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SCIENTIFIC TRENDS IN SOLAR-POWERED THERMOELECTRIC AIR CONDITIONING SYSTEMS

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Abstract. *With global warming, days are becoming increasingly hotter, making the development of efficient and non-polluting refrigeration systems essential. In this context, thermoelectric refrigeration emerges as a sustainable alternative, utilizing Peltier modules to transfer heat between two surfaces through the thermoelectric effect. This study aimed to analyze and map scientific production on thermoelectric devices applied to solar-powered air conditioning systems by conducting a bibliometric analysis of research published in the Scopus database, using Bibliometrix and VOSviewer for the analyses. The study evaluated 46 publications and provided an overview of the topic based on the following bibliometric indicators: most productive authors and institutions, publications by country, most relevant journals in the field, most cited articles, and recurring keywords. These findings are reflected in the research trends identified in this paper's bibliometric study, which analyzed 33 years of scientific production (1991-2024), showing a significant increase in publications since 2015. China stood out as the country with the largest scientific contribution, while the journals Energy and Renewable Energy established themselves as the most relevant in the field. The findings highlight the potential of Peltier devices in developing sustainable air conditioning prototypes, providing cooling without emitting harmful gases and contributing to sustainability. Additionally, the integration of solar energy enhances the system's energy efficiency, helping to overcome the lower efficiency of sustainable cooling systems compared to conventional technologies. This perspective will assist researchers in identifying promising areas for investigation and guide investments in research and development (R&D) based on scientific trends. Thus, this work aims to foster scientific progress in sustainable cooling technologies that reduce pollutant emissions, promote a cleaner environment, and help mitigate the worsening effects of global warming.*

Keywords: *Peltier, thermoelectricity, solar energy, cooling, technology prospecting*

1 INTRODUCTION

The growing climate crisis, intensified by the burning of fossil fuels and the emission of greenhouse gases, has raised the planet's average temperatures to alarming levels. Given this scenario, the search for sustainable refrigeration solutions becomes important, since traditional systems consume large amounts of energy and use refrigerants that are harmful to the environment. In this context, alternative and renewable cooling systems, such as the integration of photovoltaic panels with thermoelectric modules (Irshad *et al.*, 2019), stand out as viable solutions to reduce CO₂ emissions and provide thermal comfort, especially in tropical regions with high temperatures and humidity.

An efficient solution to provide thermal comfort are thermoelectric generators based on the Peltier effect, better known as thermoelectric coolers (TECs), which enable sustainable refrigeration by operating with direct current (DC) sources (Sarbu & Dorca, 2018). This thermoelectric phenomenon occurs when an electric current passes through the junction of two semiconductor materials (n-type and p-type), simultaneously generating heating on one side of the thermoelectric module and cooling on the opposite side (Uchida *et al.*, 2018). This physical principle allows for

compact and environmentally friendly refrigeration systems, operating with electrical energy, preferably generated by renewable sources, such as photovoltaic panels. The main applications of Peltier technology are in sustainable air conditioning systems coupled with solar energy (Irshad *et al.*, 2019, Sarbu & Dorca, 2018, Abbas *et al.*, 2020) and portable medical devices for vaccine conservation (Khan *et al.*, 2023).

The integration of TECs and solar photovoltaic energy represents a strategic solution for applications that require clean and self-sustainable refrigeration, demonstrating significant economic and environmental advantages. Studies show that hybrid systems can reduce CO₂ emissions by up to 60.24 tons and reduce ambient temperatures by up to 23% in tropical conditions (Irshad *et al.*, 2019; Abbas *et al.*, 2020). Although initial costs and thermoelectric efficiency still represent challenges, advances in materials and energy storage systems point to a promising future for this sustainable technology (Sarbu & Dorca, 2018; Uchida *et al.*, 2018).

Bibliometric analysis focuses on the systematic evaluation of quantitative indicators, including: (i) volume and temporal growth of publications; (ii) collaboration networks between authors and institutions; (iii) frequency and co-occurrence of keywords; and (iv) citation patterns. This methodological approach allows mapping the evolution of fields of knowledge and assessing the scientific impact of research in a given domain. As an example, the bibliometric study by Obileke *et al.* (2022) allowed a more precise and broad analysis of the trends and evolution of scientific research in the area of bioenergy and biological waste, providing information for the development of future research. In a complementary way, Ampese *et al.* (2022) carried out a bibliometric study to analyze the trends and gaps in research on anaerobic digestion. Revealing that, in the last five years, the main themes in the area are related to the production of biogas to reduce greenhouse gas emissions, with emphasis on microbiological and engineering parameters.

The objective of this work was to analyze and map the scientific production on thermoelectric devices applied to solar-powered air conditioning systems using a bibliometric approach. The study encompassed the entire temporal spectrum available in the Scopus database, covering research up to the most recent developments in 2024. The research aimed to identify key authors and scientific journals, as well as to map trends, gaps, and opportunities for future studies.

2 METHODOLOGY

This bibliometric study was carried out in the Scopus database, covering the period of time of available scientific productions. Figure 1 details the methodological flow adopted, from obtaining the data in Scopus to the final processing of the articles included in the bibliometric analysis. In the initial stage (Identification), the data were extracted in Comma Separated Values (CSV) format on January 19, 2025, using the Scopus 'Advanced Search' tool with the following Boolean operators: TITLE-ABS-KEY(("peltier" OR "thermoelectric" OR "thermo electric") AND "air condition" AND ("solar" OR "photovoltaic*")) AND (LIMIT-TO(DOCTYPE,"ar") OR LIMIT-TO(DOCTYPE,"re")). The search strategy combined terms related to thermoelectric technology ("peltier", "thermoelectric", "thermo electric"), as well as air conditioning systems ("air condition"), solar-powered sources ("solar" OR "photovoltaic*") and was filtered to include only original articles (ar) and reviews (re), as summarized in Table 1.

Table 1. Summary of search

Item	Value
Query string	("peltier" OR "thermoelectric" OR "thermo electric") AND "air condition" AND ("solar" OR "photovoltaic*")
Database	Scopus
Search within	Title, abstract and keywords
Limitation	Document type: Article; Review
Date of search	19/01/2025
Advanced search query string	TITLE-ABS-KEY(("peltier" OR "thermoelectric" OR "thermo electric") AND "air condition" AND ("solar" OR "photovoltaic*")) AND (LIMIT-TO(DOCTYPE,"ar") OR LIMIT-TO(DOCTYPE,"re"))

In the Screening stage, the papers that was included in the bibliometric analysis of this study are selected, as illustrated in Figure 1. This process involves two levels of evaluation: initially, a critical reading of titles and abstracts is carried out to verify whether the content is relevant and promising to advance to the second phase, which involves the complete reading of the papers, ensuring that only the papers aligned with the objectives of this bibliometric study are included. Thus, articles that did not allow for the complete reading of the text were excluded from the analysis, either because it was not possible to find the documents online, or because the text was in another language that the authors of this paper were not proficient in (Portuguese, Spanish or English).

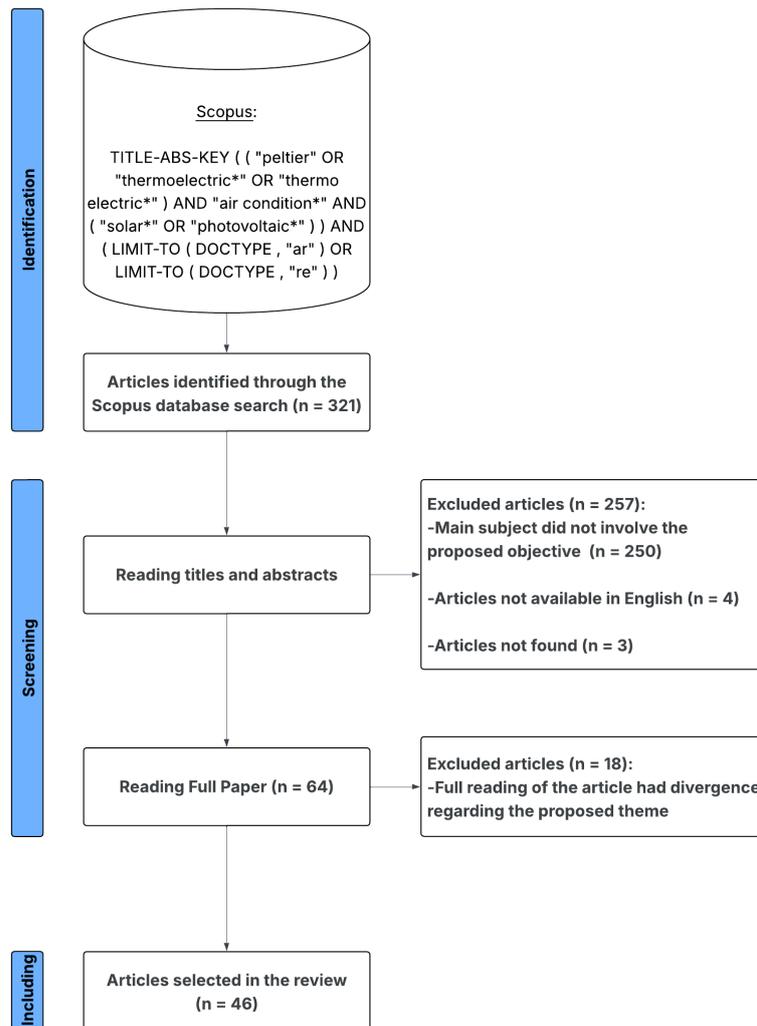


Figure 1. PRISMA-based flowchart of the article selection process in the bibliometric review

After selecting the articles, the following were analyzed: the temporal evolution of publications, identifying growth patterns and relevant milestones; the geographic distribution of scientific production, highlighting the most active countries and regions; the most productive authors and institutions, recognizing the main contributors to the field; and the most relevant journals, analyzing the sources that published the most research on the topic. This entire stage of data analysis was supported by specific bibliometric software. The Bibliometrix program was used for analyses related to the quantity of scientific productions, including: the temporal evolution of publications, the distribution by country and the identification of the most productive authors in the area. While the VOSviewer program was used to visually analyze the relationships between co-occurring keywords.

3 RESULTS AND DISCUSSION

Based on the search strategy defined in Section 2, Scopus identified 321 documents published in the time range from 1974 to 2025 (chronological range automatically established by the platform). After processing in the Screening stage (Figure 1), 46 articles were selected for bibliometric analysis. The exclusion of the remaining 250 papers (Figure 1) occurred due to the use of conventional thermal technologies (such as desiccant, evaporative or vapor compression systems) that did not incorporate the Peltier effect. Additionally, among the 64 papers read in full, 18 were discarded because they used Seebeck effect tablets for clean energy generation (unrelated to Peltier cooling) or because they presented cooling systems not integrated with renewable sources, particularly photovoltaic panels. Therefore, the main results of this study focus on the 46 selected papers, which deal with the application of thermoelectric devices (Peltier) in air conditioning systems powered by solar energy. Table 2 presents a summary of bibliometric indicators of the final selected articles.

Table 2 – Bibliometric indicators of the final selected articles

Description	Results
Timespan	1991:2024
Total number of documents	46
Types	ARTICLE 41 REVIEW 5
Sources (journals)	33
Contributing authors	153
Contributing countries	25
Contributing institutions	73
Cited references	1916
Frequently used words	145
Local citation score	7
Global citation score	29.98

3.1 PROFILE OF SCIENTIFIC PRODUCTION IN THE AREA

3.1.1 TEMPORAL EVOLUTION

Figure 2 illustrates the annual growth of publications up to the current year (2025), with 1991 marking the first scientific production on thermoelectric systems (Peltier) applied to solar-powered air conditioning. The study by Ikeda *et al.* (1991) constitutes a pioneering milestone in the area, published when research on the Peltier effect was focused on high-power industrial applications. This work broke new ground by demonstrating the technical and economic feasibility of thermoelectric modules operating at low temperature differences (~10 K), characteristics of air-conditioning systems. In addition, the article introduced the first practical integration between solar cells and Peltier modules, proving that low photovoltaic efficiency could be compensated by high thermoelectric performance under conditions of reduced temperature difference between the hot and cold faces of the Peltier module.

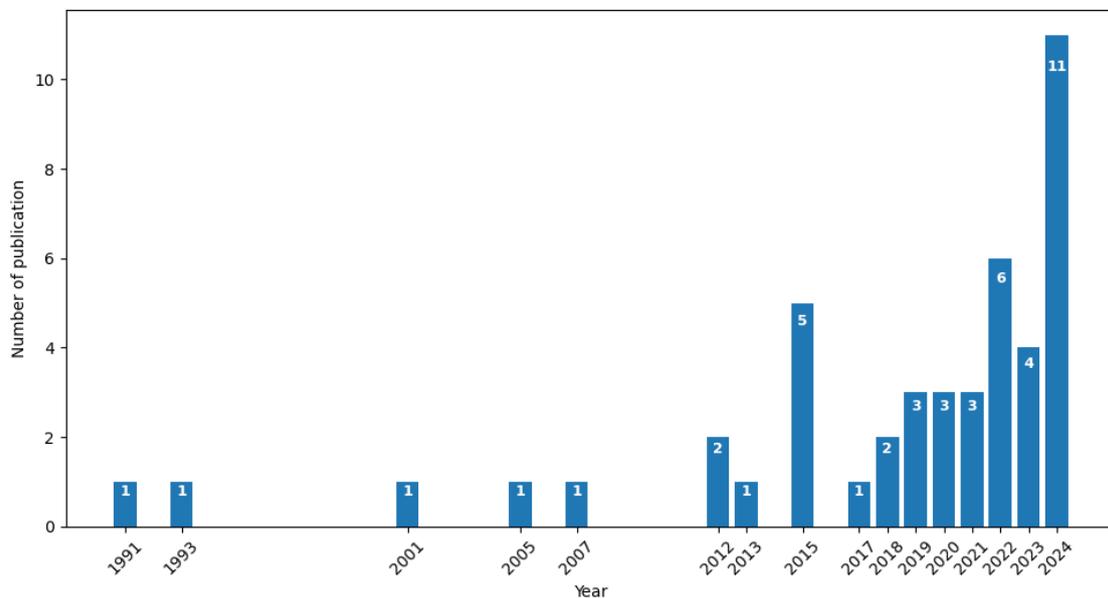


Figure 2 – Annual scientific production

Figure 2 also shows a period of more intense growth in publications on the subject, between 2015 and 2024 (there are no records for the year 2025, as the data were collected on January 19, at the beginning of the year). Analyses of the works from this period reveal that the main concern is the reduction of greenhouse gases, aiming to minimize the contribution to global warming. Examples of these studies include Irshad *et al.* (2019), Sarbu & Dorca, (2018) and Abbas *et al.* (2020), whose motivation is to reduce greenhouse gas emissions.

3.1.2 GEOGRAPHICAL DISTRIBUTION

Figure 3 presents a comparative analysis of academic production among the top ten countries investing in research in the area of thermoelectric systems (Peltier) applied to air conditioning with solar energy: China, India, Japan, Egypt, Malaysia, Saudi Arabia, United States, Canada, United Kingdom and Australia. The countries are organized in decreasing order of volume of publications, with the vertical axis representing the nations and the horizontal axis indicating the number of articles published.

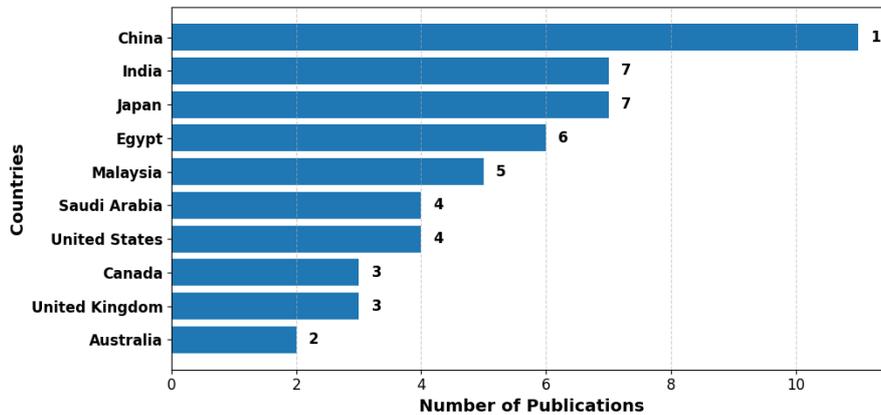


Figure 3 – Publications by country

China leads as the most prominent country (with 11 published papers), reflecting its strong investment in research in this area. The graph also highlights the growing contribution of emerging economies, such as India and Egypt, demonstrating the global expansion of interest in this technology. This geographic distribution of scientific production not only highlights traditional leaders in research, but also reveals the engagement of developing countries in this promising field of study.

3.1.3 MOST PRODUCTIVE AUTHORS AND INSTITUTIONS

Table 3 presents the most productive authors in the area of thermoelectric systems (Peltier) applied to air conditioning with solar energy, revealing important patterns of productivity and scientific impact. The authors Saha, B.B. (Japan) and Habib, K. (Malaysia) stand out for having the highest number of publications (5 and 4 respectively). In addition, Itsabad, K. (Saudi Arabia) has the highest average number of citations per document (56.3), reflecting the high relevance of their work in the area. The strong representation of authors linked to institutions in Saudi Arabia, particularly King Fahd University of Petroleum and Minerals, is also noteworthy, suggesting the growing role of this country in research in this area. The data also show temporal diversity, with Mahmud, S. (Canada) working since 2015, while researchers such as Aboelmaaref, M.M. (Egypt) and Zayed, M.E (Saudi Arabia) began their contributions more recently, in 2021.

Table 3 – Most productive authors

#	Author	Docu-ments	Total citation	Mean citation per docu-ment	Time span	Organization	Country	H-index
1	Habib, K.	5	206	41.2	2019-2022	Universiti Teknologi PETRONAS	Malaysia	31
2	Saha, B.B.	4	207	51.7	2019-2024	Kyushu University	Japan	72
3	Irshad, K.	3	169	56.3	2019-2024	King Fahd University of Petroleum and Minerals	Saudi Arabia	33
4	Zayed, M.E	3	136	45.3	2021-2023	King Fahd University of Petroleum and Minerals	Saudi Arabia	38
5	Aboelmaaref, M.M.	3	136	45.3	2021-2023	Sohag University	Egypt	8
6	Mahmud, S.	3	36	12	2015-2024	University of Guelph	Canada	42

The H-index analysis provides deeper insight into research influence, balancing productivity (publication count) and impact (citation performance). Saha, B.B. (H-index = 72) consolidates his position as the researcher with the highest impact in the table, with 72 articles that individually received at least 72 citations indicative of a long-lasting and influential career. Mahmud, S. (H-index = 42) and Zayed, M.E. (H-index = 38) present equally consistent contributions, albeit on a smaller scale. Irshad, K. (H-index = 33) and Habib, K. (H-index = 31), while relevant, demonstrate a more segmented impact. In contrast, Abdelmasref, M.M. (H-index = 8) suggests that he is an early-stage researcher or one whose work has not yet been widely cited. It is important to note that institutions such as Kyushu University and King Fahd University appear associated with the highest rates, demonstrating how links with centers of excellence amplify the visibility and impact of research.

3.1.4 MOST RELEVANT JOURNALS

Figure 4 illustrates the most relevant journals in the field of thermoelectric (Peltier) systems applied to solar-powered air conditioning. Quantitatively, the journals Energy and Renewable Energy stand out for the largest number of published documents (3 articles each). Among the other journals analyzed, such as Applied Energy, Applied Thermal Engineering, and Energy and Building, a slightly lower production (2 documents) is observed, although still significant for this research area.

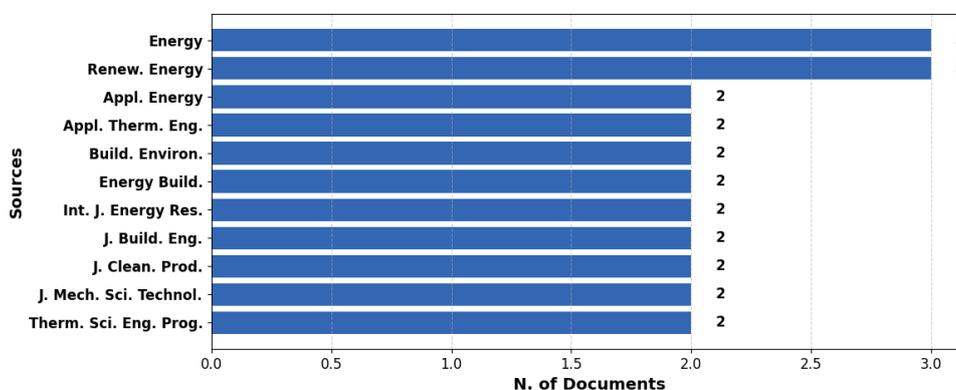


Figure 4 – Most relevant sources

3.2 RESEARCH TRENDS

Figure 5 illustrates a connected network of concepts that demonstrates the integration between solar energy and thermoelectric technologies for sustainable air conditioning applications. The bibliometric study, containing 33 years of research, highlights the 31 most frequent keywords in this area. Three terms stand out as the most visually relevant: air conditioning, solar energy and cooling. In addition, grouping the keywords into clusters allows us to understand the organization of the recurring subthemes. According to Table 4, the keywords used in the analyzed articles are divided into 4 clusters: sustainable buildings; photovoltaics; energy efficiency; thermoelectricity.

The sustainable buildings cluster highlights the concern with architectural and technological solutions that reduce the environmental impact of buildings, as in the study by Irshad *et al.* (2019), which integrates thermoelectric and photovoltaic systems in walls to improve energy efficiency. The photovoltaics cluster focuses on the application of solar panels, as in the work of Khan *et al.* (2023), which uses photovoltaic panels to power a portable medical device for vaccine preservation.

In the energy efficiency cluster, research seeks to optimize energy consumption with thermoelectric refrigeration (Sarbu & Dorca, 2018), or through hybrid solutions that combine renewable sources and low-consumption systems (Abbas *et al.*, 2020). Finally, the thermoelectricity cluster explores the potential of thermoelectric materials for applications in cooling and power generation, with studies such as that of Abbas *et al.* (2020) designing and evaluating a solar-powered domestic air cooler with Peltier plates to meet comfort criteria.

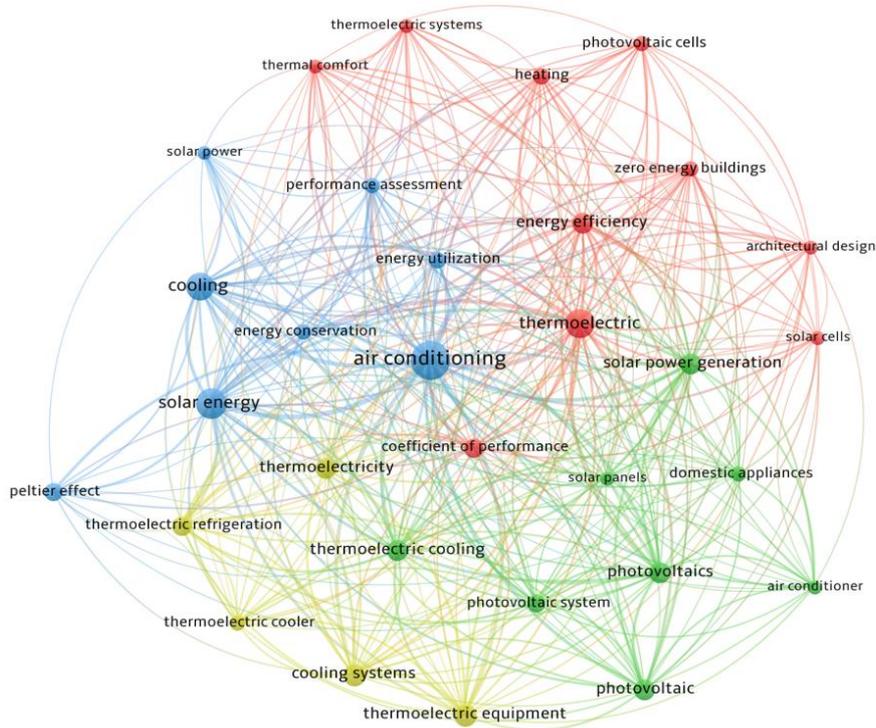


Figure 5 – Co-occurrence all keywords map

Table 4 – Cluster analysis of co-occurrence author keywords map

Cluster color	Main research topic	Keywords	Amount
Red	sustainable buildings	architectural design, coefficient of performance, energy efficiency, heating, photovoltaic cells, solar cells, thermal comfort, thermoelectric, thermoelectric systems, zero energy buildings	10
Green	photovoltaics	air conditioner, domestic appliances, photovoltaic, photovoltaic system, photovoltaics, solar panels, solar power generation, thermoelectric cooling	8
Blue	energy efficiency	air conditioning, cooling, energy conservation, energy utilization, peltier effect, performance assessment, solar energy, solar power	8
Yellow	thermoelectricity	cooling systems, thermoelectric cooler, thermoelectric equipment, thermoelectric refrigeration, thermoelectricity	5

4 CONCLUSION

This bibliometric study analyzed the scientific production on thermoelectric (Peltier) systems applied to solar-powered air conditioning, covering 33 years of research (1991-2024). The results indicate a significant growth in publications since 2015, driven by the need for sustainable solutions to reduce greenhouse gas emissions and improve energy efficiency. China emerged as the leading contributor, followed by India and Egypt. Analysis of the most productive authors highlighted notable contributions: Habib, K. (Malaysia) and Saha, B.B. (Japan) stood out for their volume of publications, while Irshad, K. (Saudi Arabia) achieved the highest scientific impact, averaging 56.3 citations per paper. The journals “Energy” and “Renewable Energy” were the most relevant, reinforcing the alignment of the research with sustainability themes. Overall, these findings map the evolution of the field and provide a foundation for guiding future investments and research, highlighting the potential of solar thermoelectric technology as a viable alternative for sustainable climate control systems.

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6 REFERENCES

- Abbas, Z., Shah, A.N., Hassan, M.T., Ali, M.S., Ud Din, Q., Naseem, B., Asghar, A. and Haider, A., 2020. "Performance evaluation of novel solar-powered domestic air cooler with Peltier modules". *Journal of Mechanical Science and Technology*, Vol. 34, No. 11, pp. 4797-4807.
- Ampese, L.C., Sganzerla, W.G., Ziero, H.D.D., Mudhoo, A., Martins, G. and Forster-Carneiro, T., 2022. "Research progress, trends, and updates on anaerobic digestion technology: A bibliometric analysis". *Journal of Cleaner Production*, Vol. 331, e130004.
- Ikeda, Y., Itsumi, J. and Haneji, N., 1991. "Semiconductor thermoelectric-energy conversion systems working at low temperature differences". *Electrical Engineering in Japan*, Vol. 111, No. 4, pp. 99-107.
- Irshad, K., Habib, K., Algarni, S., Saha, B.B. and Jamil, B., 2019. "Sizing and life-cycle assessment of building integrated thermoelectric air cooling and photovoltaic wall system". *Applied Thermal Engineering*, Vol. 154, pp. 302-314.
- Khan, N.R., Sharmin, T., Haque, M.A. and Rahman, M.H., 2023. "Photovoltaic thermoelectric cooling system for off-grid vaccine refrigerator: an experimental study". *Transactions of the Canadian Society for Mechanical Engineering*, Vol. 47, No. 4, pp. 596-617.
- Obitelke, K., Onyeaka, H., Omoregbe, O., Makaka, G., Nwokolo, N. and Mukumba, P., 2022. "Bioenergy from bio-waste: a bibliometric analysis of the trend in scientific research from 1998–2018". *Biomass Conversion and Biorefinery*, Vol. 12, No. 4, pp. 1077–1092.
- Sarbu, I. and Dorca, A., 2018. "A comprehensive review of solar thermoelectric cooling systems". *International Journal of Energy Research*, Vol. 42, No. 2, pp. 395-415.
- Uchida, K.-I., Daimon, S., Iguchi, R. and Saitoh, E., 2018. "Observation of anisotropic magneto-Peltier effect in nickel". *Nature*, Vol. 558, No. 7708, pp. 95-99.

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