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# Solar Drying Technology: Current Research Trends and Future Perspectives

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**Abstract**— Solar drying technology has become a vital innovation for sustainable food preservation and renewable energy utilization, offering an energy-efficient alternative to conventional drying methods. This study provides a comprehensive bibliometric analysis of research trends, influential authors, key institutions, and geographical contributions in the field of solar drying technology from 2004 to 2024. We analyzed 108 relevant publications using the Scopus database and VOSviewer software, revealing a significant increase in research output since 2010, with a marked surge after 2016. India and China emerge as leading contributors, driven by their large agricultural sectors and favorable solar conditions. Key research efforts have focused on improving energy efficiency, optimizing drying processes, and preserving product quality. Despite these advancements, critical gaps remain, particularly in scaling solar drying systems and integrating hybrid technologies that combine solar energy with other renewable sources. This study highlights the importance of interdisciplinary collaboration to advance technological innovation and address challenges in food security and energy sustainability. Future research should focus on developing hybrid systems, finding better ways to store energy, and studying how solar drying affects the taste and nutritional value of food in order to make it more useful in a wider range of climates and farming situations.

*Keywords: Bibliometric Analysis, Food Preservation, Hybrid Systems, Renewable Energy, and Solar Drying.*



## 1. Introduction

Solar drying technology has gained significant attention in recent years due to its potential for sustainable food preservation and renewable energy utilization [1]. Alternative drying methods have been created in response to the growing need for technologies that use less energy and are better for the environment. These include biomass [2], coal briquettes [3], solar energy [4], [5], [6], [7], [8], [9], hybrid solar-electric-biogas systems [10], and other energy sources [11], [12]. All of these lessen reliance on traditional energy sources like fossil fuels. Solar drying, which harnesses solar energy, offers a promising solution for enhancing food storage, particularly in regions with abundant solar radiation[13].

The primary focus of research in solar drying technology has been on optimizing drying efficiency while maintaining the quality of the dried products [14]. Solar drying is particularly advantageous in the agricultural sector, where post-harvest losses due to inadequate preservation techniques can be

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significant. With advancements in materials science and drying techniques, solar drying systems have evolved, offering improved energy storage capabilities and hybrid technologies that integrate other renewable energy sources [4], [10]. However, despite these advancements, several challenges remain, including the variability of solar energy across regions, the need for reliable performance under diverse climatic conditions, and the scalability of solar drying systems for industrial use.

Given the rapid development of solar drying technology, a comprehensive literature review is essential to provide insights into future research directions in the field. One widely-used approach for mapping research trends in specific fields is bibliometric analysis [15]. This analysis aims to map current research trends, identify influential countries, authors and institutions, and explore research gaps that require further advancement in the field.

In this context, the present study aims to provide a comprehensive overview of the research landscape and offer future directions for the development of solar drying technology through a bibliometric approach using VOSviewer software. This study adopts a systematic approach by analyzing data from the Scopus database, covering publications from 2004 to 2024. By examining the contributions of various countries, institutions, and authors, we aim to highlight the key drivers of innovation in this field and emphasize the importance of international collaboration in enhancing the global adoption of solar drying technology.

## 2. Method

This study employs a bibliometric approach to systematically explore the research landscape within the field of solar drying technology. The Scopus database was utilized as the sole data source for the collection of research articles and review papers, following the search protocol outlined in Table 1. A total of 108 documents were retrieved and selected for further analysis using the final query: TITLE-ABS-KEY (solar AND drying AND technology) AND PUBYEAR > 2003 AND PUBYEAR < 2025 AND (LIMIT-TO (SUBJAREA, "ENGI")) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (EXACTKEYWORD, "Solar Dryers") OR LIMIT-TO (EXACTKEYWORD, "Solar Drying") OR LIMIT-TO (EXACTKEYWORD, "Solar Drying Technology") OR LIMIT-TO (EXACTKEYWORD, "Solar Dryer")) AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO PUBSTAGE, "final"). Subsequently, VOSviewer software was used to map the research architecture related to solar drying technology and to identify research gaps by analyzing author keywords, bibliographic data, and citation networks.

**Table 1.** Protocol Used in Data Search

| **Subject** | **Description** |
|---|---|
| Database | Scopus |
| Keywords | Solar drying technology |
| Search field | Title, abstract, keywords |
| Time interval | 2004-2024 |
| Subject area | Engineering |
| Publication type | Research and review articles |
| Publication language | English |
| Source type | Journal |
| Pubstage | Final |

The discussion structure in this study follows the research questions (RQ) formulated using the PICOC method (population, intervention, comparison, outcome, and context). Table 2 presents the detailed structure of the research questions to ensure the study remains focused on the established objectives.

**Table 2.** Research Question

| ID | Research Question | Motivation |
|---|---|---|
| RQ1 | What are the research trends over time in the field of solar drying technology? | To identify current research trends related to solar drying technology. |
| RQ2 | Which countries contribute most significantly to the research advancements in solar drying technology? | To identify the countries making the most substantial contributions to research advancements in solar drying technology. |
| RQ3 | What research topics are selected by researchers in the latest advancements in solar drying technology? | To identify the research topics chosen by researchers in the latest advancements in solar drying technology. |
| RQ4 | Which institutions and researchers are the most influential and active in recent trends and advancements in solar drying technology? | To identify the most active and influential institutions and researchers in recent advancements in solar drying technology. |
| RQ5 | Which journals are the most significant and impactful in the field of solar drying technology? | To identify the most impactful papers based on citations in the field of solar drying technology. |
| RQ6 | What strategies need further exploration to enrich the development of solar drying technology? | To identify strategies and future work that can enhance the field of solar drying technology. |

## 3. Result and Discussion

### 3.1 Annual Publication Trends

The publication trend in solar drying technology from 2004 to 2024 demonstrates a steady rise, with significant growth starting around 2010, as shown in Figure 1. From 2004 to 2009, the field experienced relatively low output, with only one or two publications per year, indicating limited research activity during this period. However, in 2010, there was a notable increase, with six publications, reflecting a growing recognition of solar drying's potential as a sustainable technology for food preservation and renewable energy. Between 2011 and 2015, the number of publications fluctuated, though the general trend was upward, signaling ongoing interest in the field. A more pronounced rise occurred from 2016 onward, culminating in a peak of 20 publications in 2022. Technological advancements, a global shift towards sustainability, and increased funding for renewable energy research are responsible for this sharp growth. Although there was a slight dip in 2023, a projected recovery in 2024 (with 14 publications) suggests the field is continuing to expand, albeit with temporary fluctuations likely due to funding availability or shifts in research priorities.

Despite this positive trajectory, several research gaps remain. The fluctuations in output over the years may point to challenges in scaling and implementing solar drying technology consistently across different regions. To address these issues, future research should focus on developing hybrid solar drying systems, enhancing energy efficiency, and ensuring reliable performance under various climatic conditions. Additionally, interdisciplinary collaboration between fields such as agricultural engineering, materials science, and renewable energy will be essential in driving innovation and accelerating the adoption of solar drying technology. Expanding the scope of research to encompass both small-scale and industrial applications will be key to addressing global challenges related to food security and energy sustainability and maximizing the benefits of solar drying technology on a global scale.

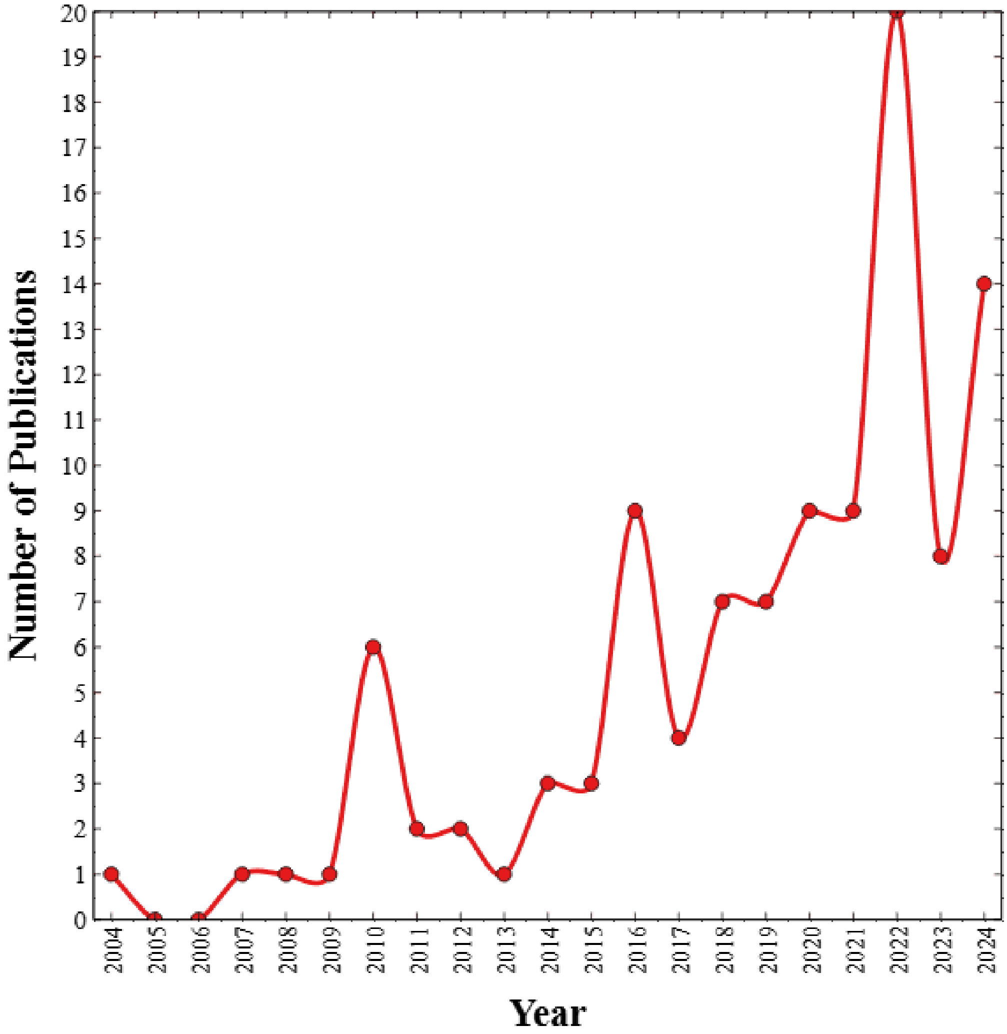


**Figure 1.** Level of the Progress of Research using Keywords Solar Drying Technology.

### 3.2 Analysis of Major Contributing Countries

Figure 2 illustrates the contributions of various countries to the field of solar drying technology, with India and China leading significantly in terms of publication output. India ranks highest with 34 publications, followed by China with 17. This strong representation underscores the prominent role these countries play in advancing solar drying technology, likely driven by their large agricultural sectors, abundant solar resources, and the urgent need for sustainable food preservation methods. Countries such as Thailand (9), the United States (7), and Spain (7) also demonstrate meaningful contributions, albeit with smaller research communities. The high output from these nations suggests that solar drying has gained recognition as an essential tool in food processing and energy efficiency, particularly in regions where agriculture is critical to the economy.

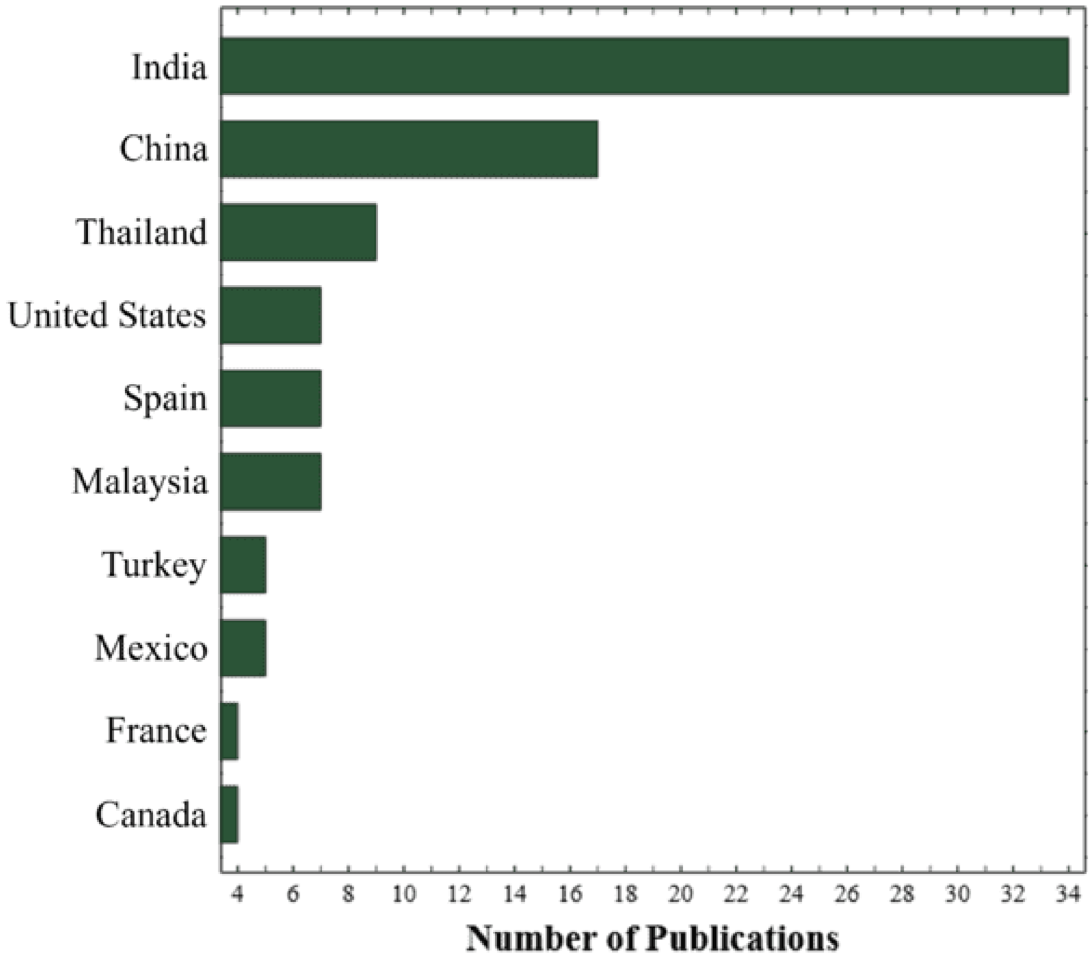


**Figure 2.** The Most Productive Top Country using Keywords Solar Drying Technology.

To bridge existing research gaps, future efforts should focus on fostering global collaboration, particularly with countries that have lower publication outputs but significant potential for solar energy utilization. Strengthening international partnerships could enhance knowledge sharing and support the development of solar drying technologies in regions with high solar potential, such as parts of Africa and Southeast Asia. Furthermore, interdisciplinary research that integrates food science, materials science, and renewable energy technologies could catalyze innovation in solar drying systems, contributing to global efforts to address food security and sustainable energy challenges. The relatively smaller contributions from countries like France, Canada, and Mexico may reflect differing regional priorities or funding constraints in agricultural and solar energy research, pointing to an opportunity for more inclusive global collaboration to advance solar drying technology worldwide.

### 3.3 Analysis of Keywords

The keywords clustered in distinct groups, as shown in Table 3, offer valuable insights into the diverse research focuses within the field of solar drying technology. Cluster 1 (red) primarily focuses on how the drying process affects food quality, emphasizing keywords like "antioxidants," "texture," "drying kinetics," and "quality control." This cluster underscores a crucial research domain that strives to maintain the nutritional and sensory qualities of food, particularly fruits and plants, throughout the drying process. Cluster 2 (green) focuses on energy efficiency and sustainability, featuring terms like "exergy," "renewable energy," and "solar heating," reflecting the global shift toward energy-efficient drying technologies and reducing reliance on fossil fuels. Meanwhile, Cluster 3 (blue) encompasses agricultural applications, food storage, and innovations, with keywords such as "hybrid solar dryers" and "phase change materials," pointing to advancements in enhancing food preservation and increasing the efficiency of solar drying systems. Cluster 4 (yellow) focuses on moisture management, a crucial factor for achieving optimal drying results, especially in "developing countries" with limited access to technology. Lastly, Cluster 5 (purple) is specialized, focusing on "air" and "drying process," indicating foundational research into airflow dynamics and drying mechanics.

**Table 3.** VOSviewer Cluster Results.

| Cluster | Items | Colour | Keywords |
|---|---|---|---|
| 1 | 16 | Red | Antioxidants, colour, curing, drying, drying characteristics, drying kinetic, drying methods, fruits, hot air, hot air drying, low temperature drying, plants (botany), quality control, radio waves, solar dryers, texture. |
| 2 | 16 | Green | Carbon dioxide, dryers (equipment), economic analysis, energy, energy efficiency, energy utilization, exergy, fossil fuels, greenhouses, open sun drying, renewable energies, renewable energy, solar dryer, solar drying, solar energy, solar heating. |
| 3 | 14 | Blue | Agriculture products, agriculture, drying efficiency, food products, food storage, heat storage, hybrid solar dryer, investments, performance, phase change material, phase change materials, solar drying technology, sustainable development, vegetables. |
| 4 | 8 | Yellow | Dehydration, developing countries, drying technology, heating, moisture, moisture content, moisture determination, thermal processing (foods). |
| 5 | 2 | Purple | Air, drying process. |

The visualization from VOSviewer (see Figure 3) further illustrates the network of co-occurring keywords in solar drying technology research based on Scopus data. "Solar dryers" is the dominant keyword, demonstrating its central role in the literature, with strong connections to terms such as "fruits," "hot air drying," "moisture," and "drying characteristics." These linkages suggest that the application of solar drying is particularly significant in the food industry, where maintaining moisture content and optimizing drying efficiency are crucial, especially for perishable goods like fruits. Furthermore, the emphasis on "solar drying technology" alongside terms such as "energy efficiency," "exergy," and "renewable energy" underscores the growing importance of sustainable drying processes. This trend is vital for reducing energy consumption and mitigating the environmental impact associated with traditional drying methods, reinforcing the role of solar drying as an eco-friendly alternative.

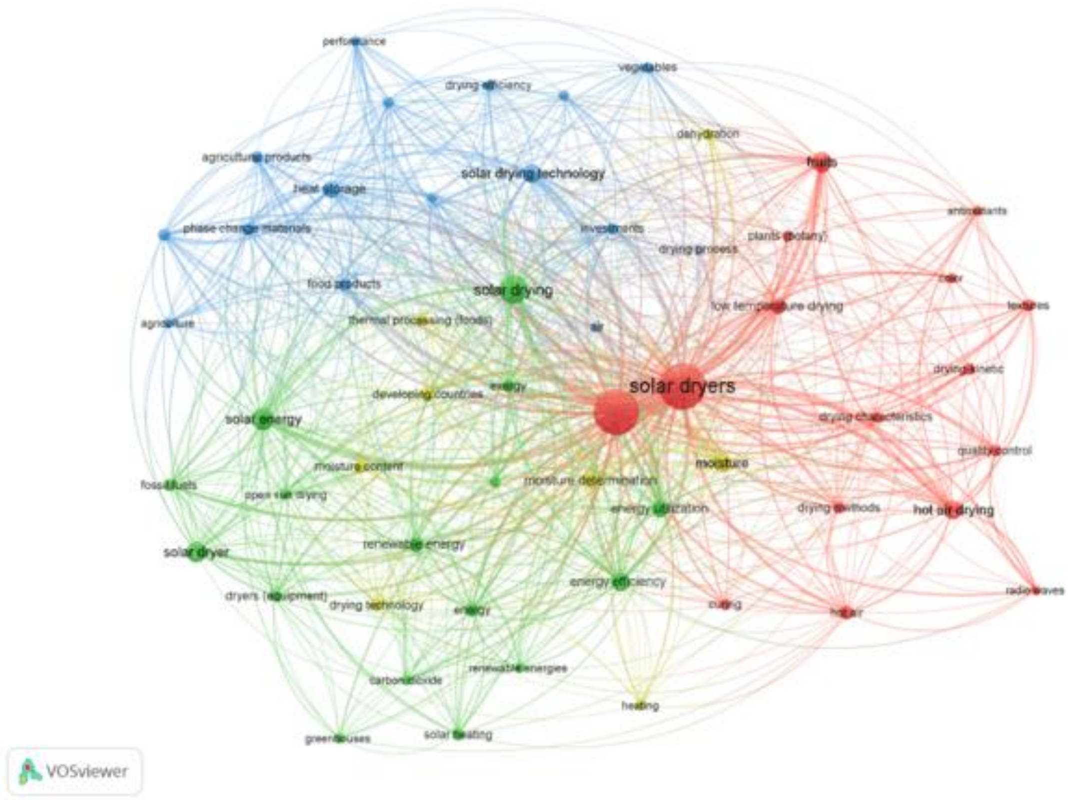


**Figure 3.** Network Visualizations Based on Keywords

While there are advancements in solar drying technology, there are notable research gaps. Keywords such as "low-temperature drying," "drying kinetics," and "drying methods" indicate the need for further investigation to fully understand the fundamental mechanisms governing the drying process, particularly in maintaining product quality. Moreover, the limited linkage between "solar dryers" and keywords such as "antioxidants," "textures," and "quality control" points to an underexplored area concerning the nutritional and sensory impacts of solar drying on food products. Future research should aim to integrate advanced materials for energy storage, such as phase change materials, to enhance system performance and reliability. Additionally, expanding solar drying applications to more delicate food products or developing hybrid systems that combine solar and other renewable energy sources can increase operational efficiency. Cross-disciplinary studies combining energy efficiency and food quality research will be critical to bridging these gaps and ensuring that solar drying becomes a more robust, commercially viable technology.

### 3.4 Analysis of Institutions and Authors

Figure 4 highlights the publication productivity of key authors in the field of solar drying technology, with Kumar A. emerging as the most prolific contributor, having published six papers. This output positions Kumar A. as a leading figure in advancing solar drying research, potentially focusing on both experimental and applied aspects of the technology. Other notable contributors, including Zhou X., Wang S., and Fudholi A., each with three publications, are important but less prolific compared to Kumar. The remaining authors, with two publications each, demonstrate a more specialized or focused involvement in the field, potentially addressing niche aspects of solar drying.

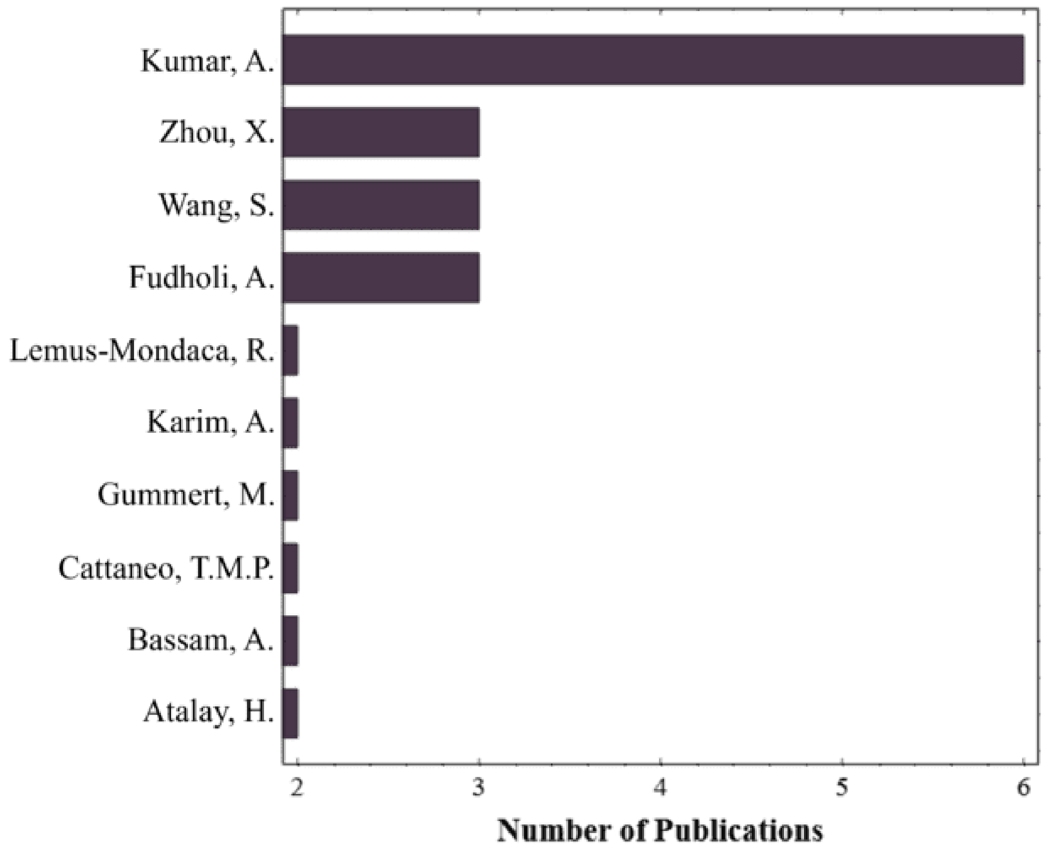


**Figure 4.** The Most Productive Top Authors used Keywords Solar Drying Technology.

The disparity in publication output between the leading author and others indicates a concentration of expertise within a small group of researchers. Kumar's prominence may reflect a well-established research group or institutional collaboration driving significant advancements in the field. However, the smaller contributions from other authors suggest the need for broader collaboration within the scientific community to diversify the research landscape. Increased interdisciplinary collaboration could stimulate innovation, addressing critical challenges such as energy efficiency, food preservation, and the scalability of solar drying technologies. To close these gaps, future research should prioritize collaborative efforts between established and emerging researchers, focusing on practical applications in agricultural and developing regions. This would bridge the gap between academic advancements and real-world implementation, facilitating the global adoption of solar drying as a sustainable solution for food preservation and energy efficiency.

Figure 5 highlights the most productive affiliations in the field of solar drying technology, with Maulana Azad National Institute of Technology and Washington State University Pullman leading the list, each contributing four publications. These institutions likely benefit from well-established research programs in renewable energy or agricultural technology, which have facilitated their significant output in solar drying research. Their prominence suggests a focus on key advancements in solar drying systems, ranging from technological innovations to practical applications in agriculture and energy efficiency. Other institutions, such as Shoolini University, Northwest A&F University, Prince of Songkla University, and Universiti Kebangsaan Malaysia, each with three publications, also demonstrate active involvement, though possibly with smaller research groups or more specialized areas of focus. This diversity of contributors reflects the growing global interest in solar drying technology, particularly in regions where solar energy is abundant and agricultural processing is critical to the economy.

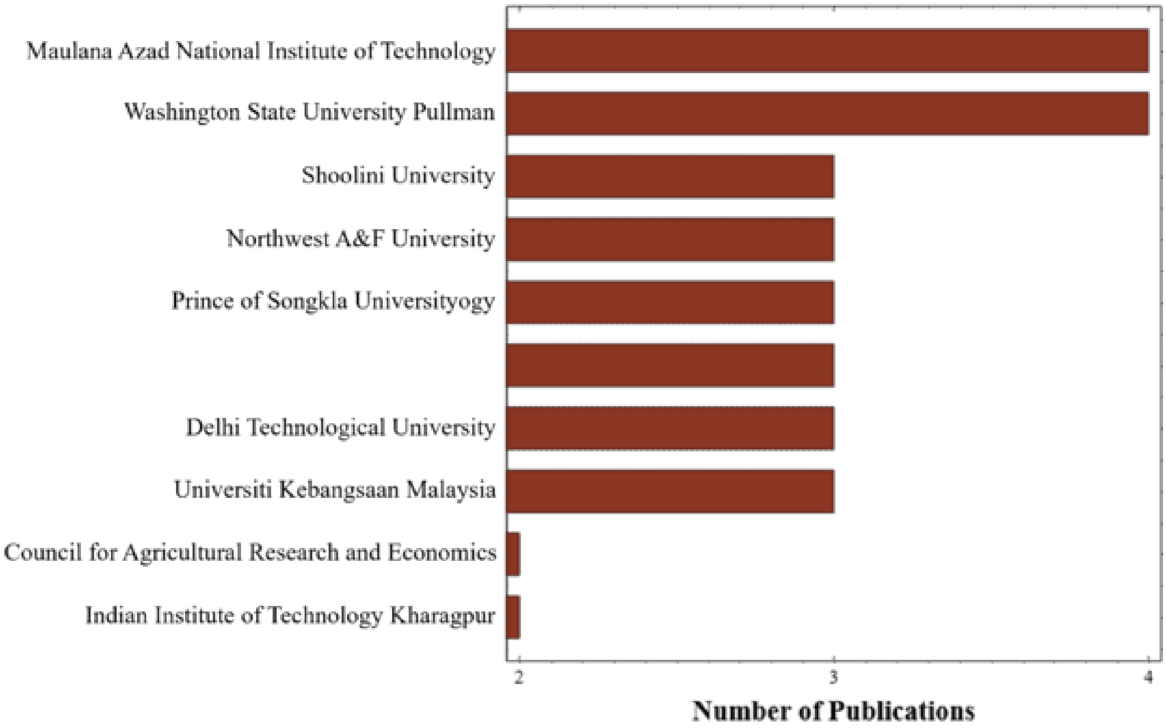


**Figure 5.** The Most Productive Top Affiliates used Keywords Solar Drying Technology.

Despite the advancements, increased collaboration between prominent institutions and those with emerging research capabilities could resolve numerous research gaps. International and interdisciplinary partnerships, particularly between developed and developing nations, could facilitate the widespread adoption of solar drying technology and accelerate innovation. Additionally, in order to enhance the commercial viability of solar drying systems, future research should concentrate on overcoming obstacles associated with scalability and enhancing energy efficiency. By broadening the scope of research to include contemporary agricultural practices, we will further advance the technology and ensure its applicability in both small-scale and industrial contexts. Such endeavors will be essential for the optimization of solar drying systems and the enhancement of their function in the promotion of sustainable agricultural and energy practices on a global scale.

### 3.5 Analysis of Highly Cited Papers

The analysis of the most cited papers using the keywords Solar Drying Technology highlights critical areas of research that have significantly advanced the field, as shown in Table 4. The most highly cited paper, Vijayan et al. (2016), focuses on mathematical modeling and performance analysis of thin-layer drying systems, specifically for bitter gourd in an indirect solar dryer. This work has been instrumental in optimizing drying efficiency and integrating sensible heat storage, which is crucial for practical applications in agricultural settings [16]. Its high citation count underscores its impact on both theoretical modeling and real-world applications, emphasizing the importance of refining solar drying processes for specific crops. Similarly, Kant et al. (2016) contributed a pivotal review of thermal energy storage in solar drying systems, highlighting the essential role of energy management in ensuring consistent dryer performance. This work has guided subsequent research on integrating energy storage solutions into solar drying technologies to enhance efficiency and reliability [17].

**Table 4.** Top Five Most Cited Articles Using Keywords Solar Drying Technology.

| No. | First Author | Title | Year | Total Citation | Ref. |
|---|---|---|---|---|---|
| 1 | Vijayan S. | Mathematical modeling and performance analysis of thin layer drying of bitter gourd in sensible storage based indirect solar dryer. | 2016 | 171 | [16] |
| 2 | Kant K. | Thermal energy storage based solar drying systems: A review. | 2016 | 160 | [17] |
| 3 | El Hage H. | An investigation on solar drying: A review with economic and environmental assessment. | 2018 | 158 | [18] |
| 4 | Sehrawat R. | Effect of superheated steam drying on properties of foodstuffs and kinetic modeling. | 2016 | 97 | [19] |
| 5 | Rathore N.S. | Experimental studies on hemi cylindrical walk-in type solar tunnel dryer for grape drying. | 2010 | 95 | [20] |

El Hage et al. (2018) expanded the scope of solar drying research by assessing the economic and environmental implications of the technology, particularly in agricultural economies. Their review addressed the need for solar drying to be both technically feasible and scalable, as well as environmentally sustainable [18]. Sehrawat et al. (2016) examined the impact of superheated steam drying on food quality, contributing important insights into food preservation and the effect of drying kinetics on product quality [19]. While these papers demonstrate significant progress, several research gaps remain. While there has been extensive exploration of energy efficiency and drying performance, research on the integration of advanced energy storage materials or hybrid systems that combine solar energy with other renewable sources remains limited. Future research should focus on developing hybrid systems capable of operating under diverse climatic conditions and exploring innovative materials, such as phase-change materials, to enhance energy retention. Furthermore, addressing the intersection between energy efficiency and food quality in commercial production contexts will be critical to transitioning solar drying technology from experimental studies to widespread practical applications.

### 3.6 Future Work

VOSviewer generated a network visualization (as shown in Figure 6) that illustrates a time-structured map of author keywords in the field of solar drying technology from 2004 to 2024. The central keyword, "solar dryers," highlights its pivotal role in this research domain, with strong associations with key terms such as "solar drying," "moisture," "energy efficiency," and "drying characteristics." These connections reflect the consistent focus on optimizing solar dryer performance, particularly in food processing, where moisture control and energy efficiency are critical. The color overlay of the network reveals that while core topics like "solar energy" and "energy efficiency" have been central throughout, more recent studies have shifted towards specific innovations, such as "phase change materials" and "drying efficiency," emphasizing advancements in energy storage and drying performance. These developments demonstrate an evolution in research, moving from basic applications of solar drying in agriculture to refining the technology for enhanced reliability and efficiency.

Despite these advancements, notable research gaps persist. The nutritional and sensory effects of solar drying on food products have received limited attention, as evidenced by the weaker connections to keywords such as "antioxidants," "texture," and "quality control." This gap points to the need for more comprehensive studies that integrate advanced drying technologies with mechanisms for preserving food quality, particularly for sensitive products. Future research should focus on developing hybrid solar drying systems that combine solar and other renewable energy sources, thereby increasing efficiency while addressing these quality concerns. Additionally, studies should explore the effects of solar drying on the nutritional value and sensory characteristics of diverse food products. Such research would not only improve the performance and applicability of solar dryers but also facilitate their broader adoption in commercial food processing industries.

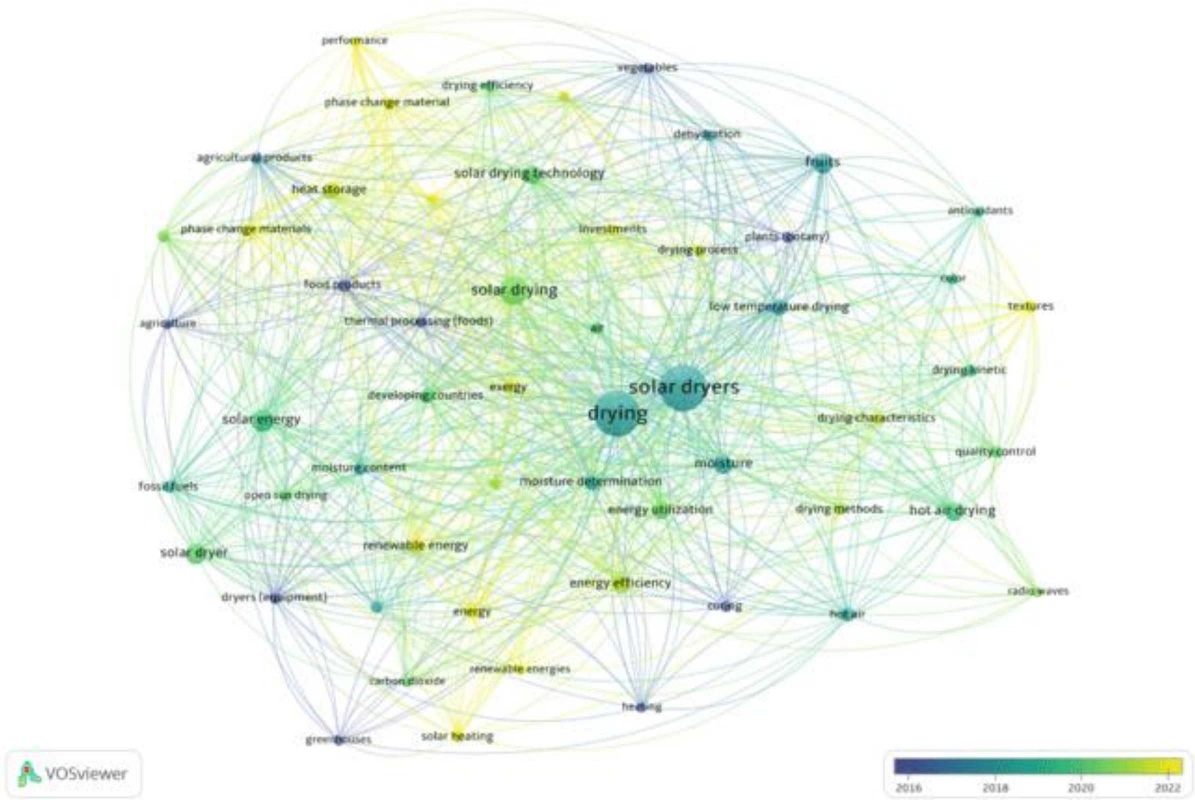


**Figure 6.** Overlay Visualizations Based on Keywords

## 4. Conclusion

This study effectively employs bibliometric analysis to map the research progress on solar drying technology. We collected data from the Scopus database using the keyword "solar drying technology" over a 20-year period (2004-2024), resulting in 108 relevant articles. Notably, research on solar drying technology has gained significant popularity since 2016. Data visualization reveals five distinct research clusters, reflecting the diversity of approaches and applications in this field. Most publications originate from Maulana Azad National Institute of Technology and Washington State University Pullman, indicating their leading roles in advancing this technology. Kumar, A. stands out as the most prolific author, and India is the country with the highest volume of publications.

The results highlight the growing interest and contributions to solar drying technology, driven by its relevance to energy efficiency and sustainable agricultural practices. These findings underscore the importance of continued collaboration among leading institutions and researchers to further accelerate innovation in this field. The concentration of research activity in specific institutions and countries suggests both leadership in solar drying research and opportunities for greater international collaboration. By fostering more interdisciplinary and cross-border partnerships, the field can expand its practical applications and enhance the scalability of solar drying technologies in diverse environmental and agricultural contexts.

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