



## TRENDS, COLLABORATION NETWORKS, AND RESEARCH IMPACT IN THERMAL MANAGEMENT OF ELECTRONIC DEVICES USING PASSIVE COOLING TECHNIQUE

Nilesh Gaikwad<sup>1</sup>, Narendra Deore<sup>2</sup> and Mahadev Madgule<sup>3</sup>

<sup>1,2,3</sup>Pimpri Chinchwad College of Engineering: Pune, Maharashtra, India

<sup>1</sup><https://orcid.org/0000-0002-4087-3266>, <sup>2</sup><https://orcid.org/0000-0003-4710-3798>, <sup>3</sup><https://orcid.org/0000-0001-6584-3787>

Email: [nilesh.gaikwad@pccoepune.org](mailto:nilesh.gaikwad@pccoepune.org), [narendra.deore@pccoepune.org](mailto:narendra.deore@pccoepune.org), [mahadev.madgule@pccoepune.org](mailto:mahadev.madgule@pccoepune.org)

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### ABSTRACT

Thermal management of electronic devices (TMED) has gained attention the worldwide trend of automating processes employing artificial intelligence approaches. Unless efficient thermal management improvements and products that can withstand increased heat loads in small areas are introduced to the market, this field will continue to advance. This study's goal is to provide a bibliometric analysis of passive cooling methods for electronic device thermal management using Scopus publishing records from the previous 25 years. a combination of best-performing nations, content and language types, author collaboration and citations, the study examines the article. Authors cooperation and concurrences, as well as keyword-based and country-wise network analysis, can be observed using the VoS viewer program. The analysis clearly shows that China has the highest contribution (32%) in terms of publications, followed by the United States of America. The Scopus-indexed documents increased by 22 times during the period of 2000 to 2024 and a total of 616 documents received citations of 16563 in the year 2024 in the domain of TMED, which shows the growing interest of researchers. Future scholars will have a thorough understanding of how heat management in electronic equipment has changed over the previous 20 years thanks to the assembled study.



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### I. INTRODUCTION

The famous "Moore's Law" was proposed in the 1960s as the integrated circuit industry expanded quickly[1]. Although "Moore's Law" is essentially an empirical relationship in manufacturing instead of a natural rule, its correctness has been proven for decades, and the semiconductor sector regularly uses the law to guide research and development goals. The integrated circuit's capacity to support transistors will continue to grow following "Moore's law" [2], [3]. While driving computational power, the exponential growth in transistor density simultaneously intensifies the thermal design power per unit area, posing a challenge to conventional cooling methods.

Heat dissipation presents a significant challenge in the current digital revolution, as electronic products, particularly smartphones, tablet computers, and data centres, increasingly evolve towards higher performance, greater integration, and miniaturisation [4], [5]. This escalation in heat flux demands innovative solutions beyond traditional thermal management, propelling the industry towards advanced three-dimensional packaging and novel material science applications [6]. The stringent cooling requirements for high-integration power electronics systems necessitate significant energy consumption and have recently raised concerns regarding carbon footprints [7]. Notice that almost 40% of energy consumption for the current data centres [8] was used in their cooling infrastructure, which consumes almost 12% of total electricity [9].

The continuous improvement in integrated circuit manufacturing processes has led to increased heat generation, necessitating the development of efficient thermal management technologies to enhance performance and reliability [10]. This growing thermal burden necessitates a paradigm shift from traditional cooling to advanced thermal management solutions, leveraging innovative

materials and architectural designs to effectively dissipate the concentrated heat loads [11]. Passive cooling techniques, like natural convection, heat pipes, vapour chambers, and phase-changing materials, are being increasingly explored to address the thermal challenges posed by compact electronic devices [12].

The use of phase change material and heat pipes offers high effective thermal conductivity [13] and is particularly attractive due to their lack of active power consumption and mechanical complexity, which enhances system reliability and reduces operational expenses. Heat pipes' capacity to passively transmit heat from the evaporating end to the condensing end by using the latent heat of the working fluid has drawn constant focus as a highly effective and reliable two-phase heat transfer technique. [14], [15]. This property makes them suitable for applications where minimal noise, vibration, and maintenance are critical design considerations [16]. Figure 1 shows the active and passive cooling technique for electronic cooling applications.

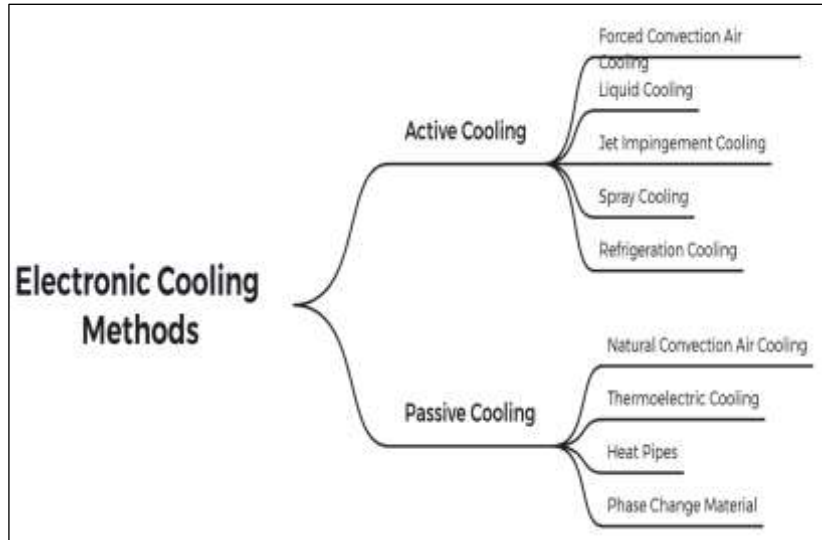


Figure 1: Different techniques for electronic cooling. Source: [5].

The flat-plate heat pipe, the thermal ground plane, and the heat spreader are synonyms for the vapour chamber, which is two-dimensional and spreads heat from smaller heater areas to larger sink areas across small temperature differences [17]. The fundamental difference between a heat pipe and a vapour chamber is that the former acts as a heat transporter, and the latter serves the purpose of spreading the heat [18]. As shown in Figure 2, vapour chambers (VC), or flat heat pipes, are sealed containers made from materials such as aluminium or copper. The bottom surface is called an evaporator, which is placed on the heat source/chip to be cooled. The top surface is known as a condenser, wherein heat is dissipated to the atmosphere via a cooling medium like air or water. The evaporator and condenser surfaces are internally covered with a thin layer of wick of different types, such as grooves, screen mesh, or sintered powder layer. Non-condensable gases are removed using a vacuum pump, which is then charged with working fluid. The working fluid evaporates due to heat from the source. Vapours travel to the condenser side due to the difference in vapour pressure, and they lose latent condensation heat on the condenser surface. The condensate is transported back to the evaporator by capillary action through the wick.

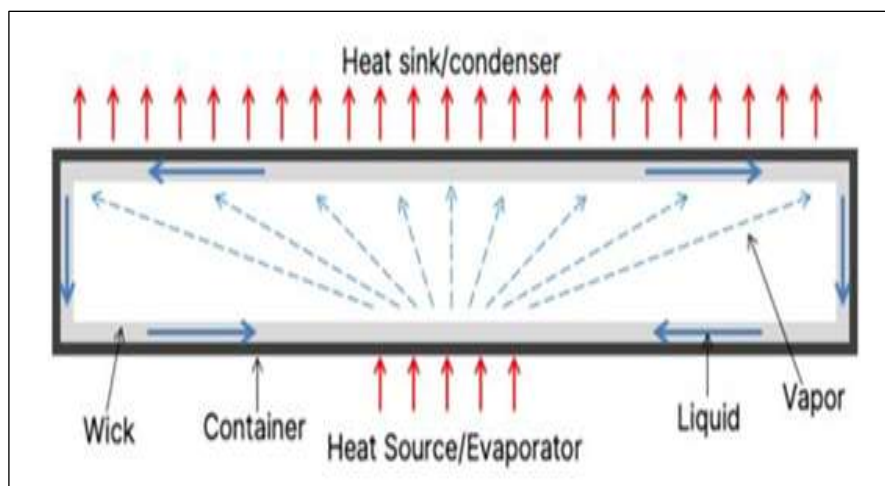


Figure 2: Working of the vapour chamber as a heat spreader. Source: Authors, (2026).

The excellent thermal dissipation performance of ultra-thin heat pipes (UTHPs) makes them an attractive solution. These advantages make UTHPs widely applicable in industries such as battery thermal management [19], solar collectors [20], [21], and electronics cooling [22].

## I.1 CHALLENGES IN USING PASSIVE COOLING TECHNIQUES:

Passive cooling technologies serve as essential heat management solutions for contemporary electronics and industrial applications. Heat pipes, phase change materials (PCMs), and vapour chambers present compelling substitutes for active cooling systems owing to their energy reliability and effectiveness [23]. Nonetheless, despite their theoretical benefits, these technologies encounter significant obstacles that hinder their actual application and market feasibility. The operational limit of a heat pipe indicates the maximum heat transport capacity it can maintain before performance declines, dictated by various physical constraints [24].

These constraints include the capillary limit, where the wick structure fails to return adequate liquid to the evaporator against gravitational and viscous forces; the sonic limit, which arises when vapour velocity nears sonic speed, resulting in choked flow; the boiling limit, where excessive heat flux induces nucleate boiling in the wick and disrupts liquid flow; and the entrainment or flooding limit, where high vapour shear entrains liquid droplets, obstructing return flow. Each limit is influenced by the heat pipe's working fluid, wick geometry, operating orientation, and temperature range [25].

Phase change material suffers operational challenges like low thermal conductivity [26], expansion/contraction during melting/solidification can cause mechanical stresses, leakage, or damage to encapsulation [27], repeated melt-freeze cycles can cause chemical instability, agglomeration, or loss of latent heat storage capacity [28], matching PCM melting temperature with component safe-operating limits is critical; mismatch can lead to thermal throttling or insufficient protection [29].

For vapour chambers, manufacturing complexity increases with the miniaturisation requirements. The integration of micropillar wick structures requires advanced manufacturing capabilities that may not be readily available [30]. Despite these limitations, the heat transfer coefficient owing to the phase change mechanism in these devices makes them a preferred candidate for TMED [31]. Figure 3 compares the heat transfer coefficient values for free convection, forced convection, and phase change mechanism techniques.

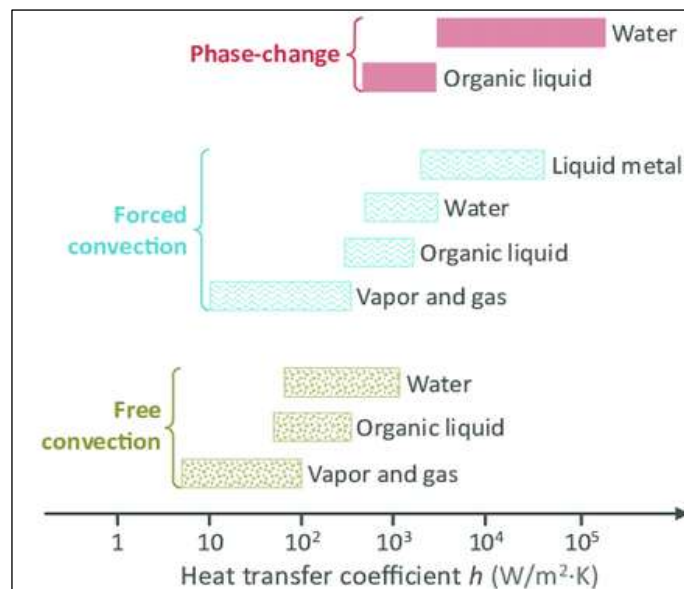


Figure 3: High heat transfer coefficient values for the phase change mechanism.

Source: [32].

The objective of this paper is to present a comprehensive evaluation that includes a bibliometric analysis to gain an understanding of the predominant research efforts and the components that comprise them. A complete analysis of global applications, authors, and published studies is provided in the ensuing sections of the bibliometric analysis. A bibliometric study is defined as a statistical or quantitative analysis of literature, including books, journals, conference proceedings, and online information, to provide insights into a particular subject area or written communication [33]. A bibliometric evaluation offers researchers a robust, data-driven perspective to comprehend the intellectual landscape, discern new trends, drive strategic decisions, and effectively scan extensive literature. When employed efficiently in conjunction with qualitative evaluations, it transforms into an essential instrument in contemporary scholarship. The author found that there is hardly any bibliometric review done in the field of TMED and believes this analysis will help new researchers to understand the trends in publications, author concurrence, and major contributing countries in the area of thermal management of electronic devices.

## II. BIBLIOMETRIC SURVEY

An essential step in the research process is gathering data. Scopus, Clarivate, SCImago, Mendeley, ScienceDirect, and Google Scholar are among the most frequently used publishing databases [34]. Scopus is the premier repository of citations and abstracts for peer-reviewed scholarly articles. The Scopus database was consulted to gather literature on Thermal Management of Electronic Devices (TMED), including articles, conference proceedings, and research papers published from 2000 to 2025. In any bibliometric research, choosing the right keywords is essential. The use of keywords often illustrates heterogeneity in the usage of the conjunctions 'AND' and 'OR.' The Scopus database advises that AND should be included when the analysis requires the use of both terms. The conjunction "OR" should be used when one or more words are included in the expected search results [35].

II.1 METHODOLOGY

For the present study shown in Figure 4, Scopus published documents are collected for the last 25 years, and a bibliometric analysis is conducted for the parameters like top ten countries, languages, document types, and citation trends.

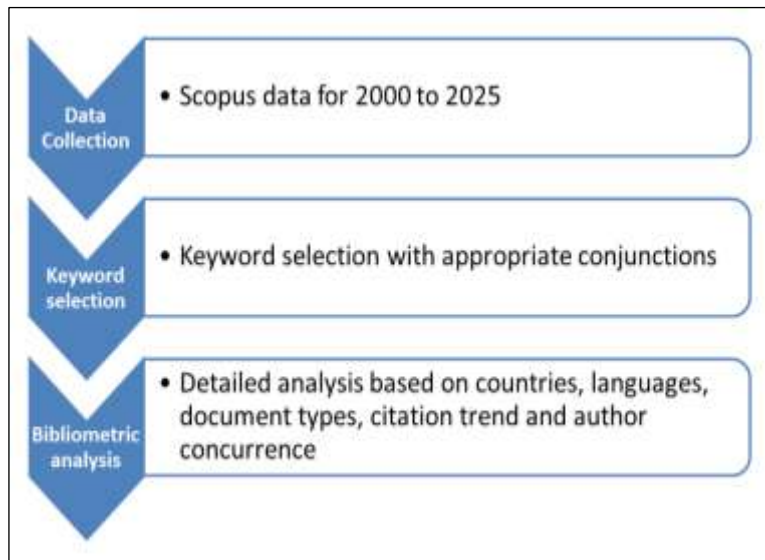


Figure 4: Methodology for the present study.  
Source: Authors, (2026).

II.1.1 Data Collection

The bibliometric analysis utilised data sourced from the Scopus website, recognised as a leading and extensive abstract and citation database for peer-reviewed literature, encompassing conference proceedings, book chapters, and articles. Scopus provides a thorough overview of international research output across various disciplines, including science, technology, medicine, social sciences, mathematics, and the arts and humanities, along with advanced tools for tracking, analyzing, and visualizing research. Table 1 presents the keywords utilized for searching Scopus. The bibliometric search keywords were carefully chosen to follow a funnel pattern, starting with broad terms about thermal management and getting more detailed as we looked for new cooling techniques.

This layout lets the frequency analysis track how research interests gradually narrow over time, showing how the field changes from broad ideas to more specific innovations. A total of 3,949 publications were identified from 2000 to 2025 for the search terms Thermal, Management, Electronic, and Devices. A total of 223 papers were identified after limiting the search to TMED with a focus on passive cooling. Upon refining keyword combinations related to TMED utilising passive cooling and vapour chambers, only 16 papers were identified. Scopus was searched with a combination of essential keywords, as shown in Table 1.

Table 1. Bibliometric distribution of technological combinations utilised in TEMD using passive cooling and vapour chamber.

S.N	Search category	Number of publications	Year
I.	thermal AND management AND electronic AND devices	3949	2000 to 2025
II.	thermal AND management AND electronic AND devices AND passive AND cooling	223	2000 to 2025
III.	thermal AND management AND electronic AND devices AND passive AND cooling AND Vapour chamber	16	2010 to 2024

Source: Authors, (2026).

The keywords were refined as outlined in Table 1 to examine both the breadth and depth of thermal management mechanisms employing passive cooling techniques and to assess the penetration of vapour chamber technology—a method widely used for efficient heat spreading in compact electronic systems.

II.1.2 Analysis of Bibliometric Data

As discussed in the previous section, the following section analysis is carried out in categories as:

Category -I: ---Thermal Management of Electronic devices;

Category -II: --- Thermal Management of Electronic devices with passive cooling;

Category -III: ---Thermal Management of Electronic devices with passive cooling and vapour chamber.

The study of global research provides insights into nations, languages, kinds of published documents and their publishing patterns, subject-specific evaluations, authors' contributions to research in certain areas, and correlates these with national characteristics. A detailed discussion of the data collected on each of these areas is provided in the sections that follow.

II.1.3 Studies on Thermal Management of Electronic Devices

(a) *Research trends in top ten countries*

Keyword search using the words “Thermal Management of Electronic devices” returned contributions by 57 different countries in between 2000 to 2025. The search results were plotted for the to 10 top countries. The country-wise distribution of documents eliciting the number of research articles on TMED is shown in Figure 5, displays data on the 10 most productive countries.

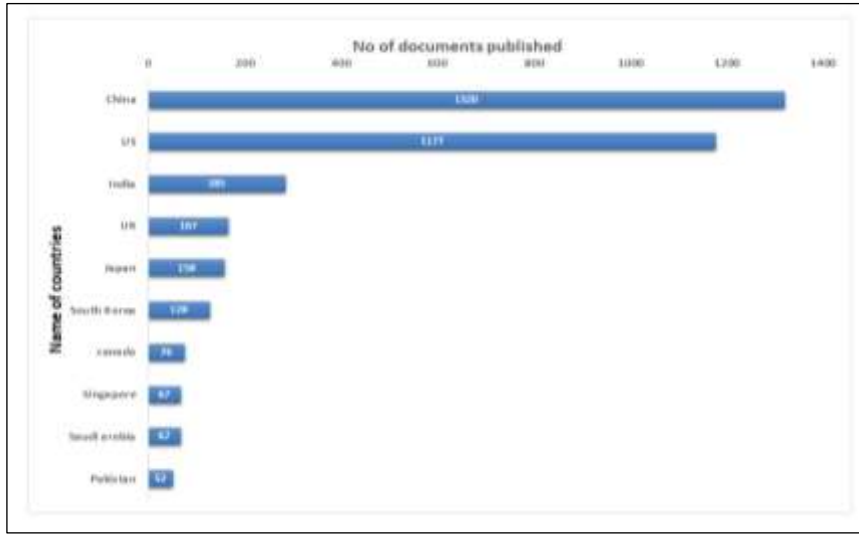


Figure 5: Country-wise research trend from 2000 to 2025.  
Source: Authors, (2026).

Figure 5 shows that China leads in terms of publications (1320, 33.43%), followed by the United States of America (1177, 29.80%). The remaining countries are behind in terms of publishing the research in such a crucial domain.

(b) *Collaboration between Countries*

Data acquired from the Scopus database using VOS Viewer [36] version 1.6.18. Bibliographic coupling research was used to generate network maps linking nations based on their joint publications. The thickness of the lines linking the nodes in each network map is dictated by the "link strength" and signifies network connectedness or co-citations. Fifty-seven countries have been effectively represented on a network analysis diagram. Figure 6 illustrates the network of many nations and their collaborations with coauthors. minimum threshold of five papers was established for a nation to be included in the list.

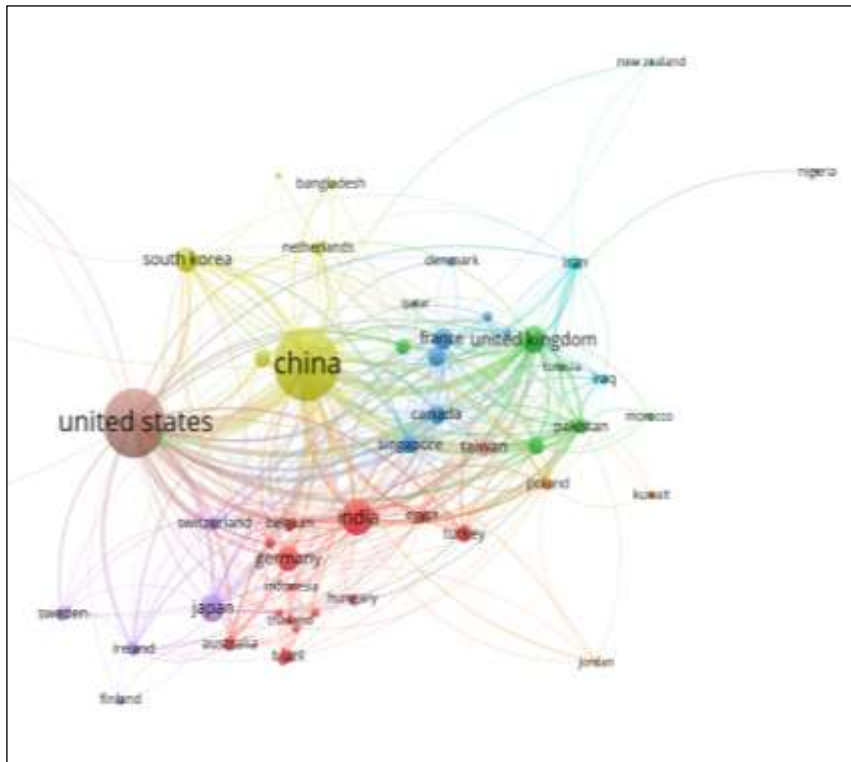


Figure 6: Network analysis diagram based on country keywords.  
Source: Authors, (2026).

(c) *Languages and Document Types*

This section discusses the languages and document types seen in the subject matter. The documents were mainly published in four languages, namely English (3863), Chinese (74), French (5), Japanese (5), Korean (3), Turkish (2), Polish (2) and 1 paper each in Spanish, Italian and German. English accounted for more than 98% of total publications. In terms of document type, book chapters (104), conference reviews (66), short surveys (6), articles (2232), conference papers (1351), reviews (176), and other document types contribute far less to this field of study as shown in Figure 7. The majority of the additional analysis was conducted using document-type articles, which are commonly found in these journals.

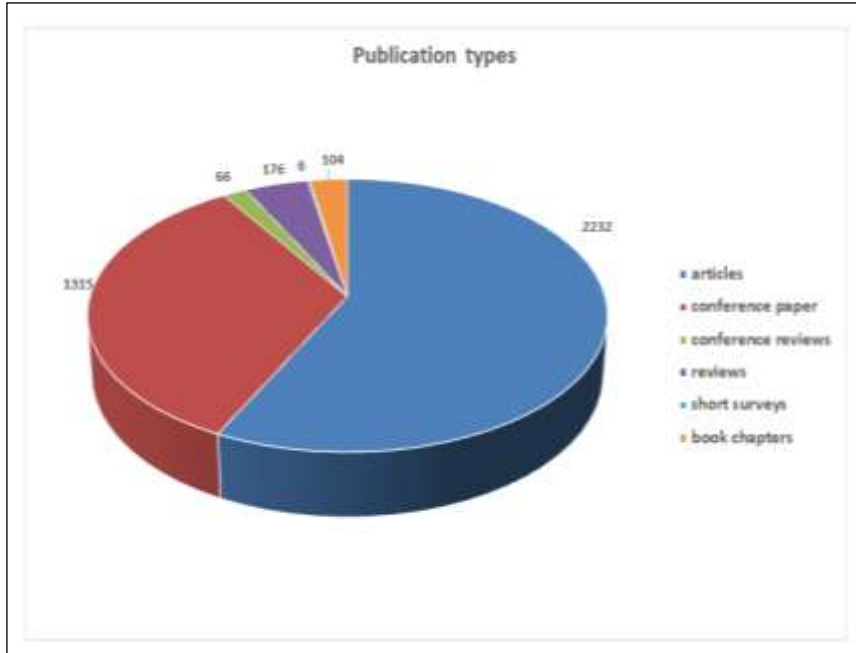


Figure 7: Document type distribution on TMED.  
Source: Authors, (2026).

d) *Publication Trend*

Figure 8 shows the publication trend increasing rapidly post-2015. The year 2024 received a maximum publication of 617 on the topic of TMED. The trendline shows the research initiatives taken by various authors across the globe to address the challenges faced by the electronic community on the thermal front.

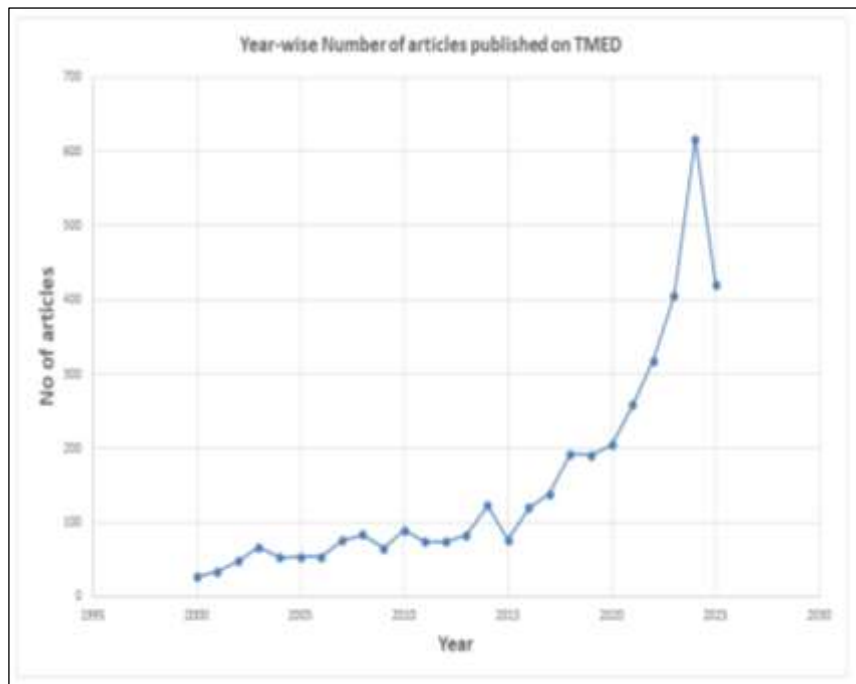


Figure 8: Publication trend year-wise on TMED.  
Source: Authors, (2026).



The network of different authors and their partnerships with co-authors is depicted in Figure 11. The author's minimum document count was limited to 5. Out of 13742 authors, it was possible to plot 261 of them on the graph. Data shows Yu Jinhong (21 articles, Citation 1730), Sun Rong (26 articles, Citation count 2006), Suresh Garimella (20 articles, Citation count 1224) and Avram Bar Cohen (25 articles, Citation count 498) did a lot of collaborative work.

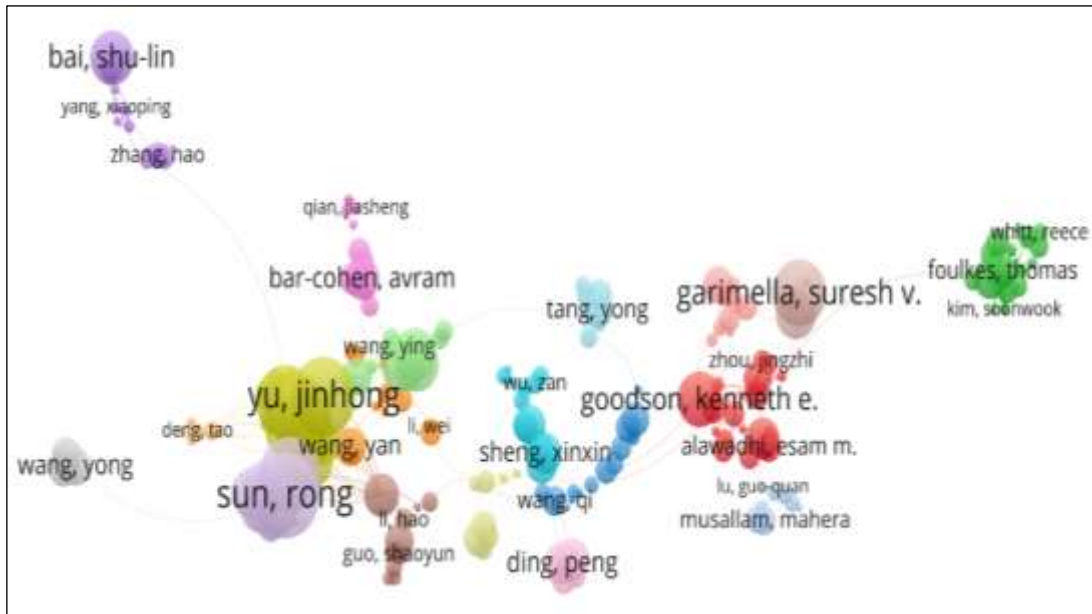


Figure 11: Diagram of the network analysis based on the authors' collaboration for TMED between 2000 and 2025. Source: Authors, (2026).

Figure 12 shows that citations are continuously increasing over the years, which depicts the inclination of researchers in the domain. The year 2024 received the highest citations of 16563 for the total 616 documents published in Scopus database. Till June 2025, the citation count and published documents have reached 70% of previous year.

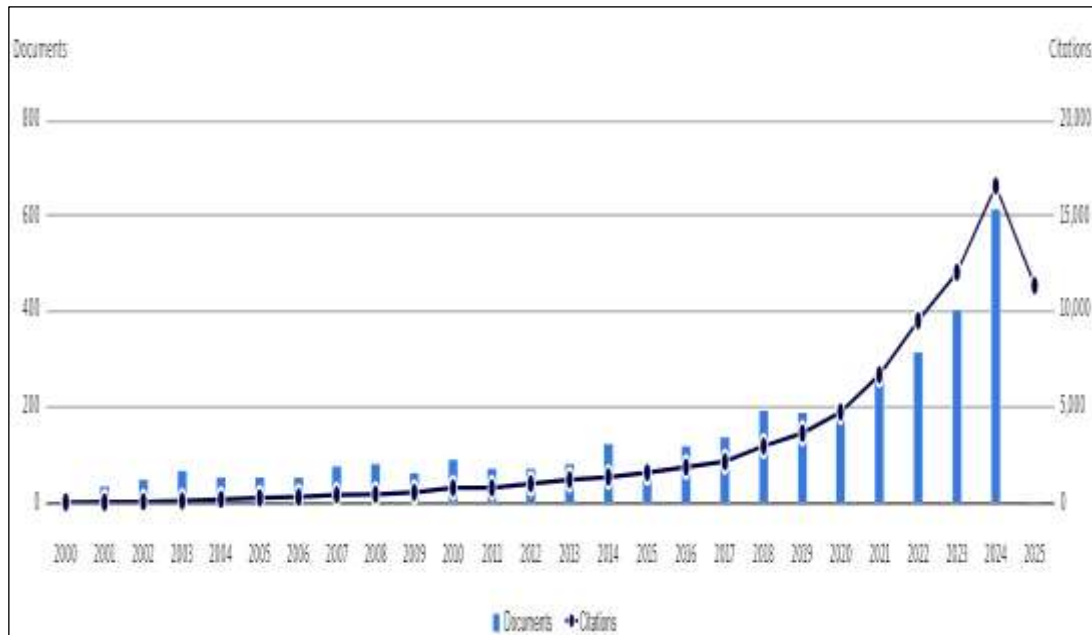


Figure 12: Diagram of the network analysis based on the citation trend on TMED between 2000 and 2025. Source: Authors, (2026).

#### II.1.4 Studies on Thermal Management of Electronic Devices With Passive Cooling

##### (a) Research trends in the top ten countries

Keyword search using the words “Thermal Management of Electronic devices with passive cooling” returned contributions by 40 different countries in between 2000 to 2025. The search results were plotted for the to 10 top countries. The country-wise distribution of documents eliciting the number of research articles on TMED with passive cooling is shown in Figure 13, displays data on the 10 most productive countries.

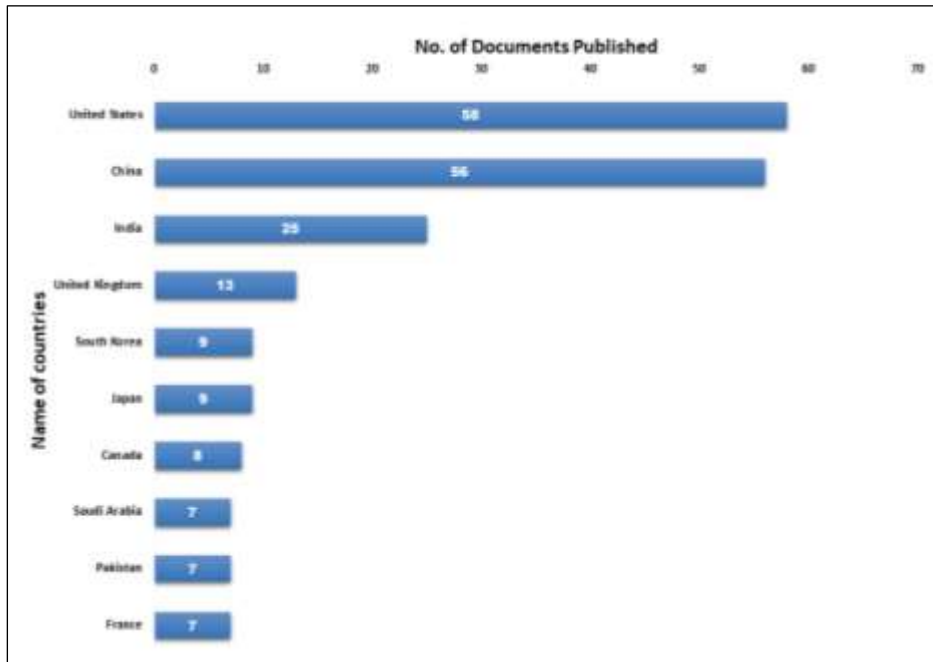


Figure 13: Country-wise research trend from 2000 to 2025.  
Source: Authors, (2026).

China and the United States are almost equal in terms of publications, followed by India. The other Asian countries are behind in the domain publication.

(b) *Collaboration between Countries*

Data obtained from Scopus database using VOS viewer version 1.6.18. Bibliographic coupling analysis was performed to create network maps, as shown in Figure 14, connecting countries based on their collaborative publication. Authors from China, the United States and Saudi Arabia are collaborating more compared to other countries, as visible from the “link strength”. It could be the reason why research is on an increasing trend in those countries.

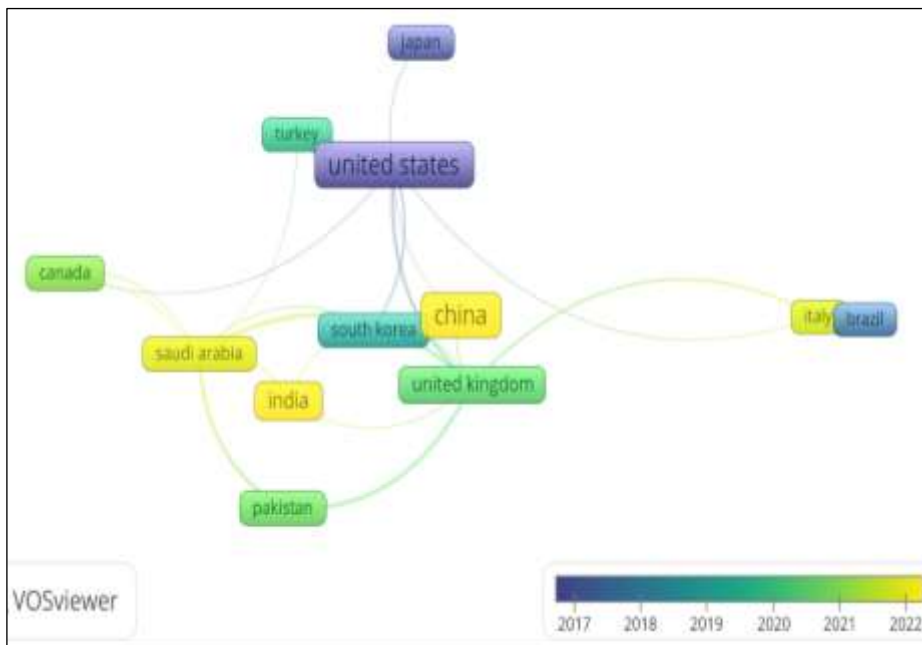


Figure 14: Network analysis diagram based on country keywords.  
Source: Authors, (2026).

(c) *Languages and Document Types*

This section discusses the languages and document types seen in the subject matter. The documents were mainly published in four languages, namely English (219), Chinese (4). In terms of document type, book chapters (8), conference reviews (05), notes (1), articles (124), conference papers (76), reviews (10), and other document types contribute far less to this field of study as shown in Figure 15. The majority of the additional analysis was conducted using document-type articles, which are commonly found in these journals.

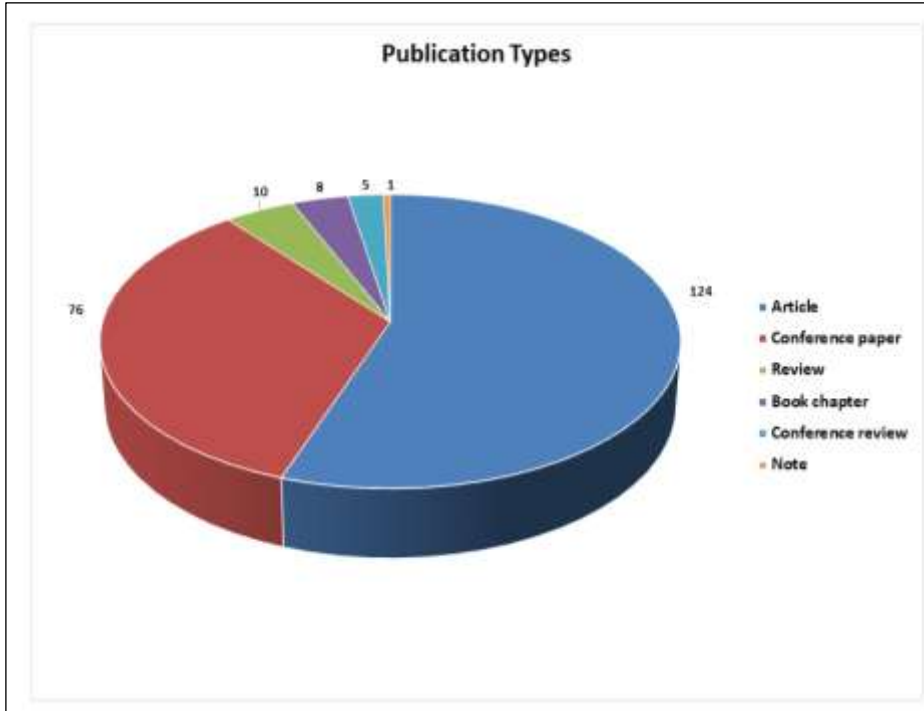


Figure 15: Document type distribution on TMED with passive cooling.  
Source: Authors, (2026).

(d) *Publication Trend*

Figure 16 shows similar trend as that of earlier publications trend, signifying the interest of researchers in using passive cooling technologies like phase change materials, heat pipes in mitigating the challenges posed by electronic cooling.

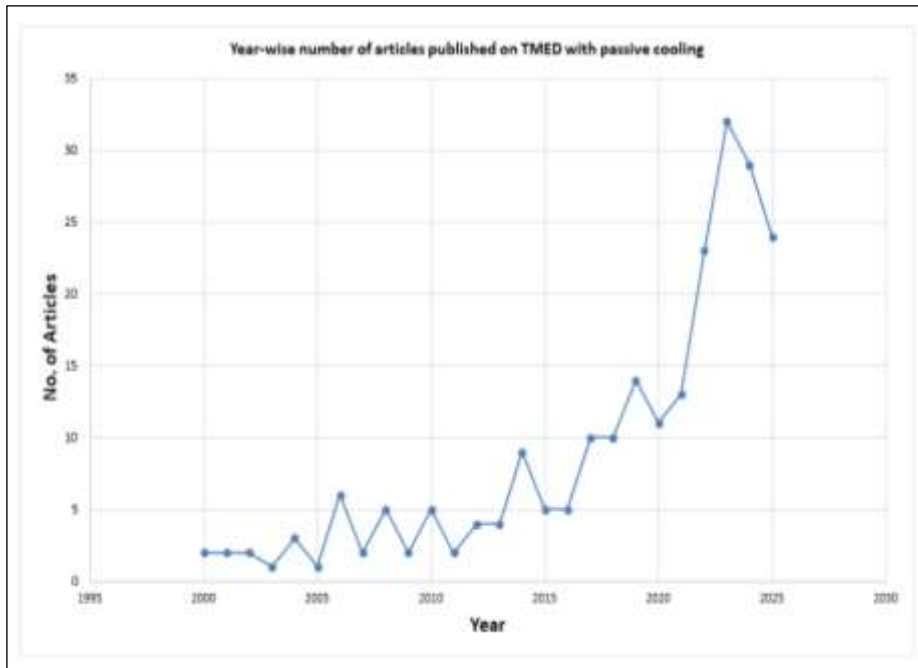


Figure 16: Publication trend year-wise on TMED with passive cooling.  
Source: Authors, (2026).

(e) *Subject area analysis*

Figure 17 shows that significant research articles are published in other subject areas apart from the engineering domain, which shows that the cooling of electronic devices using passive cooling techniques holds many applications.

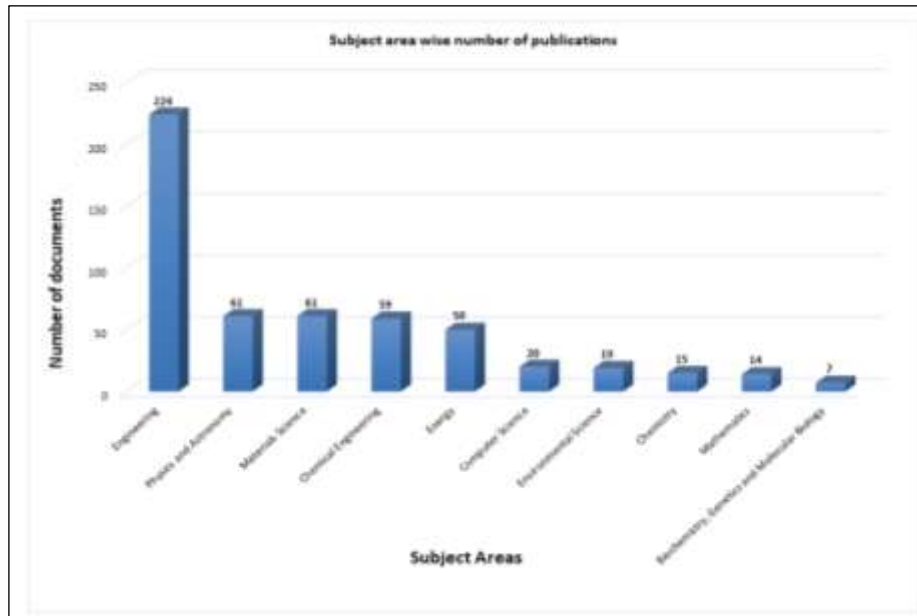


Figure 17: Subject area-wise on TMED with passive cooling.  
Source: Authors, (2026).

(f) *Keyword-Based Network Analysis and Author Collaboration*

Figure 18 shows the network analysis performed on VOS viewer for cited author collaboration. The minimum number of documents of an author are considered as 2 and 66 authors meet the criteria out of 869. Figure 15 depicts the density visualization of 9 major clusters.

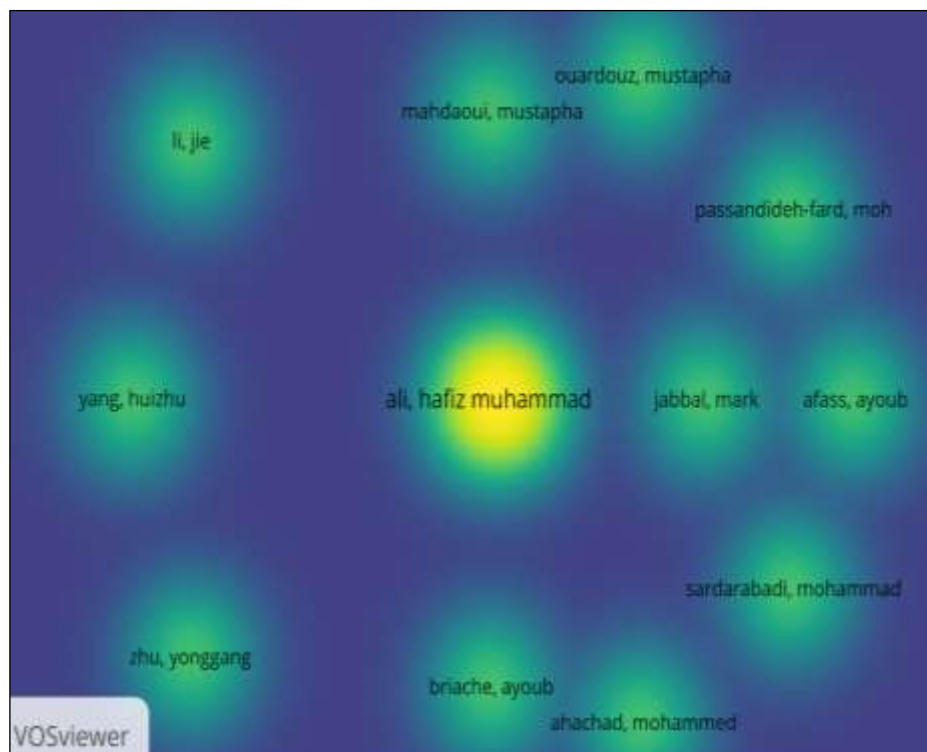


Figure 18: A network analysis diagram for TMED with passive cooling and vapour chamber from 2007 to 2024.  
Source: Authors, (2026).

II 1.5 Studies On Thermal Management Of Electronic Devices With Passive Cooling And Vapour Chamber

(a) *Research trends in the top ten countries*

Referring to figure 19 fetched from Scopus data between 2010 to 2025, the number of documents published in this niche area is significantly lower. The United States is leading the way, followed by China and India. This shows there is a lot of scope for research in this domain.

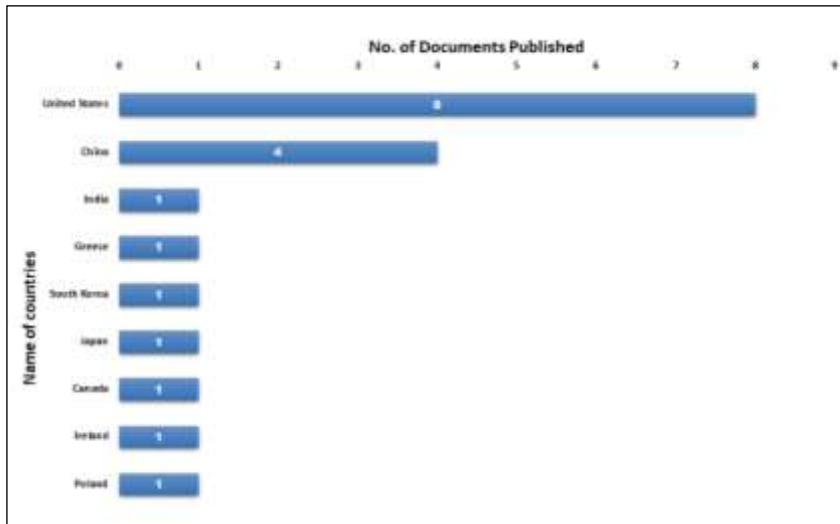


Figure 19: Country-wise research trend from 2010 to 2025.  
Source: Authors, (2026).

(b) *Collaboration between nations*

For the term "Thermal management of electronic devices with passive cooling and vapour chamber " Figure 20 shows the network of different nations and their partnerships with other writers. A requirement of 1 document was set as a qualifying criterion in order to be reflected on the graph. United nation authors show more collaboration with other countries in publishing research articles in this domain.

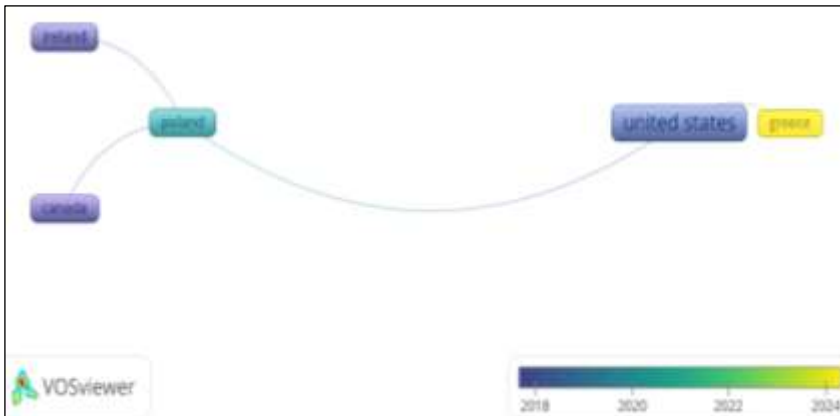


Figure 20: A country network analysis diagram for TMED with passive cooling and vapour chamber 2010 to 2024.  
Source: Authors, (2026).

(c) *Types of Documents*

Figure 21 shows the research articles and the conference papers contribution is more as compare to other document types.

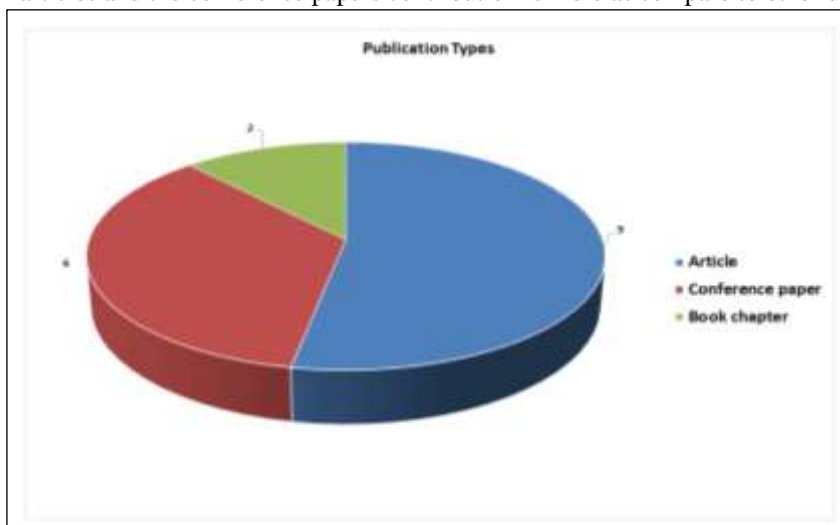


Figure 21: Document type distribution on TMED with passive cooling and vapour chambre.  
Source: Authors, (2026).

(d) *Publication Trend*

Since only Scopus database is referred here, figure 22 shows the number of publication year wise is on the lower side. The count till 2016 is very less but the trend is gradually increasing from last two years.

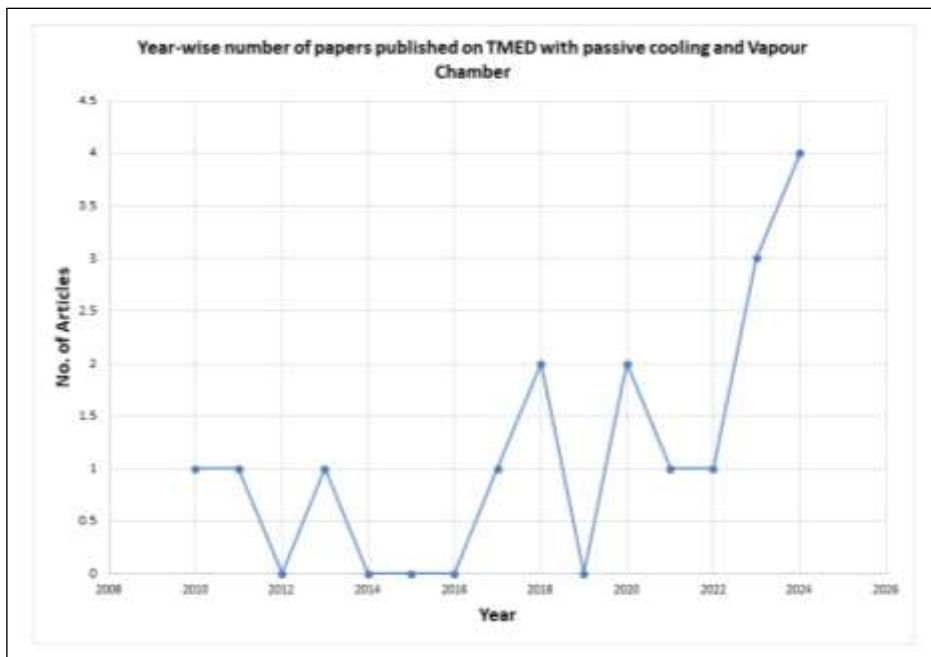


Figure 22: Publication trend year-wise on TMED with passive cooling and vapour chambre. Source: Authors, (2026).

(e) *Subject area analysis*

Figure 23 shows the similar pattern as that of earlier two keywords. Physics and astronomy (7), Material science (6), Chemical engineering (3) follows the lead after engineering subject area due to relevant application in respective domain.

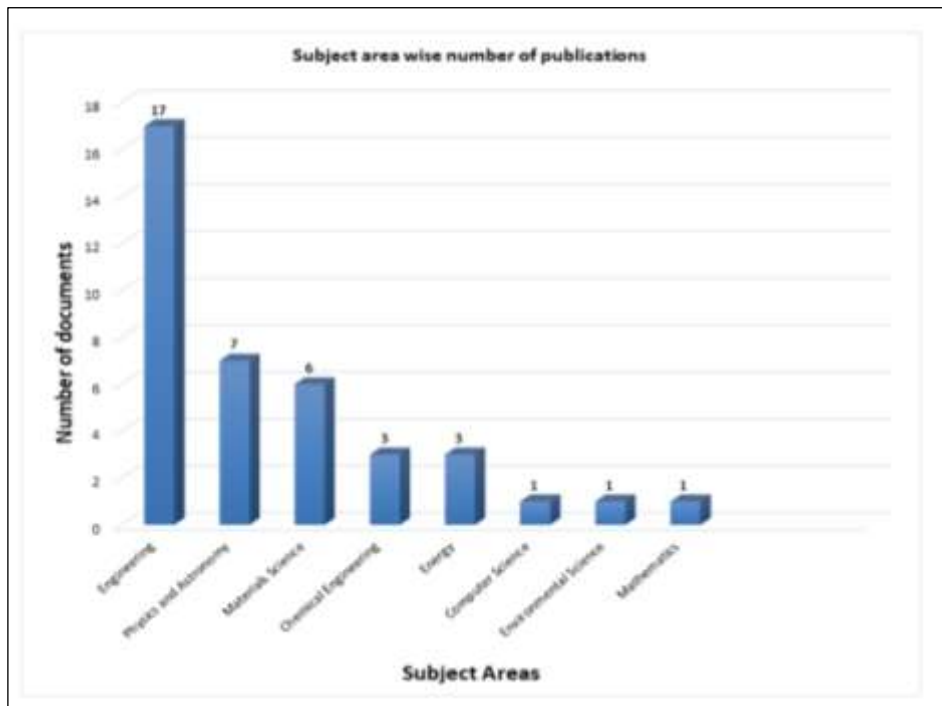


Figure 23: Subject area-wise on TMED with passive cooling and vapour chambre. Source: Authors, (2026).

### III COMPARATIVE ANALYSIS OF BIBLIOMETRIC TRENDS FOR ALL THE CATEGORIES

In this study, it is decided to do bibliometric analysis by three keyword search which narrow downs the research domains in following three categories:

Category -I: ---Thermal Management of Electronic devices

Category -II: --- Thermal Management of Electronic devices with passive cooling

Category -III: ---Thermal Management of Electronic devices with passive cooling and vapour chamber

The following section investigates all the three categories to arrive at meaningful conclusions

#### III.1 COUNTRY-WISE CONTRIBUTION

Overall, the number of publications started significantly rising after 2015 in the area of TMED. China (1380 documents, 32%) is at the top of graph, followed by United states may be due to the funding provided by universities and the allied industries. This helped the creation of value research and publication in the said countries. The Scopus data shows that more than 40 times Chinese universities are giving acknowledgement for sponsoring the required funds. Apart from China, there is hardly any country in Asia that is contributing to strengthening the domain. India, being a developing economy, shall focus on this research domain by extending a helping hand to the MSME sector in the creation of state-of-the-art manufacturing capabilities like 3D printing and rapid prototyping. The USA spends 3.59% of GDP on R&D in 2022, followed by China at 2.56%, while India falls far behind at 0.65%, according to the most recent data available.

With yearly growth rates of 8.7%, China exhibits the greatest development trajectory, whereas the US and India display more moderate growth trends [37]. The industry and academia shall come together to foster the research in such emerging areas [38] to bridge the gap between industrial needs and academic ecosystem. The limited availability of domestic funding compels researchers to pursue and depend on international collaboration. National scientific performance relies not solely on domestic R&D investments but is also affected by foreign investments from other countries [39]. Lower-income countries contribute minimally to Sustainable Development Goal (SDG) research, indicating a global misalignment [40]. This eventually affects the contribution of academia research in national/international environmental policies [41].

#### III.2 TYPE OF DOCUMENT

The data indicates that the number of research articles published (2365) is higher across all three categories, with 56%, 55% and 56% contributions in the first (2232 nos), second (124 nos) and third (9 nos) categories, respectively. The analysis reveals significant scope in the third category to explore the vapour chamber as a passive cooling medium in the thermal management of electronic devices, due to its superior thermal performance in a compact space.

The citation number of a publication tells volume about the significance and its penetration in research community. It also paves the path to take the current research ahead. The research trend in figure 12 clearly shows the spike in number of documents published as well as citations received are all time high in the year 2024 and similar trend is observed till mid-2025. This also indicates that there is growing need and market for research in this domain. It is very likely that the growing need of end user and progression of semiconductor technology is inviting more researchers to address the issues related to heat dissipation in compact spaces.

Data shows that engineering is not the only field wherein thermal issues related to electronic devices are pertinent. Physics and astronomy, owing to the development of semiconductor technology, and chemical engineering, owing to thermal management of control devices used in process industries and material science, owing to the development of lightweight and high thermal conductivity material development are following the similar trend of engineering as subject area. Overall, multidisciplinary research can lead to groundbreaking research in the area of TMED [41].

### IV. CONCLUSIONS

The bibliometric analysis conducted based on Scopus publication data reveals that the thermal management of electronic devices is picking up pace in the market due to the digitalisation and use of compact high-power electronic equipment. The present study shows that China, followed by the United States of America, is leading the trend in terms of publication and research. This trend is because the funding agencies and the government policies are more oriented towards research and development. It is also observed that the author collaboration is more prevalent in these countries. This trend will attract more talent pool across the globe to seek higher education opportunities in these countries. Indian authors are gradually making progress in the area of thermal management and electronic cooling. In document types, the research articles are at the top, having more than 50% contribution for all three keywords chosen.

### V. AUTHOR'S CONTRIBUTION

**Conceptualization:** Nilesh Gaikwad, Narendra Deore and Mahadev Madgule.

**Methodology:** Nilesh Gaikwad, Narendra Deore and Mahadev Madgule.

**Investigation:** Nilesh Gaikwad, Narendra Deore and Mahadev Madgule.

**Writing – Original Draft:** Nilesh Gaikwad, Narendra Deore and Mahadev Madgule.

**Writing – Review and Editing:** Nilesh Gaikwad, Narendra Deore and Mahadev Madgule.

**Resources:** Nilesh Gaikwad, Narendra Deore and Mahadev Madgule.

**Supervision:** Nilesh Gaikwad, Narendra Deore and Mahadev Madgule.

**Approval of the final text:** Nilesh Gaikwad, Narendra Deore and Mahadev Madgule.

## VII. REFERENCES

- [1] N. Alam and M. Alam, "The Trend of Different Parameters for Designing Integrated Circuits from 1973 to 2019 and Linked to Moore's Law," *Aust. J. Eng. Innov. Technol.*, vol. 2, no. 2, pp. 16–23, 2020, doi: 10.34104/ajeit.020.016023.
- [2] G. Moore and O. N. M. S. Law, "Moore's Law is live Moore's," 2005.
- [3] F. Zhu, P. Xu, and J. Zong, "Moore's Law: The potential, limits, and breakthroughs," *Appl. Comput. Eng.*, vol. 10, no. 1, pp. 307–315, 2023, doi: 10.54254/2755-2721/10/20230038.
- [4] Z. He, Y. Yan, and Z. Zhang, "Thermal management and temperature uniformity enhancement of electronic devices by micro heat sinks: A review," *Energy*, vol. 216, p. 119223, Feb. 2021, doi: 10.1016/J.ENERGY.2020.119223.
- [5] A. R. Dhumal, A. P. Kulkarni, and N. H. Ambhore, "A comprehensive review on thermal management of electronic devices," *J. Eng. Appl. Sci.*, vol. 70, no. 1, pp. 1–18, 2023, doi: 10.1186/s44147-023-00309-2.
- [6] H. Chen, T. Zhang, Q. Gao, J. Lv, H. Chen, and H. Huang, "Thermal management enhancement of electronic chips based on novel technologies," *Energy*, vol. 316, p. 134575, Feb. 2025, doi: 10.1016/J.ENERGY.2025.134575.
- [7] H. Lv, D. Jing, and W. Zhan, "Research on thermal management technology of system-level electronic integrated package," *J. Phys. Conf. Ser.*, vol. 2033, no. 1, 2021, doi: 10.1088/1742-6596/2033/1/012138.
- [8] M. Azarifar, M. Arik, and J. Y. Chang, "Liquid cooling of data centers: A necessity facing challenges," *Appl. Therm. Eng.*, vol. 247, no. December 2023, p. 123112, 2024, doi: 10.1016/j.applthermaleng.2024.123112.
- [9] H. Liang, W. Zhang, J. Huang, S. Yang, and P. Gupta, "Leveraging Hotspots and Improving Chip Reliability via Carbon Nanotube Grid Thermal Structure," *IEEE Trans. Very Large Scale Integr. Syst.*, vol. 23, no. 4, pp. 731–742, Apr. 2015, doi: 10.1109/TVLSI.2014.2321182.
- [10] J. Shalf, "The future of computing beyond Moore's Law Subject Areas :," *Philos. Trans. R. Soc.*, vol. 378, no. 20190061, pp. 1–14, 2020.
- [11] Tanushree P, "Effect of using PCM as Cooling Medium in Different Types of Heat Sinks," *Int. J. Eng. Res.*, vol. V9, no. 08, pp. 201–206, 2020, doi: 10.17577/ijertv9is080103.
- [12] H. Wang et al., "Bioinspired thermally conducting packaging for heat management of high performance electronic chips," *Commun. Eng.*, vol. 4, no. 1, pp. 2–10, 2025, doi: 10.1038/s44172-024-00338-6.
- [13] H. Jouhara, D. Reay, R. McGlen, P. Kew, and J. McDonough, "Chapter 7 - Cooling of electronic components," in *Heat Pipes (Seventh Edition)*, Seventh Ed., H. Jouhara, D. Reay, R. McGlen, P. Kew, and J. McDonough, Eds., Butterworth-Heinemann, 2024, pp. 271–306. doi: <https://doi.org/10.1016/B978-0-12-823464-8.00006-1>.
- [14] N. Sharifi, H. Shabgard, C. Millard, and U. Etufugh, "Hybrid Heat Pipe-PCM-Assisted Thermal Management for Lithium-Ion Batteries," *Batteries*, vol. 11, no. 2, 2025, doi: 10.3390/batteries11020064.
- [15] S.-J. Kim, J.-S. Lee, and S.-H. Rhi, "Heat Pipe Embedded Battery Cooling System for Future Electric Vehicle," *Batteries*, vol. 11, no. 4, 2025, doi: 10.3390/batteries11040164.
- [16] M. A. Gómez, R. Bellas, A. González-Gil, A. Cacabelos, and A. Larrañaga, "Thermal study of a passive cooling device operating through a bubble lifting CLTPT of NOVEC 7000 with a two-fluid condenser," *Int. J. Heat Mass Transf.*, vol. 177, 2021, doi: 10.1016/j.ijheatmasstransfer.2021.121530.
- [17] A. Ghanbarpour, M. J. Hosseini, A. A. Ranjbar, M. Rahimi, R. Bahrapoury, and M. Ghanbarpour, "Evaluation of heat sink performance using PCM and vapor chamber/heat pipe," *Renew. Energy*, vol. 163, pp. 698–719, 2021, doi: 10.1016/j.renene.2020.08.154.
- [18] A. A. Litvintseva, N. I. Volkov, N. I. Vorogushina, V. A. Moskovskikh, and V. V. Cheverda, "The effect of operating parameters on the heat transfer in the heat pipe," *J. Phys. Conf. Ser.*, vol. 2119, no. 1, 2021, doi: 10.1088/1742-6596/2119/1/012088.
- [19] Y. Luo, Y. Tang, X. Zhang, H. Wang, G. Zhou, and P. Bai, "A novel composite vapor chamber for battery thermal management system," *Energy Convers. Manag.*, vol. 254, no. February, p. 115293, 2022, doi: 10.1016/j.enconman.2022.115293.
- [20] J. Zhao, M. Du, Z. Zhang, and X. Ling, "Thermal management strategy for electronic chips based on combination of a flat-plate heat pipe and spray cooling," *Int. J. Heat Mass Transf.*, vol. 181, p. 121894, Dec. 2021, doi: 10.1016/J.IJHEATMASSTRANSFER.2021.121894.
- [21] A. Shafieian, M. Khiadani, and A. Nosrati, "Strategies to improve the thermal performance of heat pipe solar collectors in solar systems: A review," *Energy Convers. Manag.*, vol. 183, pp. 307–331, Mar. 2019, doi: 10.1016/J.ENCONMAN.2018.12.115.
- [22] M. Bulut, S. G. Kandlikar, and N. Sozbir, "A Review of Vapor Chambers," *Heat Transf. Eng.*, vol. 40, no. 19, pp. 1551–1573, 2019, doi: 10.1080/01457632.2018.1480868.
- [23] D. Reay, R. J. McGlen, and P. A. Kew, "Heat Pipes: Theory, Design and Applications," 2006.
- [24] T. Zhao and Z. Hu, "Opportunities and Challenges for the Development of Ultra-Thin Heat Pipe," *Front. Energy Res.*, vol. 10, no. June, pp. 1–3, 2022, doi: 10.3389/fenrg.2022.923454.
- [25] P. Nemeč, A. Čaja, and M. Malcho, "Mathematical model for heat transfer limitations of heat pipe," *Math. Comput. Model.*, vol. 57, no. 1–2, pp. 126–136, 2013, doi: 10.1016/j.mcm.2011.06.047.
- [26] M. M. Farid, A. M. Khudhair, S. A. K. Razack, and S. Al-Hallaj, "A review on phase change energy storage: Materials and applications," *Energy Convers. Manag.*, vol. 45, no. 9–10, pp. 1597–1615, 2004, doi: 10.1016/j.enconman.2003.09.015.
- [27] A. Sharma, V. V. Tyagi, C. R. Chen, and D. Buddhi, "Review on thermal energy storage with phase change materials and applications," *Renew. Sustain. Energy Rev.*, vol. 13, no. 2, pp. 318–345, 2009, doi: <https://doi.org/10.1016/j.rser.2007.10.005>.

- [28] A. B. Etemoglu and M. Can, "Classification of geothermal resources in Turkey by exergy analysis," *Renew. Sustain. Energy Rev.*, vol. 11, no. 7, pp. 1596–1606, 2007, doi: 10.1016/j.rser.2006.01.001.
- [29] A. Mohammed Adham, N. Mohd-Ghazali, and R. Ahmad, "Thermal and hydrodynamic analysis of microchannel heat sinks: A review," *Renew. Sustain. Energy Rev.*, vol. 21, pp. 614–622, 2013, doi: 10.1016/j.rser.2013.01.022.
- [30] Z. Yuan, G. Vaartstra, P. Shukla, S. Reda, E. Wang, and A. K. Coskun, "Modeling and Optimization of Chip Cooling with Two-Phase Vapor Chambers," *Proc. Int. Symp. Low Power Electron. Des.*, vol. 2019-July, pp. 1–6, 2019, doi: 10.1109/ISLPED.2019.8824965.
- [31] S. M. Kim and I. Mudawar, "Universal approach to predicting saturated flow boiling heat transfer in mini/micro-channels – Part II. Two-phase heat transfer coefficient," *Int. J. Heat Mass Transf.*, vol. 64, pp. 1239–1256, 2013, doi: 10.1016/j.ijheatmasstransfer.2013.04.014.
- [32] R. Wen, W. Liu, X. Ma, and R. Yang, "Coupling Droplets/Bubbles with a Liquid Film for Enhancing Phase-Change Heat Transfer," *iScience*, vol. 24, p. 102531, 2021, doi: 10.1016/j.isci.2021.102531.
- [33] H. T. N. Ho and H. T. Luong, "Research trends in cybercrime victimization during 2010–2020: a bibliometric analysis," *SN Soc. Sci.*, vol. 2, no. 1, p. 4, 2022, doi: 10.1007/s43545-021-00305-4.
- [34] N. Donthu, S. Kumar, D. Mukherjee, N. Pandey, and W. M. Lim, "How to conduct a bibliometric analysis: An overview and guidelines," *J. Bus. Res.*, vol. 133, no. May, pp. 285–296, 2021, doi: 10.1016/j.jbusres.2021.04.070.
- [35] G. Chen and L. Xiao, "Selecting publication keywords for domain analysis in bibliometrics: A comparison of three methods," *J. Informetr.*, vol. 10, no. 1, pp. 212–223, 2016, doi: 10.1016/j.joi.2016.01.006.
- [36] U. A. Bukar, M. S. Sayeed, S. F. A. Razak, S. Yogarayan, O. A. Amodu, and R. A. R. Mahmood, "A method for analyzing text using VOSviewer," *MethodsX*, vol. 11, no. May, p. 102339, 2023, doi: 10.1016/j.mex.2023.102339.
- [37] A. Pratap, "A look at R&D spending plans across the globe.," *C&EN Global Enterprise*, p. 103, 2025. doi: <https://doi.org/10.1021/cen-10301-feature5>.
- [38] F. Ahmed, M. T. Fattani, S. R. Ali, and R. N. Enam, "Strengthening the Bridge Between Academic and the Industry Through the Academia-Industry Collaboration Plan Design Model," *Front. Psychol.*, vol. 13, no. July 2016, pp. 1–11, 2022, doi: 10.3389/fpsyg.2022.875940.
- [39] L. Miao, V. Larivière, F. Wang, Y.-Y. Ahn, and C. R. Sugimoto, "Cooperation and interdependence in global science funding," 2023, [Online]. Available: <http://arxiv.org/abs/2308.08630>
- [40] H. Confraria, T. Ciarli, and E. Noyons, "Countries' research priorities in relation to the Sustainable Development Goals," *Res. Policy*, vol. 53, no. 3, p. 104950, 2024, doi: 10.1016/j.respol.2023.104950.
- [41] A. Singh, S. H. Qasim, and S. S. Singh, "Importance of research in the development of the nation," *Int. J. All Res. Educ. Sci. Methods*, vol. 9, no. 7 July, pp. 5–9, 2021.