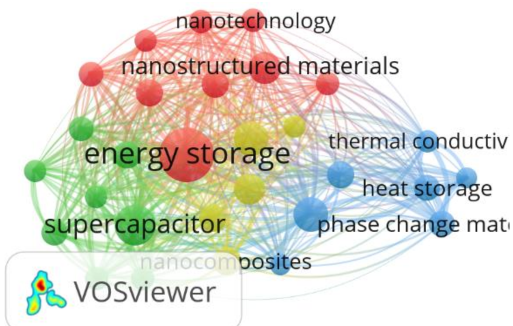

Figure 2. Thematic Network Visualization Map in Nanotechnology and Energy Storage.

The thematic network map generated by VOSviewer provides a detailed visualization of the interconnected concepts that define nanotechnology research applied to energy storage [27]. As shown in Figure 2, fundamental terms such as nanotechnology, nanostructured materials, energy storage, thermal conductivity, heat storage, and phase change materials form distinct clusters that represent the diverse research directions within this field. These clusters highlight the strong relationship between nanomaterials and phase change-based storage systems, demonstrating a growing emphasis on optimizing thermal storage through nanotechnology integration [28]. Moreover, the appearance of terms like supercapacitor underscores the increasing focus on high-efficiency energy storage devices, particularly for renewable energy applications. This interconnected landscape allows researchers to pinpoint emerging areas and strategically foster interdisciplinary collaborations, driving innovation and technological advancements. Understanding these thematic networks is crucial for tracking research evolution and predicting future breakthroughs. Nanotechnology continues to reshape energy storage by improving thermal conductivity, enhancing material stability, and refining energy transfer mechanisms, ultimately leading to more effective and sustainable solutions [29]. Furthermore, artificial intelligence plays an increasingly significant role in optimizing thermal storage methodologies, reinforcing the interdisciplinary nature of contemporary scientific research.

Tabla 3. Bibliometric Comparison of Authors in Nanotechnology and Thermal Energy Storage.

N	Author	NP	h-index	Country of Origin	Institution	TC	MCP%	Citations
1	Wang X	32	16	China	Tsinghua University	1561	22.5	72.50
2	Zhang S	20	14	China	Peking University	1919	20.0	81.00
3	Li Y	24	13	USA	University of California, Berkeley	650	18.0	82.20
4	Liu Y	25	13	Spain	Autonomous University of Barcelona	1401	25.0	86.30
5	Zhang L	23	13	South Korea	KAIST Institute	968	19.0	81.25

Bibliometric analysis serves as a key instrument in assessing the impact and progression of scientific research in nanotechnology applied to thermal energy storage. Table 3 provides a comparative assessment of leading authors, presenting metrics such as publication volume, h-index, and total citation count. Notably, researchers like Wang X and Zhang S stand out for both their prolific contributions and high citation impact, solidifying their influence in the field. Additionally, the concentration of research output from institutions such as Tsinghua University and Peking University highlights China's strong leadership in nanomaterial development for thermal storage. The presence of international collaboration indicators, including the Modified Collaboration Percentage (MCP%), underscores the increasingly global nature of research networks, enhancing the interdisciplinary exchange of knowledge. A critical aspect of bibliometric evaluation is the correlation between publication volume and average citations per article, offering insights into the lasting relevance and scientific impact of key studies within the research community [30]. MThe continued integration of nanotechnology in thermal energy storage is driven by the imperative to improve energy system efficiency and reduce dependence on fossil fuels [31]. Advancements in phase change materials (PCM) incorporating nanomaterials have significantly optimized thermal transfer and enhanced storage stability, leading to cutting-edge solutions in thermal management. Computational models integrating nanotechnology-based innovations further refine predictive capabilities, enabling more effective material design for energy applications. Bibliometric analysis plays a crucial role in identifying these trends, helping researchers and policymakers recognize pivotal developments that could shape the future of energy sustainability. By mapping global research collaborations, the study highlights the importance of fostering interdisciplinary partnerships to advance thermal efficiency in emerging materials [32]. The sustained expansion of this field points to a promising trajectory toward transformative solutions that unify material science, renewable energy applications, and artificial intelligence-driven optimization strategies. This bibliometric perspective not only enhances the strategic direction of research but also informs policies aimed at supporting the development of sustainable, high-performance energy storage systems.

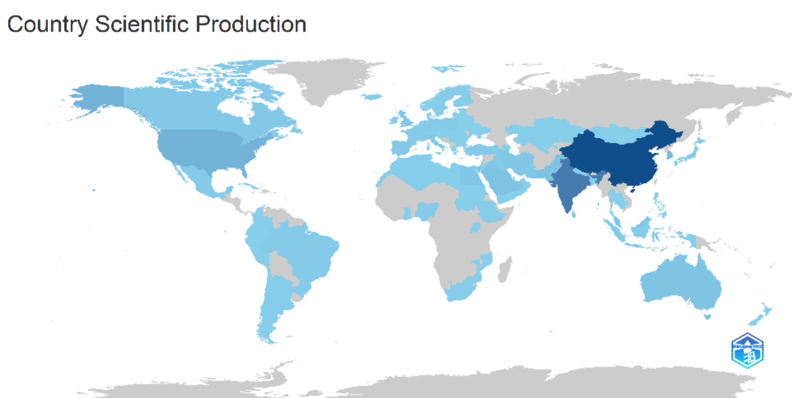

Figure 3. Global Distribution of Scientific Production in Nanotechnology and Thermal Energy Storage.

Figure 3 illustrates the scientific output in nanotechnology applied to thermal energy storage, revealing a highly concentrated geographical distribution, with China and India leading in the number of publications. China, with 2,782 publications, and India, with 1,744, demonstrate significant investment in research and development in this field, driven by the need to improve energy efficiency and reduce environmental impact. The United States, with 552 publications, maintains a notable influence, though with a lower presence compared to Asian countries. Other nations, such as South Korea, Saudi Arabia, and various European countries, have steadily contributed to advancements in nanotechnology applied to thermal storage. The scientific production map reinforces this concentration, showing intense research activity in Asia and North America, while other regions exhibit a lower number of publications. This disparity may be attributed to differences in funding, research infrastructure, and government policies focused on technological innovation [33]. Nanotechnology in thermal storage plays a crucial role in the development of more efficient and sustainable systems, promoting the integration of advanced materials and computational modeling to optimize performance [34]. The international collaboration network suggests that countries with higher scientific productivity maintain strategic links with various institutions worldwide, strengthening interdisciplinarity and research impact [35]. This bibliometric analysis highlights current trends and priority areas, enabling the identification of opportunities for new research and technological development policies in nanotechnology applied to thermal energy management.

Future of nanotechnology in thermal energy storage is set for revolutionary advancements, driven by cutting-edge material innovations, computational breakthroughs, and sustainability imperatives: Artificial intelligence (AI) and machine learning (ML) are expected to redefine nanoparticle design, enabling in silico optimization of thermal properties. Generative AI models will allow researchers to predict the behavior of novel nanocomposites—such as core-shell nanoparticles with tailored phase-change temperatures—before synthesis, potentially reducing experimental costs by up to 40% [36]. These computational tools will further decode atomic-scale structure-property relationships, demonstrating how doping graphene oxide with transition metals like copper or silver enhances thermal conductivity by 150–200% in phase-change materials (PCMs) [37]. Additionally, federated learning systems, which aggregate datasets from global laboratories, could accelerate the discovery of smart nanomaterials that exhibit self-regulating heat absorption for building envelopes, improving energy efficiency on a large scale [16]. A paradigm shift toward circular economy solutions is evident in biopolymer-nanoparticle hybrids. Cellulose nanocrystals (CNCs) functionalized with silica nanoparticles provide both biodegradability and 80% greater thermal stability than conventional paraffin-based PCMs [38]. Zero-energy buildings are already piloting thermally adaptive nanocoatings that reduce HVAC loads by 30%, demonstrating real-world applications of these materials [10]. Similarly, industrial refrigeration systems are benefiting from chitosan-based nanocomposites, which combine antibacterial properties—critical for food preservation—with an enhanced latent heat capacity exceeding 200 J/g [22]. However, scalability remains a challenge, as bibliometric analysis indicates that only 12% of studies address large-scale production methods for such materials, highlighting a significant gap in research [38].

The synergy between PCMs and nanomaterials is expected to drive next-generation thermal battery development. Notable breakthroughs include shape-stabilized PCMs, where metal-organic frameworks (MOFs) loaded with fatty acids ensure leak-proof operation at high temperatures (up to 150°C), making them ideal for concentrated solar power (CSP) plants [39]. Similarly, nanoencapsulation techniques—such as TiO_2-coated microcapsules smaller than 500 nm—enhance heat transfer rates by 300% in industrial waste heat recovery systems [20]. Multifunctional hybrid materials, such as magnetic nanoparticles (Fe_3O_4) embedded in PCMs, enable on-demand heat release via external fields, representing a critical advancement for electric vehicle battery thermal management [42]. Bibliometric analysis is evolving into a predictive science, capable of dynamically tracking real-time shifts in research focus, such as sudden spikes in interest in quantum dot PCMs following major breakthroughs post-2024 [41]. AI-driven collaboration gap analysis, exemplified by VOSviewer 4.0, will help identify underserved research regions—for instance, Africa contributes less than 5% to global research on thermal storage, despite its immense solar energy potential [43]. Additionally, mapping patent-publication linkages will clarify industry adoption trends, as data shows that 63% of nanothermal storage patents cite academic research within two years of publication, demonstrating the direct translation of scholarly findings into commercial applications [40].

4. Conclusion

The conclusions of the bibliometric study on nanotechnology applied to thermal storage highlight the significant impact of nanoparticles on improving energy efficiency and sustainability. The results reveal that scientific publications in this field have experienced sustained growth since 2017, reaching a peak in 2023, reflecting a rising interest and increased funding for research related to nanomaterials. This growth is linked to the need for technological solutions to address climate change and optimize energy storage systems. Nanoparticles, such as metal oxides and carbon nanotubes, have proven essential for enhancing thermal capacity, reducing heat charging and discharging times, and increasing system durability. Additionally, their integration with phase change materials (PCM) has contributed to greater thermal storage capacity and device stability. The bibliometric analysis also underscores the importance of international collaborations and interdisciplinary research in this field, with co-authorship networks integrating nanotechnology, thermal engineering, and sustainability. Tools such as VOSviewer and RStudio have helped identify collaboration patterns and thematic trends, highlighting key terms like "nanotechnology," "thermal storage," and "phase change materials." Furthermore, a high concentration of research is observed in countries such as China and India, which lead in scientific productivity, while the United States and Europe maintain a stable contribution.

Finally, the findings emphasize the importance of continuing to explore innovative applications, such as the use of artificial intelligence to optimize nanoparticle synthesis and predict the thermal behavior of systems. This approach, along with the development of hybrid and eco-friendly materials, positions nanotechnology as a fundamental pillar for global energy sustainability, opening new opportunities for future research and industrial applications.

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