J Data Sci. Info. Citation Studies., 2023; 2(2):110-122.
https://www.jcitation.org

Research Article

Quantifying the Evolution of Cooling Technologies Research: A Bibliometric Journey from 2012 to 2021

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ABSTRACT

This study presents a comprehensive analysis of the research landscape in cooling technologies from 2012 to 2021, focusing on publication output, citation impact, and collaborative patterns within the field. The findings reveal a consistent increase in global research output and citations, indicating a growing interest and impact. However, a decline in citations in 2021 suggests a need for further investigation into the factors influencing research visibility and impact. India's research contribution to cooling technologies shows positive growth, but efforts are needed to enhance its visibility. The distribution of research publications across categories highlights the most prolific areas, such as "Energy Fuels," "Thermodynamics," and "Materials Science Multidisciplinary." Key contributing countries include China, the USA, Germany, Italy, and the UK, with variations in citation impact per publication. International collaboration is prominent, with varying levels observed among countries. Highly cited papers and influential authors play a significant role in shaping the field. The multidisciplinary nature of cooling technologies research offers collaboration opportunities and avenues for further advancements. This analysis provides valuable insights for policymakers, researchers, and stakeholders in understanding the research landscape, identifying collaboration opportunities, and enhancing research impact within the domain of cooling technologies.

Keywords: Bibliometric Analysis, Cooling Technologies, Research Landscape, Publication Output, Citation Impact, International Collaboration, Highly Cited Papers.

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Received: 21-05-2023;
Revised: 09-06-2023;
Accepted: 25-07-2023.

INTRODUCTION

In the rapidly evolving landscape of technology, the drive towards smaller and faster devices has resulted in a significant upsurge in heat generation, leading to higher failure rates and shorter lifespans. The reduction in the size of high-tech electronic devices, coupled with the exponential growth of integrated components and a substantial increase in power density, has presented a critical challenge: the need for rapid and efficient cooling. Conventional cooling techniques are struggling to keep pace with the escalating cooling demands, necessitating the exploration of advanced and innovative cooling technologies to meet the cooling requirements of modern devices, systems, and processes.

Consequently, the field of cooling technologies has witnessed a surge in research and development endeavours, accompanied by an intensified quest for improved cooling systems, generating widespread interest on a global scale. Notably, the recognition of cooling technologies as a burgeoning industry was reinforced by their recent feature in a BBC News technology report. However, a delicate equilibrium must be struck between the pressing need to mitigate global warming and the growing cooling requirements of modern devices, systems, appliances, and human comfort, including district heating and cooling. Developing and implementing advanced cooling technologies are imperative to effectively address these challenges.

To comprehensively comprehend the research landscape and advancements in cooling technologies, this paper presents a detailed bibliometric analysis spanning the period from 2012 to 2021. By employing this quantitative approach, the aim is to identify key research areas, track publication trends, discern influential authors and institutions, and unravel collaborative networks within the field. The chosen timeframe provides an extensive view of almost a decade of research, encapsulating the latest developments and tracing the trajectory of the evolution of cooling technologies.

Through this rigorous bibliometric analysis, underlying patterns can be uncovered, research gaps can be identified, and opportunities for further exploration in the field of cooling technologies can be pinpointed. The findings of this study hold

OPEN ACCESS

DOI: 10.5530/jcitation.2.2.15

EPUBL editing. publishing. technology

Publishing Partner : EManuscript Tech. [www.emanuscript.in]

immense significance for policymakers, industry professionals, and researchers, empowering them to make informed decisions, foster effective collaborations, and drive advancements in cooling technologies.

LITERATURE REVIEW

Balaras *et al*., 2007 provided an overview of solar air conditioning technologies in Europe, highlighting the progress made in terms of system efficiency and integration with renewable energy sources. However, the study identified the gap in terms of standardization, policy support, and large-scale implementation of solar air conditioning systems. Hepbasli, 2008 provided a comprehensive review on exergetic analysis and assessment of renewable energy resources. The study emphasized the significance of exergy-based evaluations for optimizing the efficiency and sustainability of renewable energy systems. However, there is a gap in terms of integrating exergetic analysis into policy frameworks and decision-making processes. Kim and Infante Ferreira, 2008 conducted a state-of-the-art review of solar refrigeration options. The study identified various solar refrigeration technologies, such as absorption refrigeration and adsorption refrigeration, and discussed their applications and performance. However, there is a need for further research on the cost-effectiveness, scalability, and optimization of these technologies for different cooling demands. Al-Alili *et al*., 2014 conducted a comprehensive review of solar thermal air conditioning technologies, highlighting their potential for sustainable cooling applications. The study identified the key advancements and challenges in this field, emphasizing the need for further research on system efficiency, cost-effectiveness, and integration with existing cooling infrastructure. Anand *et al*., 2015 reviewed solar cooling systems as a means of mitigating climate change. The study revealed that solar cooling technologies have shown promising results in reducing greenhouse gas emissions associated with cooling, but there is a gap in terms of the economic viability and scalability of these systems for widespread adoption. Mao *et al*., 2015 conducted a bibliometric analysis of biomass energy research. The study revealed the increasing research interest in biomass energy utilization and highlighted the importance of sustainability, efficiency, and feedstock availability in biomass energy systems. However, further research is needed to address the challenges of biomass resource management, conversion technologies, and environmental impacts. de Paulo and Porto, 2017 examined the relationship between solar energy technologies and open innovation using bibliometric and social network analysis. The findings highlighted the interdisciplinary nature of solar energy research and the importance of collaboration between academia, industry, and policymakers. However, further research is needed to explore the potential barriers and strategies for successful open innovation in the solar energy sector. Montagnino, 2017 provided an overview of solar cooling technologies, showcasing existing projects and their performance. The study revealed the potential of solar cooling for reducing energy consumption and environmental impact in various applications. However, there is a gap in terms of long-term monitoring and assessment of these projects to evaluate their real-world performance and economic viability. Park and Nagy, 2018 conducted a comprehensive literature review on the relationship between thermal comfort and building control research. The study highlighted the need for integrated approaches that consider human factors, building systems, and environmental conditions to achieve optimal thermal comfort. However, there is a gap in terms of developing standardized methodologies and tools for assessing and improving thermal comfort in diverse building types and climates. Ayadi and Al-Dahidi, 2019 compared solar thermal and solar electric space heating and cooling systems in different climatic regions. The findings indicated that the choice between the two technologies depends on the specific climatic conditions and energy demands of a region. However, further research is needed to optimize the design and performance of these systems to ensure their effectiveness and practicality in diverse environments. Zhang and Yuan, 2019 performed a bibliometric analysis of energy performance contracting research. The study revealed the increasing research interest in energy performance contracting as a mechanism for improving energy efficiency. However, there is a gap in terms of the evaluation of performance contracting models, policy frameworks, and financial mechanisms to ensure successful implementation and long-term sustainability. Calderón *et al*., 2020; Miranda *et al*., 2021 conducted a bibliometric analysis on Thermal Energy Storage (TES) research. The study revealed the increasing research interest in TES, with a focus on various storage materials, phase change materials, and system design. However, a research gap exists in terms of the practical application and scalability of TES technologies in real-world energy systems.

The reviewed articles shed light on the research landscape of cooling technologies, particularly in the context of solar cooling, thermal energy storage, and exergetic analysis. The studies identified several key themes and emerging trends in these fields, including advancements in technology, economic viability, scalability, and integration with existing infrastructure. However, research gaps were identified, such as the need for further investigation into system efficiency, economic feasibility, standardization, policy support, and real-world application of these technologies. Future research should address these gaps to facilitate the widespread adoption and implementation of sustainable cooling solutions.

Need for Research

The demand for energy-efficient and sustainable cooling technologies has intensified in recent years due to the increase in global temperatures and the negative impact of greenhouse gas emissions on the environment. With the growth of the global population, there is a greater need for cooling technologies in homes, commercial buildings, and industrial applications. Research on cooling technologies can aid in the development of new, cost-effective, and energy-efficient solutions to meet these demands.

Research Objectives

This research aims to quantify the evolution of cooling technologies research, focusing on trends, innovations, and key breakthroughs over the years. The objectives are:

- To examine the overall research landscape of cooling technologies from 2012 to 2021.
- To analyse the publication trends and growth patterns in cooling technologies research over the past decade.
- To identify the key themes and research frontiers within the field of cooling technologies during the specified time period.
- To determine the most influential countries, authors, institutions, and journals in the field of cooling technologies.
- To investigate collaboration patterns and networks among researchers in the field of cooling technologies.
- To identify highly cited papers and distribution of citations within the field of cooling technologies research.
- To identify the main research themes and topics by analysing the co-occurrence of keywords.

METHODOLOGY

The methodology employed for identifying and obtaining publications on "cooling technologies" from the Web of Science database followed a comprehensive approach. The authors developed a search strategy using the term "cooling technolog*" and restricted the search period to 2012-2021. This strategy resulted in 13,653 records, which were further analysed using additional features available in the database. To assess output quality, the presence of publications in peer-reviewed journals was considered a reliable indicator. The study also adopted a complete count approach, assigning full credit to authors, organizations, and countries irrespective of their position in the list of authors. Furthermore, qualitative indicators such as citation per paper and share in highly cited papers were utilized to evaluate research impact. To gain insights into the research landscape, the authors utilized VOSviewer and Biblioshiny applications for visualizing interactions among countries, organizations, authors, and keywords. Lastly, citation data were collected until December 30, 2021.

Overview of the data

Table 1 presents an overview of the collected data during 2012 – 2021. The dataset comprises 13,653 documents sourced from various outlets, including journals, books, and other document types. The average CPP for the collected documents is 18.88, indicating the impact and influence of the research in the field. Articles represent most of the publications, accounting for 11,484 documents. Other document types include review papers (1,283), proceedings papers (795), editorial materials (52), meeting abstracts (13), book chapters (18), letters (4), corrections (2), book reviews (1), and news items (1). The diverse range of document types underscores the comprehensive nature of the analysis, encompassing different forms of scholarly communication.

Keywords associated with the documents were also extracted, revealing a total of 18,617 plus keywords and 32,199 author(s) keywords. This information provides valuable insights into the main themes and focal areas within the field of cooling technologies. The dataset comprises contributions from 43,353 authors, with 627 papers being single-authored, indicating individual research output. The majority of papers (13,026) were multi-authored, highlighting the collaborative nature of research in cooling technologies. On average, each author contributed

Table 1: Summary of the collected data.

Description	Results
Timespan	2012:2021
Sources (Journals, Books, etc)	2056
Documents	13653
Average citations per documents	18.88
Article	11484
Review	1283
Proceedings Paper	795
Editorial Material	52
Meeting Abstract	13
Book Chapter	18
Letter	4
Correction	2
Book Review	1
News Item	1
Keywords Plus	18617
Author(s) Keywords	32199
Authors	43353
Single-authored papers	627
Multi-authored papers	13026
Documents per Author	0.315
Authors per Document	3.18
Collaboration Index	3.28

Table 2: Annual research performance in cooling technologies (Global v/s India).

Global Contribution					Indian Contribution			
Year	TP	Cumulative	TC	CPP	TP	Cumulative	TC	CPP
2012	739	739	26707	36.139	23	23	3109	135.174
2013	754	1493	24485	32.473	19	42	1975	103.947
2014	953	2446	30775	32.293	33	75	1496	45.333
2015	956	3402	29912	31.289	31	106	974	31.419
2016	1147	4549	33657	29.344	45	151	649	14.422
2017	1286	5835	31730	24.673	56	207	470	8.393
2018	1485	7320	30415	20.481	66	273	224	3.394
2019	1714	9034	24261	14.155	64	337	140	2.188
2020	2029	11063	17521	8.635	98	435	46	0.469
2021	2590	13653	9080	3.506	135	570	5	0.037

TP= Total Publications; TC= Total Citations; CPP= Citations per Paper.

to approximately 0.315 documents, and each document had an average of 3.18 authors, indicating the level of collaboration within the field. The collaboration index, calculated as the ratio of multi-authored papers to single-authored papers, was found to be 3.28, further emphasizing the collaborative nature of research in cooling technologies.

Table 1 offers a comprehensive overview of the research landscape in cooling technologies from 2012 to 2021. It presents the extensive publication output, diverse document types, citation impact, and collaborative patterns within the field. These findings lay the groundwork for further analysis and exploration of key research areas, influential authors, and collaborative networks in the domain of cooling technologies.

DATA ANALYSIS AND INTERPRETATION

Year-wise research performance (Global v/s India)

Table 2 presents a year-wise comparative analysis of research performance in cooling technologies, examining the contributions from a global perspective and specifically from India. In 2012, the global research output in cooling technologies amounted to 739 publications, while India contributed 23 publications. Over the years, both global and Indian cumulative publications steadily increased, reaching 13,653 and 570, respectively, by 2021.

While considering the total citations received, global research in cooling technologies received a substantial number of citations in 2012, with 26,707 citations, and maintained a relatively high level throughout the years. However, there was a notable decline in the number of citations in 2021, with only 9,080 citations. In contrast, the citations received by Indian research in cooling technologies were comparatively lower, starting at 3,109 in 2012 and declining to just 5 citations in 2021.

An analysis of the average CPP reveals that global research consistently exhibited a higher CPP compared to Indian research. In 2012, the CPP for global research stood at 36.139, indicating a relatively higher impact and visibility of publications, while the CPP for Indian research was substantially higher at 135.174. However, over the years, both global and Indian research experienced a decline in CPP. The CPP for global research gradually decreased to 3.506 in 2021, while the CPP for Indian research also decreased significantly to 0.037 during the same period.

The year-wise comparative analysis highlights several trends in the research performance of cooling technologies. Globally, there has been a consistent increase in research output, cumulative publications, and citations, indicating a growing interest and impact in the field. However, the decline in citations in 2021 suggests a need for further investigation into the factors influencing research visibility and impact. On the other hand, India's research contribution to cooling technologies has shown positive growth, albeit at a relatively lower scale compared to the global output. The decline in citations received by Indian research, along with the decrease in CPP, indicates a potential area for improvement and increased visibility of Indian research in the field.

Web of Science Categories in Cooling Technology

Table 3 provides the distribution of research publications in cooling technologies across various Web of Science categories. The category "Energy Fuels" emerges as the most prolific, encompassing 4,019 publications, which accounts for approximately 29.435% of the total publications in the field. Notably, this category also exhibits a significant number of citations, with a total of 110,651 citations and a CPP value of 27.532. Furthermore, it boasts 198 Highly Cited Publications (HCP), highlighting its influential role in the field. Followed by

Table 3: Web of Science Categories on Cooling Technologies.

Web of Science Categories	TP	% TP	TC	CPP	HCP
Energy Fuels	4019	29.435	110651	27.532	198
Thermodynamics	2203	16.134	43207	19.613	47
Materials Science Multidisciplinary	1890	13.842	36372	19.244	66
Engineering Mechanical	1510	11.059	25048	16.588	27
Physics Applied	1264	9.257	20130	15.926	33
Mechanics	1238	9.067	24354	19.672	24
Engineering Chemical	1164	8.525	31107	26.724	55
Green Sustainable Science Technology	1029	7.536	33393	32.452	78
Nuclear Science Technology	1023	7.492	9942	9.718	8
Metallurgy Metallurgical Engineering	889	6.511	9452	10.632	8
Engineering Electrical Electronic	726	5.317	8848	12.187	7
Environmental Sciences	719	5.266	12702	17.666	16
Construction Building Technology	714	5.229	16702	23.392	26
Chemistry Physical	600	4.394	13222	22.037	25
Engineering Civil	582	4.262	15103	25.950	24

TP= Total Publications; TC= Total Citations; CPP= Citations per Paper; HCP= Highly Cited Papers.

the category "Thermodynamics" comprises 2,203 publications, representing around 16.134% of the total publications and has received 43,207 citations, resulting in a CPP of 19.613, and encompasses 47 HCP. The "Materials Science Multidisciplinary" ranks third in terms of publication count, with 1,890 publications constituting approximately 13.842% of the total. It has accumulated 36,372 citations, yielding a CPP of 19.244, and includes 66 HCPs.

Other notable categories include "Engineering Mechanical" with 1,510 (11.059%) publications, "Physics Applied" with 1,264 (9.257%) publications, and "Mechanics" with 1,238 (9.067%) publications. These categories have also garnered substantial citation counts, with CPP values of 16.588, 15.926, and 19.672, respectively. Additionally, categories such as "Engineering Chemical," "Green Sustainable Science Technology," and "Nuclear Science Technology" contribute moderately in terms of publication count and citations. These categories exhibit notable citation metrics, with CPP values of 26.724, 32.452, and 9.718, respectively.

Further, the categories such as "Metallurgy Metallurgical Engineering," "Engineering Electrical Electronic," and "Environmental Sciences" demonstrate relatively lower contributions in terms of publication count. However, they have received citations with varying CPP values. The distribution of research publications in cooling technologies across different Web of Science categories offers insights into the dominant categories in terms of publication count and citations, showcasing their significance and impact within the field.

Top countries research performance in Cooling Technology.

Table 4 and Figure 1 presents an analysis of research performance of cooling technologies across different countries. China emerges as the leading country in terms of research output, with 3,706 publications, constituting 27.144% of the total publications. However, the CPP is relatively low at 14.128 for China. Nevertheless, China has received a significant number of citations, totalling 52,360. Followed by the USA with 2,389 (17.498%) publications, and a higher CPP value of 17.796. The USA has also garnered a substantial number of citations, reaching 42,514. Germany ranks third with 1,050 (7.691%) publications, and a CPP value of 12.159. Germany has received 12,767 citations, highlighting its impact in the field. Italy and the UK are notable contributors as well, with 957 (7.009%) and 922 (6.753%) publications, respectively. Both countries exhibit higher CPP values, indicating a higher impact per publication, with values of 16.129 and 20.063, respectively.

Other countries, such as Spain, India, France, Japan, and South Korea, also demonstrate varying levels of contributions in terms of publications, citations, and CPP values. Additionally, Malaysia, Singapore, Denmark, and Belgium stand out for their relatively lower publication counts but higher CPP values, suggesting a focus on producing research with a higher impact within the field.

The research performance of the countries in the realm of cooling technologies. China, the USA, Germany, Italy, and the UK emerge as key contributors in terms of research output. The variations in CPP values across countries highlight differences in

Table 4: Countries Research Performance in Cooling Technologies.

Country	TP	%TP	TC	CPP
China	3706	27.144	52360	14.128
USA	2389	17.498	42514	17.796
Germany	1050	7.691	12767	12.159
Italy	957	7.009	15435	16.129
UK	922	6.753	18498	20.063
Spain	611	4.475	9470	15.499
India	570	4.175	9088	15.944
France	543	3.977	4581	8.436
Japan	541	3.962	5205	9.621
South Korea	483	3.538	5980	12.381
Australia	483	3.538	9009	18.652
Canada	428	3.135	5989	13.993
Russia	377	2.761	1304	3.459
Iran	353	2.586	5708	16.170
Poland	345	2.527	2624	7.606
Switzerland	304	2.227	3926	12.914
Brazil	229	1.677	1895	8.275
Saudi Arabia	225	1.648	1983	8.813
Netherlands	224	1.641	2620	11.696
Sweden	210	1.538	2561	12.195
Turkey	198	1.450	2339	11.813
Malaysia	176	1.289	4119	23.403
Singapore	175	1.282	3325	19.000
Denmark	174	1.274	4975	28.592
Belgium	153	1.121	1098	7.176

TP= Total Publications; TC= Total Citations; CPP= Citations per Paper.

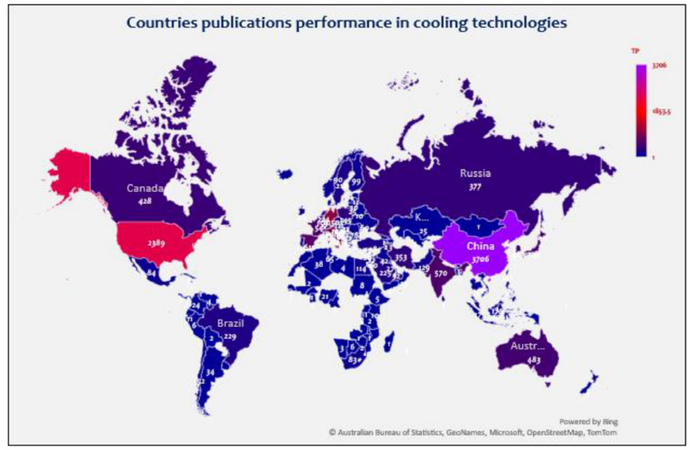

Figure 1: Countries Research Performance.

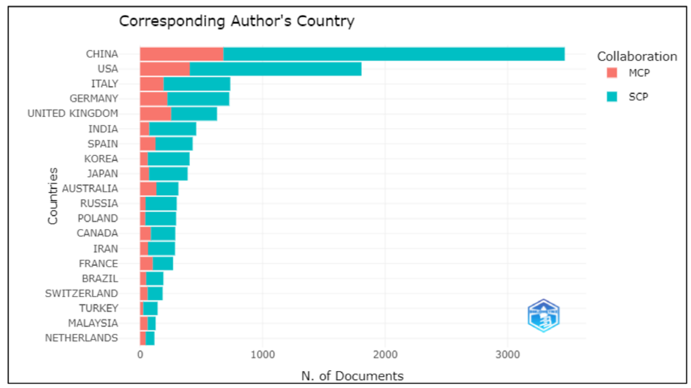

Figure 2: Corresponding Authors Country.

the average impact per publication. These findings can inform policymakers, researchers, and stakeholders in understanding the global research landscape in cooling technologies, identifying collaboration opportunities, and further enhancing research impact within their respective countries.

Corresponding Author's Countries

Figure 2 shows the distribution of countries with corresponding authors in cooling technologies publications. China is the leading country in terms of total articles and Single Country Publications (SCP) count. The United States ranks second in terms of total articles, but shows a higher proportion of Multi-Country Publications (MCP_Ratio), indicating a greater inclination towards international collaboration. Italy, Germany, and the United Kingdom also make significant contributions to cooling technology research. Germany and the UK show relatively higher proportions of multi-country publications, indicating their active engagement in international research collaborations within the field. Several other countries such as India, Spain, Korea, and Japan also demonstrate substantial involvement in cooling technology research. However, their MCP_Ratios are relatively lower, suggesting a prevalence of single-country publications. On the other hand, countries like Australia, Switzerland, and the Netherlands show higher MCP_Ratios, indicating a strong inclination towards international collaboration in their cooling technology research efforts. Malaysia stands out with a noteworthy MCP_Ratio, suggesting a higher tendency for multi-country collaborations.

Most Productive and Impactful Authors in Cooling Technologies

Table 5 presents the top 30 authors in cooling technologies research. Notably, Wang J from Hebei University of Technology, China, Zhang L from Southeast University, China, and Zhang Y from Georgia Institute of Technology, USA, are the most productive authors. They have collectively published 240 papers, received 3,407 citations, and possessed an average *h*-index of 17. Wang RZ from Kyushu University, Japan, and Li J from Nice America Research, USA, have the highest CPP with 36.073 and

Table 5: Most Productive Authors in Cooling Technologies.

Author	Affiliation	TP	TC	CPP	*h*-index	*g*-index
Wang J	Hebei University of Technology, China	72	1152	16.000	18	30
Zhang L	Southeast University, China	63	1230	19.524	21	32
Zhang Y	Georgia Inst Technology, USA	63	1055	16.746	19	29
Li Y	Shanghai Jiao Tong University, China	54	1146	21.222	20	32
Wang Y	Guangdong University Technology, China	52	1155	22.212	18	33
Zhang J	Mississippi State University, USA	47	687	14.617	15	24
Wang L	Southwest Jiao Tong University, China	45	577	12.822	15	22
Liu Y	Lanzhou University, China	44	700	15.909	16	24
Wang RZ	Kyushu University, Japan	41	1479	36.073	20	38
Li J	Nice America Research, USA	38	1327	34.921	13	36
Cabeza LF	University Lleida, Spain	37	2323	62.784	21	37
Wang X	University of Nottingham, UK	37	700	18.919	12	26
Zhang H	University of Kentucky, UK	36	602	16.722	12	24
Wang H	Tongji University, China	35	1201	34.314	13	34
Yang Y	Northeast Forestry University, China	35	555	15.857	15	22
Liu J	University of Leeds, UK	34	666	19.588	13	25
Li H	Hebei United University	33	711	21.545	12	26
Chen Y	University of Southern California, USA	32	507	15.844	12	21
Santamouris M	University of Georgia, USA	32	2884	90.125	19	32
Yang L	Chang'an University, China	31	1295	41.774	14	31
Zhao L	National University, Singapore	31	691	22.290	13	26
Li X	Beihang University, China	30	507	16.900	12	22
Calise F	University of Naples Federico II, Italy	29	901	31.069	17	29
Li Q	Institute of PLASMA Physics, Czech Republic	29	1854	63.931	12	29
Wang JJ	University of Chinese Academy of Sciences, China	29	690	23.793	13	26

34.921, respectively. These authors have made a significant impact on the field, as their papers have received high citations.

The top authors, such as Wang J and Zhang Y, have achieved impressive h-indices of 18 and 19, respectively. This indicates that they have published influential papers cited at least 18 times. The authors in Table 5 are primarily from China, the United States, and Japan, reflecting their substantial contributions to cooling technologies research.

The top 10 authors in the Table 5 are from Asia, with China and Japan being the most prominent countries. They have published over 50 papers, received more than 1,000 citations, and achieved h-indices of at least 15. These findings highlight the influential role of Asian researchers in the field of cooling technologies. Further, the most productive authors, with Wang J, Zhang L, and Zhang Y leading the field. These authors, along with others on the list, have significantly contributed to the field and citation counts also. Their work has influenced the advancement of cooling technologies.

Most Productive Institutions in Cooling Technologies

Table 6 provides a list of the most productive institutions in the field of cooling technologies. The Chinese Academy of Sciences emerges as the most productive institution in cooling technologies with 484 publications, accounting for approximately 3.545% of the total publications. It has received 9,319 citations, resulting in a Citations Per Publication (CPP) value of 19.254. The League of European Research Universities (LERU) follows closely with 469 publications, representing about 3.435% of the total publications. It received 13,418 citations, resulting in a relatively high CPP value of 28.61. The United States Department of Energy ranks third in productivity with 398 publications, comprising around 2.915% of the total publications. It received 13,775 citations, leading to a CPP of 34.611, which is one of the highest values in the Table 6.

Other notable institutions include the Helmholtz Association with 309 publications (2.263% of TP), Tsinghua University with 234 publications (1.714% of TP), and the Centre National De La

Table 6: Most Productive Institutions in Cooling Technologies.

Sl. No.	Affiliations	TP	% TP	TC	CPP
1	Chinese Academy of Sciences	484	3.545	9319	19.254
2	League of European Research Universities (LERU)	469	3.435	13418	28.61
3	United States Department of Energy	398	2.915	13775	34.611
4	Helmholtz Association	309	2.263	5749	18.605
5	Tsinghua University	234	1.714	4194	17.923
6	Centre National De La Recherche Scientifique	216	1.582	5408	25.037
7	Karlsruhe Institute of Technology	196	1.435	3064	15.633
8	UDICE French Research Universities	193	1.414	5034	26.083
9	University of California	193	1.414	6212	32.187
10	Xi AN Jiao tong University	185	1.355	2980	16.108
11	Shanghai Jiao Tong University	179	1.311	4267	23.838
12	Indian Institute of Technology	154	1.128	2532	16.442
13	French Alternative Energies and Atomic Energy Commission (CEA)	144	1.055	3166	21.986
14	University of Chinese Academy of Sciences	137	1.003	2933	21.409
15	Huazhong University of Science Technology	132	0.967	2873	21.765
16	Tianjin University	132	0.967	2802	21.227
17	University of Science Technology of China	131	0.959	1679	12.817
18	Massachusetts Institute of Technology	121	0.886	4053	33.496
19	Russian Academy of Sciences	116	0.85	911	7.853
20	Italian National Agency New Technical Energy Sustainable Economics Development	111	0.813	2555	23.018
21	Consiglio Nazionale Delle Ricerche	107	0.784	1924	17.981
22	Egyptian Knowledge Bank	107	0.784	1959	18.308
23	Harbin Institute of Technology	106	0.776	1837	17.33
24	Northeastern University China	105	0.769	1068	10.171
25	University System of Georgia	103	0.754	2303	22.359

Recherche Scientifique (CNRS) with 216 publications (1.582% of TP). These institutions have received varying numbers of citations and CPP values, reflecting their research impact in the field. The University of California and the Massachusetts Institute of Technology (MIT) also demonstrate significant productivity with 193 publications (1.414% of TP) and 121 publications (0.886% of TP), respectively. These institutions received substantial citations with relatively high CPP values of 32.187 and 33.496, indicating the impact of their research. Additionally, institutions such as the Indian Institute of Technology, French Alternative Energies and Atomic Energy Commission (CEA), and the Russian Academy of Sciences show notable contributions in terms of the number of publications and citations.

The most productive institutions in the field of cooling technologies highlights the global distribution of research output and the institutions driving advancements in the field. These findings can assist researchers, policymakers, and stakeholders in identifying key institutions for collaboration, knowledge exchange, and fostering further developments in cooling technologies.

Most Productive and Impactful Journals in Cooling Technologies

A total of 2056 journals were published these 13653 papers. Among, 1664 journals published 1 – 5 papers each, 174 journals published 6 – 10 papers each, 182 journals published 11 – 50 papers each, 19 journals published 51 – 100 papers each, 16 journals published 101 – 400 papers each and one journal published 461 papers. Table 7 presents the top 20 journals highly regarded publications in the field of cooling technologies. These 20 journals together published 4486 (32.86%) of the total publications and have a significantly higher citation impact than the rest of the journals. The average citation per paper for the top 20 journals is 29.702, while the average citation per paper for all journals is 10.228. This suggests that the research published in the top 20 journals is more likely to be cited by other researchers. The number of funded papers is also a good indicator of the

Table 7: **Most Productive Journals in Cooling Technologies.**

Journal	TP	TC	CPP	*h*-index	*g*-index	FU	HCP
Applied Thermal Engineering	461	9421	20.436	46	66	339	8
Applied Energy	399	17702	44.366	66	107	306	35
Energies	383	2924	7.634	24	34	278	1
Energy	382	11346	29.702	48	86	275	13
Energy Conversion and Management	354	9112	25.740	47	69	234	13
Energy and Buildings	352	11705	33.253	55	91	258	20
Renewable and Sustainable Energy Reviews	311	20854	67.055	83	128	187	63
Fusion Engineering and Design	298	3079	10.332	26	42	147	3
International Journal of Heat and Mass Transfer	191	3177	16.634	30	44	155	1
Journal of Cleaner Production	167	3504	20.982	33	49	115	3
IEEE Transactions on Applied Superconductivity	166	1385	8.343	20	29	108	0
Solar Energy	151	5623	37.238	41	69	97	10
Renewable Energy	148	3241	21.899	31	47	99	4
Nuclear Engineering and Design	122	981	8.041	16	25	68	0
International Journal of Advanced Manufacturing Technology	117	1458	12.462	19	30	94	0
Journal of Materials Science and Technology	114	2270	19.912	26	42	107	2
International Journal of Energy Research	106	1289	12.160	19	31	70	1
International Journal of Refrigeration	90	2521	28.011	28	46	64	3
Sustainability	89	886	9.955	13	27	58	1
Materials	85	434	5.106	10	17	72	0

TP= Total Publications; TC= Total Citations; CPP= Citations per Paper; FU= Funded Papers; HCP= Highly Cited Papers.

impact of a journal. The top 20 journals have a total of 633 funded papers, which is 46.4% of all funded papers in the field of cooling technologies.

These top 20 journals have a wide range of publication outputs, with Renewable and Sustainable Energy Reviews is the most productive journal, publishing 311 papers, while Materials has the fewest with 85 papers. In terms of total citations, Renewable and Sustainable Energy Reviews leads with 20,854 citations, while Materials has the lowest count at 434 citations. Renewable and Sustainable Energy Reviews also has the highest citations per paper (67.055), indicating a strong influence. The journal has 187 funded papers and 63 highly cited papers, distinguishing it as a prominent publication in the field.

Other influential journals include Applied Thermal Engineering, Applied Energy, and Energy, with substantial publication outputs ranging from 382 to 461 papers. These journals exhibit high citation rates, ranging from 20.436 to 29.702 citations per paper, and a notable number of funded papers ranging from 306 to 339.

Conversely, journals such as Materials, Nuclear Engineering and Design, and International Journal of Advanced Manufacturing Technology have lower publication outputs, citations per paper, and funded paper counts, indicating relatively lower prominence in the field.

Distribution of Citations and Highly Cited Papers

Table 8 presents a compilation of highly cited papers (TC ≥ 500) in the field of cooling technologies. A total of 13,653 papers published. Among these papers, 87.45% (11,939 papers) received at least one citation, indicating their recognition and engagement within the scholarly community. Conversely, 12.55% (1,714 papers) remained uncited throughout the study period, suggesting limited attention or impact. Among the cited papers, a subset of 404 (3.39%) emerged as highly influential, accumulating 100 or more citations during the study period. These highly cited papers signify a significant contribution to the advancement of knowledge in cooling technologies, underscoring their remarkable influence in the field. They have attracted substantial attention and recognition among researchers, playing a pivotal role in shaping the progress of cooling technologies.

Analysing highly cited papers is of great importance as they provide insights into seminal works and influential research that have significantly impacted the field of cooling technologies. These papers serve as primary sources for researchers and practitioners, offering fundamental concepts, methodologies, and findings that form a solid foundation for further exploration and advancements in the field Grover *et al.*, 2022; Gupta *et al.*, 2023.

Table 8: High Cited Papers (TC≥500).

Paper Details	DOI	TC	TCpY
LIU HL, 2012, NAT MATER	10.1038/NMAT3273	1276	106.33
KIM SI, 2015, SCIENCE	10.1126/science.aaa4166	1111	123.44
LUND H, 2014, ENERGY	10.1016/j.energy.2014.02.089	1086	108.60
MOORE AL, 2014, MATER TODAY	10.1016/j.mattod.2014.04.003	844	84.40
SANTAMOURIS M, 2014, SOL ENERGY	10.1016/j.solener.2012.07.003	831	83.10
HOLMBERG K, 2012, TRIBOL INT	10.1016/j.triboint.2011.11.022	788	65.67
ZHAI Y, 2017, SCIENCE	10.1126/science.aai7899	752	107.43
THOMPSON MK, 2016, CIRP ANN-MANUF TECHN	10.1016/j.cirp.2016.05.004	732	91.50
MANCARELLA P, 2014, ENERGY	10.1016/j.energy.2013.10.041	691	69.10
AHMED M, 2014, RADIOLOGY	10.1148/radiol.14132958	657	65.70
SOMIYA K, 2012, CLASSICAL QUANT GRAV	10.1088/0264-9381/29/12/124007	622	51.83
FRANCO V, 2018, PROG MATER SCI	10.1016/j.pmatsci.2017.10.005	567	94.50
MATHIESEN BV, 2015, APPL ENERG	10.1016/j.apenergy.2015.01.075	559	62.11
AHN Y, 2015, NUCL ENG TECHNOL	10.1016/j.net.2015.06.009	536	59.56
CHUA KJ, 2013, APPL ENERG	10.1016/j.apenergy.2012.10.037	507	46.09
JU YG, 2015, PROG ENERG COMBUST	10.1016/j.pecs.2014.12.002	501	55.67

DOI= Digital Object Identifier; TC= Total Citations; ACpY= Average Citations per Year.

Among the 404 HCPs in the compilation, one is "LIU HL, 2012, NAT MATER", which has accumulated 1,276 citations at an ACpY of 106.33. Another influential paper is "KIM SI, 2015, SCIENCE" garnering 1,111 citations at a ACpY of 123.44. These papers have received significant attention within the scientific community, highlighting their impact and influence on the development of cooling technologies.

Additionally, noteworthy contributions include papers such as "LUND H, 2014, ENERGY" with 1,086 total citations and an ACpY of 108.60, and "MOORE AL, 2014, MATER TODAY" with 844 total citations and an ACpY of 84.40. These papers have made substantial contributions to the advancement of cooling technologies and have garnered recognition within the scientific community. The high citation counts and citation rates of these papers indicate their significance and impact in the field of cooling technologies. Researchers and practitioners can rely on these papers as valuable resources, offering insights, and serving as a guide for further research endeavours, building upon existing knowledge.

Author Keywords

The 50 most significant author keywords in the field of cooling technologies provide valuable insights into the prominent research areas. A total of 32,199 author keywords were identified across the 13,653 publications analysed. Among these keywords, 30,553 keywords appeared 1 to 4 times, while 1,646 (5.2%) appeared 5 or more times, suggesting a relatively higher level of importance within the analysed publications. Notably, the word 'Energy Efficiency' appeared 274 times. VOSviewer was used to analyse the co-occurrence of the top 50 keywords with a frequency of 50 or more times. The network comprised 5 distinct clusters, each representing a group of closely related keywords. The network included 557 links between the keywords and a cumulative total link strength of 1611 (Table 9 and Figure 3) and the cloud map of these keywords is displayed in Figure 4.

Cluster 1 encompasses keywords related to sustainable and alternative energy sources. Keywords such as "solar energy", "renewable energy", "waste heat recovery", and "geothermal energy" are included in this cluster. This cluster demonstrates a strong focus on exploring renewable energy options and optimizing energy systems in cooling technologies. Researchers are likely investigating the use of solar power, waste heat utilization, and geothermal energy for efficient and sustainable cooling solutions.

Cluster 2 revolves around heat transfer and thermal management. Keywords such as "heat transfer", "thermal management", and "thermal energy storage" indicate a significant emphasis on understanding and optimizing heat transfer mechanisms in cooling systems. Researchers in this cluster are likely exploring techniques such as phase change materials, thermal conductivity enhancement, and heat exchangers to improve heat dissipation and overall thermal performance.

Cluster 3 highlights keywords related to energy efficiency and environmental impact. Terms such as "energy efficiency", "energy saving", "thermal comfort", and "sustainability" are included in

Table 9: 50 Most Significant Author Keywords.

Cluster	Keyword	Occ.	TLS	Cluster	Keyword	Occ.	TLS
1	Solar Energy	210	176	2	Heat Transfer	239	118
1	Renewable Energy	155	120	2	Thermal Management	154	96
1	Optimization	154	93	2	Thermal Energy Storage	112	102
1	Simulation	101	62	2	Phase Change Material	93	80
1	Energy	100	66	2	Temperature	70	33
1	Energy Storage	100	88	2	Photovoltaic	67	58
1	Heat Pump	100	79	2	Phase Change Materials	64	44
1	Waste Heat Recovery	96	51	2	Heat Pipe	63	39
1	Solar Cooling	89	74	2	Thermal Conductivity	62	24
1	Refrigeration	78	51	2	Nanofluid	60	35
1	Organic Rankine Cycle	72	55	2	Thermal Performance	57	31
1	Absorption Chiller	68	62	2	Heat Exchanger	54	45
1	Cogeneration	66	59	2	Heat Transfer Enhancement	51	24
1	Geothermal Energy	65	42	3	Energy Efficiency	274	147
1	Exergy	63	55	3	Energy Saving	128	85
1	District Heating	62	41	3	Thermal Comfort	110	75
1	Trigeneration	57	59	3	Passive Cooling	96	73
1	Biomass	52	31	3	Evaporative Cooling	94	58
1	Hydrogen	50	23	3	Air Conditioning	88	90
4	Microstructure	217	84	3	Energy Consumption	84	36
4	Additive Manufacturing	167	48	3	Climate Change	80	33
4	Mechanical Properties	135	71	3	Sustainability	78	51
4	Cooling Rate	67	33	3	Radiative Cooling	72	36
5	Cooling	251	184	3	Urban Heat Island	66	22
5	Heating	51	55	3	Heat Recovery	53	25

this cluster. This cluster signifies a focus on developing cooling technologies that are energy-efficient, environmentally friendly, and provide enhanced thermal comfort. Researchers may be investigating passive cooling techniques, energy-efficient air conditioning systems, and sustainable cooling practices to minimize energy consumption and address climate change concerns.

Cluster 4 centers around material properties and manufacturing processes. Keywords such as "microstructure", "additive manufacturing", and "mechanical properties" suggest a focus on characterizing cooling materials and exploring advanced manufacturing techniques. Researchers in this cluster may be studying the microstructural behavior of materials, such as nanofluids and phase change materials, and investigating the impact of additive manufacturing on cooling system components.

Cluster 5 represents the broad category of cooling itself, including keywords like "cooling", "heating", and "cooling rate". This cluster indicates a general focus on understanding and improving cooling processes across various applications and industries. Researchers in this cluster may be exploring cooling technologies, refrigeration systems, and thermal control strategies.

Overall, the clustering analysis of the keywords reveals the multidisciplinary nature of cooling technologies research, covering areas such as sustainable energy, heat transfer, energy efficiency, material science, and system optimization. These clusters provide a comprehensive framework for understanding the different research directions and themes within the field, enabling researchers to identify common areas of interest and potential collaboration opportunities.

KEY FINDINGS AND CONCLUSION

The analysis of the research landscape in cooling technologies from 2012 to 2021 provides a comprehensive overview of publication output, citation impact, and collaborative patterns within the field. The findings lay the groundwork for further exploration of key research areas, influential authors, and

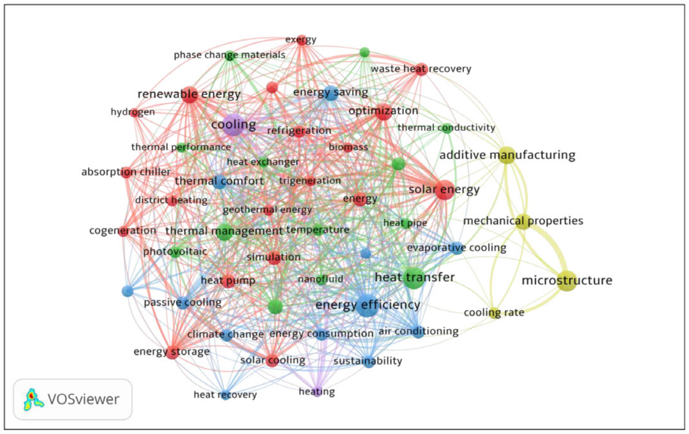

Figure 3: 50 Most Occurred Author Keywords Co-occurrence Network.

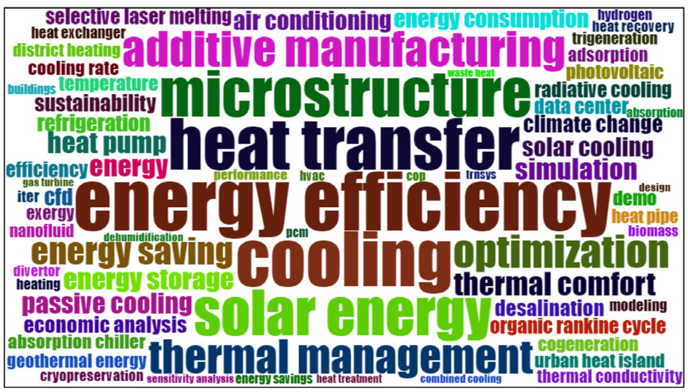

Figure 4: Cloud map of top-100 author keywords.

collaborative networks. Globally, there has been a consistent increase in research output and citations, indicating a growing interest and impact. However, the decline in citations in 2021 suggests a need for further investigation into factors influencing research visibility and impact. India's research contribution to cooling technologies has shown positive growth, although at a relatively lower scale compared to the global output. The decline in citations received by Indian research, along with the decrease in cumulative publications per year, indicates a potential area for improvement and increased visibility.

The distribution of research publications across various categories reveals insights into the most prolific areas. The "Energy Fuels" category emerges as highly productive, with significant citation impact and a substantial number of highly cited publications. The "Thermodynamics" and "Materials Science Multidisciplinary" categories also demonstrate notable publication output and citation impact. China, the USA, Germany, Italy, and the UK emerge as key contributors in terms of research output. Variations in citation impact per publication across countries highlight differences in research quality. These findings inform policymakers, researchers, and stakeholders about the global research landscape, identifying collaboration opportunities and enhancing research impact within their respective countries. The distribution of countries with corresponding authors in cooling technologies publications highlights the leading countries and their engagement in international collaborations. China leads in total articles, while the USA shows a higher proportion of multi-country publications, indicating a greater inclination towards international collaboration. Italy, Germany, and the UK also make significant contributions, with active engagement in international research collaborations. Other countries demonstrate substantial involvement in cooling technology research, albeit with varying levels of international collaboration.

The analysis of highly cited papers underscores their significant influence on the field. These papers have attracted substantial attention, recognition, and citations, playing a pivotal role in shaping the progress of cooling technologies. They serve as primary sources for researchers and practitioners, providing fundamental concepts, methodologies, and findings for further exploration. Noteworthy contributions include papers by influential authors that have garnered high citation counts and rates, indicating their impact and significance. These papers offer valuable insights and serve as a guide for further research endeavors. The clustering analysis of keywords reveals the multidisciplinary nature of cooling technologies research, encompassing sustainable energy, heat transfer, energy efficiency, material science, and system optimization. These clusters provide a comprehensive framework for understanding different research directions and themes within the field, facilitating the identification of common areas of interest and potential collaboration opportunities.

The research output demonstrates a global increase in publication output and citations. While India's research contribution shows positive growth, efforts are needed to enhance its visibility and impact. The most prolific categories and key countries contributing to cooling technology research have been identified. International collaboration plays a crucial role, with varying levels of engagement observed among different countries. Highly cited papers and influential authors shape the advancement of cooling technologies. The multidisciplinary nature of research within the field presents opportunities for collaboration and further advancements.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Cite this article: Mallikarjuna B, Kappi M. Quantifying the Evolution of Cooling Technologies Research: A Bibliometric Journey from 2012 to 2021. Journal of Data Science, Informetrics, and Citation Studies. 2023;2(2):110-22.