STATISTICS, OPTIMIZATION AND INFORMATION COMPUTING
Stat., Optim. Inf. Comput., Vol. **x**, Month 2025, pp 0–20.
Published online in International Academic Press (www.IAPress.org)

Enhancing the Efficiency of Solar Cells Based on Tin Sulfide (SnS): a Bibliometric Analysis

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Abstract Among the most promising approaches to improve the efficiency and cost-effectiveness of solar cells, the exploration of new absorber materials plays a central role. In this context, tin sulfide (SnS), a class IV-VI compound, is emerging as a prime candidate for next-generation thin film solar cells. This article provides a comprehensive bibliometric analysis of the latest efforts aimed at enhancing the efficiency of tin sulfide (SnS) solar cells. This study identifies important trends, emerging themes along with the most prolific authors and publications by analyzing scientific literature over the last decade (2015-2025) using the Web of Science and Scopus databases. The findings reinforce the idea that there is a heightened level of interest concerning SnS due to its non-toxic, abundant nature and the research efforts on its optimized optical and electrical properties engineering thin film devices, as well as exploring novel architectures. The study also outlines other critical research gaps, especially in long-term stability and scalability, reinforcing the need for further research in this important field within renewable energy.

Keywords bibliometrics; bibliometrix; CiteSpace; R package; Tin sulfide; SnS; IV-VI semiconductors; Chalcogenide; SCAPS-1D.

DOI: 10.19139/soic-2310-5070-3332

1. Introduction

The global energy transition toward sustainable and environmentally friendly sources of energy have placed photovoltaic technologies at the heart of research and development priorities. The limited efficiency and Poor stability in new materials of solar cells. However, Tin sulfide (SnS) seems to beas an increasingly promising absorber material for thin film solar cells. Tin sulfide (SnS) also exhibits attractive intrinsic characteristics, like a direct band gap between 1.3 and 1.5 eV, a high absorption coefficient ($> 10^5$ cm^{-1}) [1], natural abundance, and non-toxicity, which favorably differentiate it from traditional materials such as cadmium telluride or silicon [2]. These properties make it a strategically suited material for efficient absorption of the solar spectrum and the development of low-cost, low-impact photovoltaic technologies.

However, despite its theoretical potential efficiency exceeding 31%,According to the Shockley-Queisser limit, practical devices have often struggled to surpass 5-6% efficiency due to challenges like poor crystallinity, interface defects, and unfavorable band alignment. Recent advances in doping, interface engineering, and heterostructure design aim to overcome these limitations and unlock SnS's full photovoltaic potential However, despite these advantages, the current performance of SnS-based solar cells remains below their theoretical potential. Technical challenges include conductivity control, intrinsic defect reduction, interface passivation, and long-term device stability [3]. Numerous strategies have been explored to improve conversion efficiency: optimization of deposition processes, heterojunction engineering, addition of improved buffer layers, and integration into tandem architectures

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ISSN 2310-5070 (online) ISSN 2311-004X (print)

[4], [5]. Faced with increasing scientific output, it is becoming essential to have a structured and quantitative view of research efforts.

Many studies have been dedicated to improving the performance, stability, and cost-effectiveness of solar cells over material innovation, architectural design, and advanced fabrication techniques. Researchers have discovered novel absorber materials such as tin sulfide (SnS), perovskites, and quantum dots to surpass the limitations of traditional silicon-based cells. At the same time, tandem and multi-junction architectures have appeared as promising approaches to overcome the Shockley-Queisser efficiency limit by collecting a larger spectrum of solar radiation. To this end, bibliometric studies offer powerful tools for analyzing scientific publications, identifying underlying trends, mapping collaboration networks, and highlighting the most influential authors, institutions, and topics [6].

This study provides a comprehensive bibliometric analysis of scientific publications focused on improving the efficiency of SnS-based solar cells. It is based on the analysis of 266 articles published between 2015 and 2025, extracted from the Scopus and Web of Science databases, and processed using Biblioshiny (from the R package Bibliometrix) [7].

This paper aims to provide a recent map of this field of research: to identify current scientific dynamics, identify promising areas and reveal gaps that require future investigations.for this reason we emerged two trusted academic databases: Web of Science (WoS) and Scopus for metadata retrieval.

2. Related works and motivation

Over the past decade, tin sulfide (SnS) has attracted growing interest as an absorber material for thin-film solar cells. Although several bibliometric analyses have been conducted to explore scientific trends and collaborations, none have yet systematically combined the Scopus and Web of Science databases using tools such as Bibliometrix-R or VOSviewer.

This study fills this gap by producing a comprehensive and comparative bibliometric map of research on SnS-based solar cells, covering the period 2015–2025. By cross-referencing the two databases, rigorously cleaning the metadata and analysing authors, institutions, keywords and collaborations, it highlights scientific dynamics, geographical hotspots of innovation and current issues in the field. This analytical approach provides both an accurate overview and a strategic framework to guide future research in support of sustainable energy transition.

Several studies have explored tin sulfide-based materials, whether from a fundamental [8], bibliometric [9],[10], or experimental [11] perspective. Some focus on SnS_2, others on PV/T systems or general photovoltaic absorption. However, these studies have limitations: heterogeneous time coverage, focus on specific subsets, or lack of integrated network and visual analysis.

Table 1 compares these studies with the present analysis, which stands out for its scope focused exclusively on SnS, the joint use of Scopus and Web of Science, and a combined bibliometric and structural approach (network, keywords, co-authors, SCAPS-1D). We have expanded this table to provide a more critical overview, highlighting the specific methodological limitations of prior works and how our integrated, dual-database approach addresses these shortcomings. This approach fills a gap in the literature by providing a cartographic and evolving view of scientific trends in this strategic field.

A critical analysis of the works in Table 1 reveals why our integrated approach is both timely and necessary. Prior bibliometric studies on related topics, such as the analysis of tin disulphide by Al-Hadeethi et al., were often limited in either their focus on only one database, Scopus, or a wider material scope that did not allow for an in-depth look into the particular challenges of SnS-based solar cells. Our study directly addresses this with the combination of two major databases for a more complete dataset focused exclusively on SnS photovoltaics.

Furthermore, our results both complement and expand previous observations. For example, the leading Chinese contribution we have identified post-2022 is in line with the trend observed by Al-Hadeethi et al. within the broader field of tin sulfide; however, our temporal analysis enables us to identify this acceleration as a “technological intensification phase” driven by a focus on simulation and device engineering. By providing this deeper, more focused analysis, our work builds upon the foundational understanding established by previous reviews and offers a more granular, up-to-date, and actionable map of the current research landscape.

To better position the present study in the existing scientific literature, it is important to highlight some quantitative differences with the existing research. Indeed, the bibliometric studies on the subject matter generally explored broader or related fields, such as the study on “Tin Disulfide Bibliometric Trends Comprising 2,391 Documents from 1961 to 2022” or “Bibliometric Trends on PV/T from 1,659 Documents from 1981 to 2021,” while non-bibliometric reviews on SnS generally focused on the material potential of SnS up to 2016. By contrast, the present study focuses on the analysis of 266 journal articles from 2015 to 2025, with a focus on efficiency-oriented research on SnS-based solar cells from the merged Scopus and Web of Science databases.

Table 1. Related work vs Current study

scope	**Review Type**	**Database**	**Dataset**	**Time span**	**Key findings**
Tin-based binary sulfides (SnS, SnS_2...)	Fundamental review	Nanomaterials (MDPI)	Syntheses reports from literature	up to 2021	Lists the physical properties of chemically synthesised tin sulphides, polymorphism, PV applications [8].
Tin disulphide	Bibliometric analysis	Scopus & Web of Science	2391 documents	1961-2022	Focus on SnS_2 nanomaterials, dominant Chinese contribution, trend in photocatalysis and energy applications [9].
PV/T bibliometric analysis	Bibliometric review	Scopus	1659 documents	1981-2021	Reveals gaps, growth in applied AI, multiphase flows, magnetism [10].
SnS review for PV absorber	Fundamental review	Scopus	Theory & experiments SnS	up to 2016	Potential of SnS as a photovoltaic absorber, thin-film deposition techniques [11].

3. Methodology

3.1. Data retrieval and filtering protocol

The bibliometric analysis of recent research on SnS-based solar cells presented in this study is based on a systematic retrieval of metadata from two of the most trusted academic databases: Web of Science (WoS) and Scopus. These databases are well known for their wide coverage and reliability when conducting bibliometric investigations [7], [12]. The search was performed on July 3, 2025, and targeted peer-reviewed journal articles published between 2015 and 2025. We used a carefully designed Boolean query in the “Topic” field (which searches in titles, abstracts, author keywords, and Keywords Plus):

(”SnS” OR ”tin(II) sulfide” OR ”tin sulfide”) AND (”solar cells” OR ”thin-film solar cells”) AND (”efficiency improvement” OR ”efficiency enhancement” OR ”power conversion efficiency” OR ”photovoltaic performance”)

In order to narrow the scope of the analysis to studies directly related to photovoltaic performance, the search strategy focused on terms related to efficiency improvement. These terms include “efficiency improvement,” “efficiency enhancement,” “power conversion efficiency,” and “photovoltaic performance.” It is important to note that this is not meant to be an exhaustive list of all the work done on SnS. It is also important to note that this search strategy is not exhaustive in the sense that it might miss fundamental work related to material properties, deposition techniques, and defect physics, which can contribute to efficiency improvement even if the terms are not used. To support the internal consistency of this strategy, we verified whether highly cited papers in the final corpus could be retrieved using the adopted query [13].

From this search, a total of 439 records were retrieved initially (228 records from Scopus and 211 records from Web of Science). After that, the combined results were further refined with an exhaustive stepwise cleaning process, as shown later in Fig. 2. To remove the first set of irrelevant records due to similarity of titles/keywords of the references with the query, an automated deduplication step was performed with the help of the Bibliometrix R-package based on DOIs, citation titles, and the list of authors on the papers. This step automatically removed the first set of irrelevant records amounting to 112 records that appeared with the same details on the DB’s indexed records. Further refining the final set of records amounting to the rest of the unique set of records of 327 records that appeared on the combined result set of Scopus and the DB indices of the WoS on their respective DB’s indexed records with the help of their titles and abstracts a rigorous manual refinement step to ensure that only the most fitting results that contained details with the inclusion criteria of this particular study automatically removed an additional set of records based on their relevance that led to the exclusion of the first set of irrelevant records of a pooling amounting to 61 records.

The exclusion of 173 records was conducted in two strict phases to ensure data integrity and prevent the loss of relevant research. The primary reduction resulted from the removal of duplicate entries caused by the significant indexing overlap between Web of Science and Scopus. The remaining exclusions were strictly content-based. Specifically, we removed records that appeared in the initial keyword search but focused on Tin Disulfide (SnS_2) rather than Tin Sulfide (SnS), as these are distinct chemical compounds with different optoelectronic properties. Furthermore, studies utilizing SnS solely as a buffer layer or hole transport layer (HTL) in other device architectures (e.g., CIGS or Perovskite cells) were excluded to ensuring the analysis focused exclusively on SnS as the primary absorber material. Finally, review articles and conference abstracts were removed to ensure that the bibliometric indicators such as citation growth and keyword evolution reflected original experimental contributions rather than We believe these revisions significantly enhance the replicability of the study without compromising the quality of the data source.

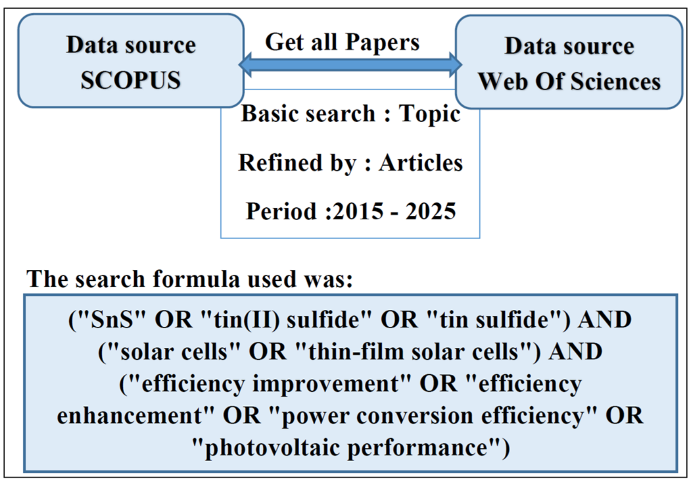


Fig. 1. The meta-data compilation search query.

The collected metadata included details such as publication years, authors, titles, affiliations, abstracts, author keywords, Keywords Plus, source journals, citation counts, and the countries of corresponding authors. Fig. 1 visually summarizes the process used to compile this data. To ensure clarity and reproducibility, our analysis followed the bibliometric workflow introduced by Zupic and Čater [7], which is illustrated in Fig. 2.

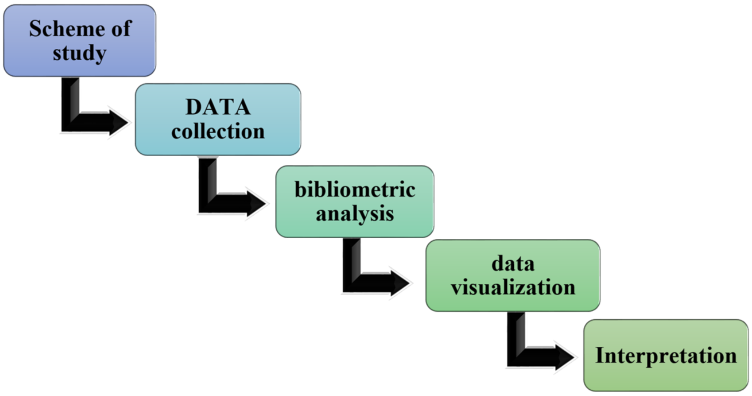


Fig. 2. Scheme of bibliometric analysis procedure.

Fig. 3 Flowchart for the selection of literature included in this study, it is diagram of the publication selection process. A total of 439 records were identified (Scopus: 228; Web of Science: 211). After the removal of 112 duplicates, 327 articles were screened based on title and abstract; 61 were excluded (work not directly related to solar cells or reviews/abstracts only), leading to the final inclusion of 266 studies in the bibliometric analysis.

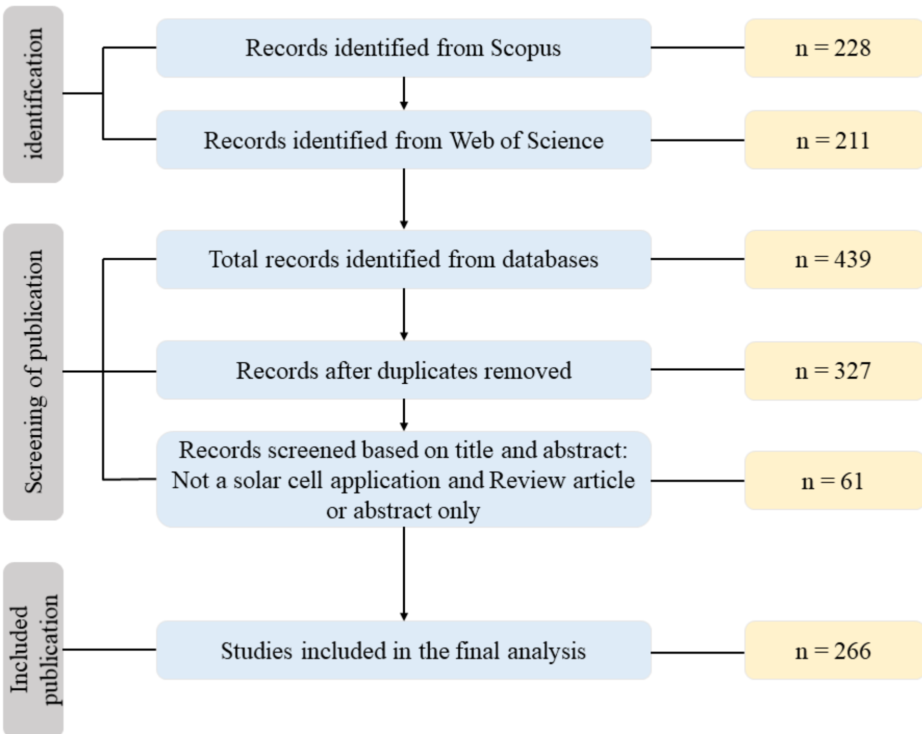


Fig. 3. Flowchart for the selection of literature included in this study.

3.2. Data analysis

After the data collection phase, we performed a structured and multi-step analysis to explore scientific trends and patterns in SnS-based solar cell research. All analyses were conducted using the open-source RStudio environment with the Bibliometrix package and its user-friendly web interface, Biblioshiny [6]. Microsoft Excel was used for organizing and cleaning data, while OriginPro was employed to generate detailed graphs and calculate citation metrics such as the h-index.

To visualize collaboration networks and keyword relationships, we used VOSviewer [14]. We built co-occurrence matrices using terms from “author keywords,” “Keywords Plus,” and keywords from abstracts. These were normalized with similarity measures like the Jaccard and Salton indices. This allowed us to highlight strong conceptual linkages and reveal thematic clusters within the field.

For mapping conceptual structures, we applied Principal Component Analysis (PCA) and hierarchical clustering techniques. These tools helped identify core and emerging topics in the SnS solar cell literature. Additional performance metrics were also considered, including authors’ h-indices and the journals’ impact factors.

Geographical analyses were included as well, highlighting the distribution of research across countries and regions. The annual evolution of publications was tracked to observe the growth trajectory of this research area.

Overall, this mixed-method approach provided a comprehensive and reliable summary of the scientific dynamics in the field. It helped identify not only leading contributors and topics, but also gaps and opportunities for future exploration.

4. Results and discussion

4.1. Temporal dynamics of research

4.1.1 General characteristics of scientific production

Table 2 highlights the main information about the metadata. In total, 266 documents in the form of articles only (8 early access) from 129 sources. A total of 1298 authors have researched on tin sulfide SnS during this period (2015–2025). We observe a steady growth in publications (+4.14%/year) with an average of 22.31 citations for each article. The works are recent (average age: 4.21 years) and highly collaborative, with 6.48 authors on average and 24.81% international collaborations. The majority of documents are classic scientific articles, reflecting standard academic dissemination. These data confirm the dynamism and growing interest in SnS-based solar cells.

Table 2. Primary information about the retrieved documents.

Data Main Information	**No.**
Timespan	2015-2025
Sources	129
Documents	266
Annual Growth Rate %	4.14
Document Average Age	4.21
Average citations per documents	22.31
Keywords Plus (ID)	983
Author’s Keywords (DE)	704
Authors	1298
Authors of single-authored documents	6
Single-authored documents	6
Co-Authors per documents	6.48
International co-authorships %	24.81
article	253
article article	2
article; early access	8
article; proceedings paper	3

4.1.2 Quantitative trends in publications

The histogram (Fig. 4) above shows the annual change in the number of articles published on tin sulfide (SnS) applied to solar cells for the period 2015–2025. There has been an irregular but overall rising trend in the publications volume.

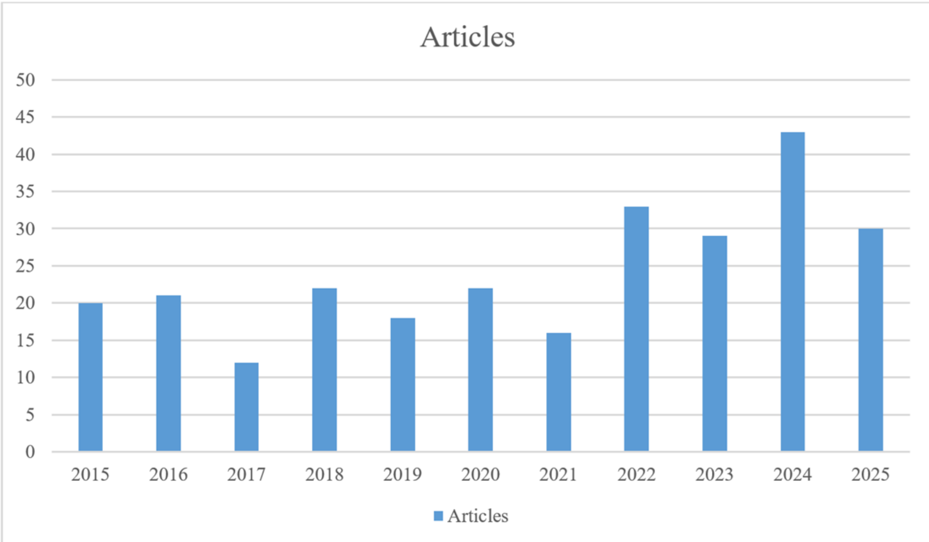


Fig. 4. Distributions of annual scientific production by year.

Between 2015 and 2017, the articles number remained relatively stable at approximately 20 publications per year, with a slight decline in 2017. After a recovery in 2018 and 2020, there was another decline in 2021. However, from 2022 onwards, a significant increase was observed, peaking in 2024 with more than 40 publications. This sudden increase can be attributed to the growing interest in alternative photovoltaic materials in connection with the global energy transition.

This peak in 2024 probably reflects increased research efforts on SnS, motivated by its interesting properties (abundance, non-toxicity, good band alignment) and recent technological advances in deposition methods and device architectures. The year 2025 shows a slight decline, but the level remains significantly higher than in the years prior to 2022.

This evolution pattern indicates that the field is expanding, with a major turning point starting in 2022, reflecting scientific and industrial dynamics favorable to the integration of SnS into next-generation solar technologies. This trend is consistent with other recent bibliometric studies on thin film materials for solar energy [7].

4.2. Authors analysis

4.2.1 Most prolific authors

Taken together, Figures 5, 6, and 7 offer a comprehensive view of the author network in the SnS-based solar cell research domain by integrating various elements of analysis. The results obtained by applying the h-index in a local context point towards a set of researchers who have shown a high level of productivity in association with a high level of prominence in the domain; however, KIM J and RAHMAN M are at the high-end tail of the h-index results. The results obtained by applying the Total Citations (TC) analysis tool support these results by pointing towards a set of researchers whose work has a high level of citation impact; however, a limited number of researchers have a high level of impact, which points towards a set of structuring research works in the domain. The results obtained by applying Lotka's law analysis support these results by pointing towards a set of researchers in the domain whose work has a high level of impact; however, more than 80% of the researcher population has contributed a single work in the domain, while a limited number of researchers have contributed more than one work in the domain. These results point towards a set of highly active and highly prominent research groups in the domain; however, the researcher population is highly scattered in terms of engagement in the domain. These results are consistent with a set of bibliometric indicators that point towards a research domain in a state of emergence and consolidation [15-16].

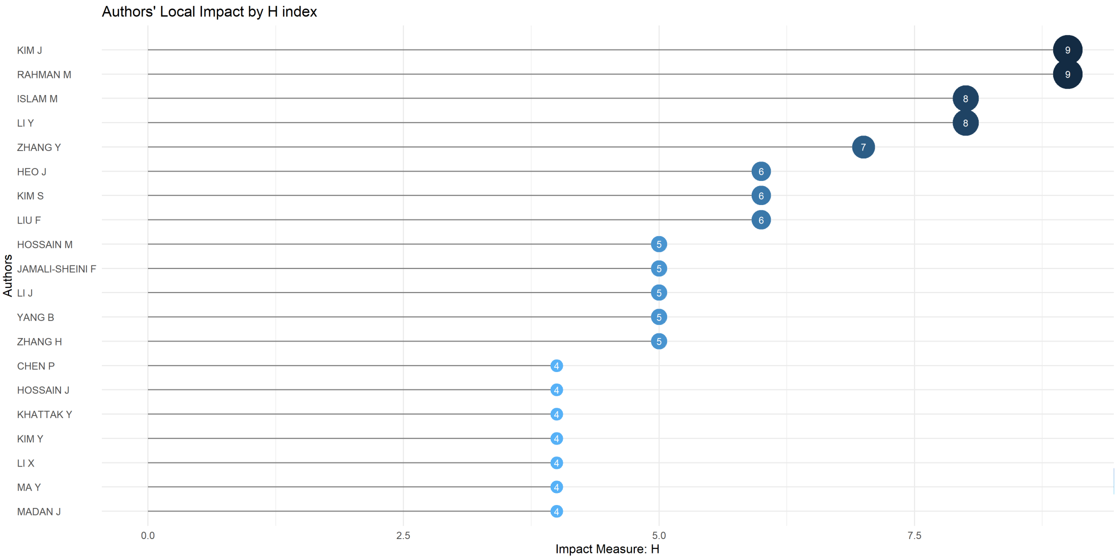


Fig. 5. Local impact of authors in the domain of SnS-based solar cells according to the h-index.

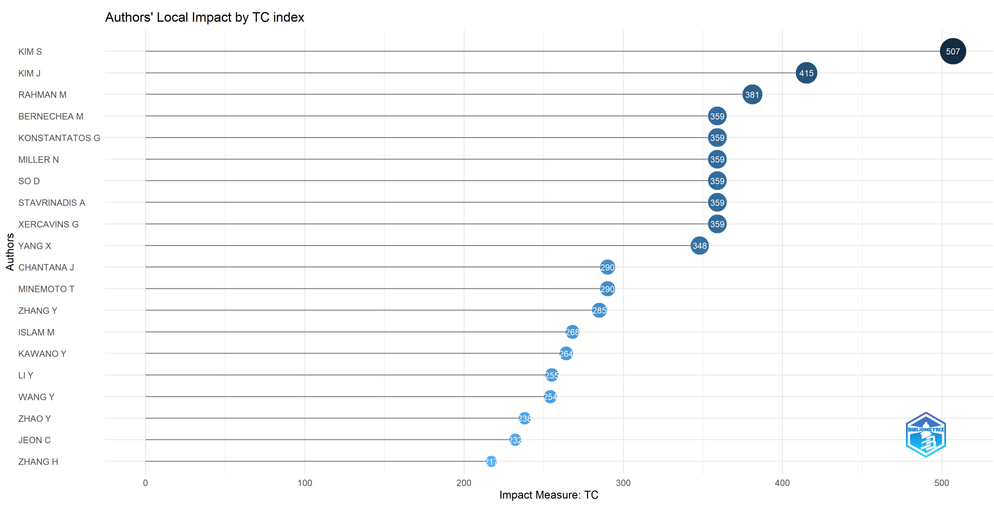


Fig. 6. Authors' local impact according to the Total Citations (TC) index.

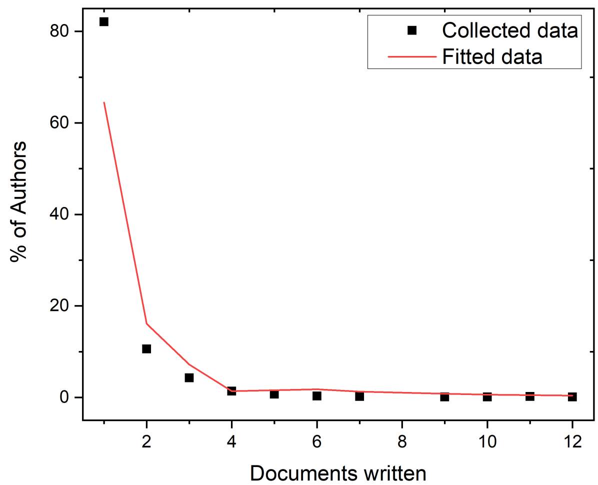


Fig. 7. Author productivity according to Lotka's law

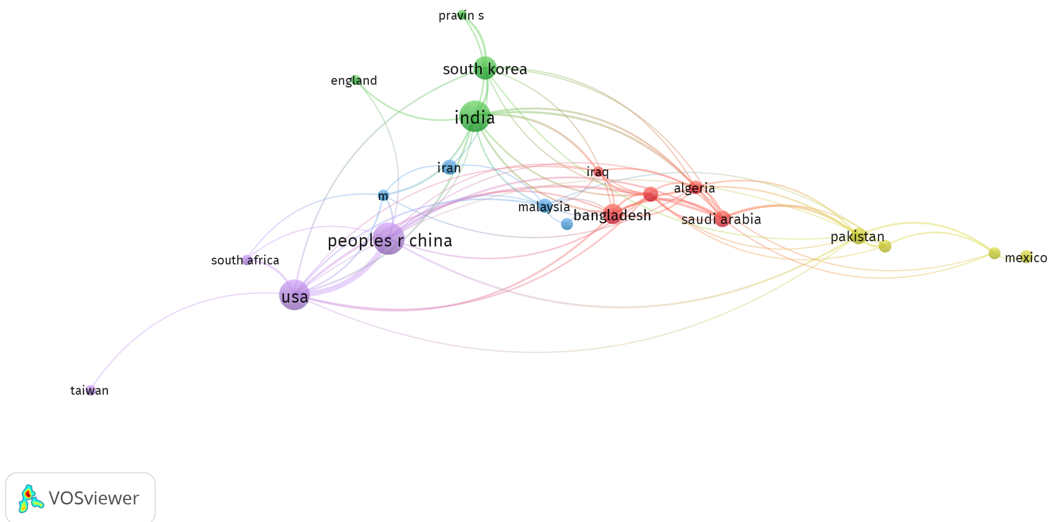


Fig. 8. Network of co-authors by country in the domain of SnS-based solar cells.

4.2.2 Co-authorship network

This co-authors-countries collaboration map visualises scientific interactions between countries involved in solar cell research at SnS (Fig. 8). The nodes represent countries, and their size is proportional to the volume of co-authored publications. The thickness of the lines shows the intensity of bilateral collaborations. Several collaboration clusters are clearly distinguishable: one centered around India and South Korea, another dominated by China and the United States, and a third including the North Africa and Middle East, with Algeria, Saudi Arabia and Iraq. This network suggests a regional structure for scientific cooperation, but also the existence of global hubs (notably China, the United States and India) playing a pivotal role in knowledge sharing.

The international co-authorship rate of 24.81% (Table 1) indicates that roughly three-quarters of the research is conducted within national borders, suggesting that while international partnerships exist, there remains significant potential for growth. A deeper analysis could investigate whether these internationally co-authored papers receive higher citations, indicating a positive impact of collaboration on research quality, a key direction for future bibliometric studies in this field. These dynamics enhance the international visibility of the field while revealing opportunities for broader collaboration, particularly with less represented countries.

4.3. Countries analysis

4.3.1 Most contributing countries

The Fig. 9 reflects the spreading number of scientific publications related to tin sulfide (SnS) solar cells by country. China dominates the scientific landscape with nearly 70 publications, underscoring its role as a global leader in this field.China's leading position in publication output should not be read only as a numerical result, but as an indicator of the broader research structure shaping the field. Its dominance likely reflects the convergence of strong institutional publication capacity, sustained investment in advanced photovoltaic materials, and a strategic focus on absorber technologies that combine earth abundance with low toxicity. India and South Korea also occupy important positions, suggesting that SnS research has become especially dynamic in Asian scientific ecosystems where device engineering, simulation, and thin film processing are strongly connected. More broadly, the geographical concentration of output in Asia suggests that the development of SnS photovoltaics is being driven not only by scientific interest, but also by regional innovation strategies centered on scalable, lower-cost alternatives to conventional photovoltaic materials. Other countries such as Iran, the United States, Algeria, Mexico, Japan and South Africa appear with more modest but significant scientific activity. This distribution demonstrates a strong concentration of research in Asia, particularly in East and South Asia, while the contribution from Africa and South America remains relatively limited. This heterogeneity suggests opportunities for strengthening international scientific collaborations to balance research efforts on a global scale.

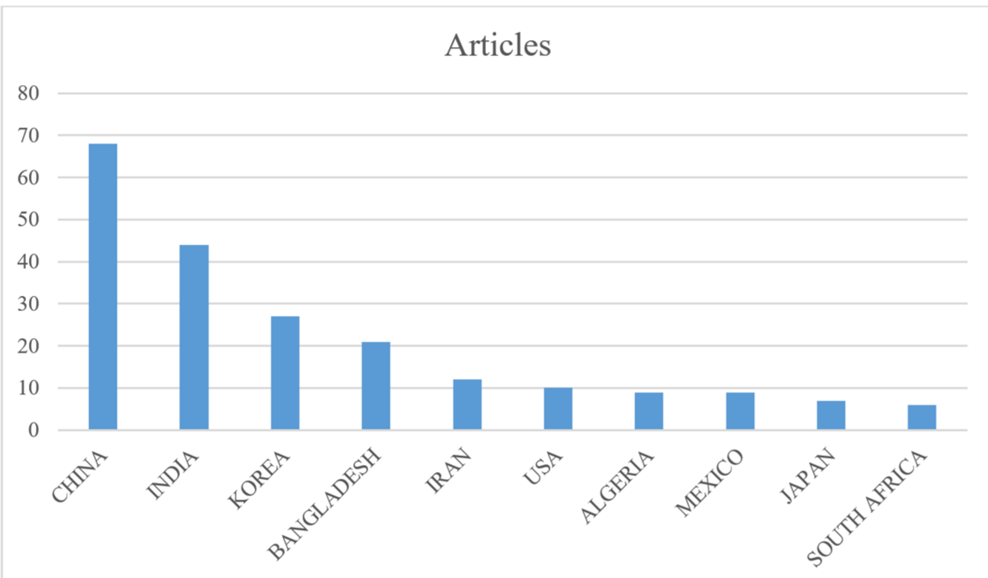


Fig. 9. Distribution of scientific publications by country in the domain of SnS-based solar cells.

4.3.2 International collaboration network

Fig. 10 and Fig. 11 illustrate the geographical distribution of scientific output regarding tin sulfide (SnS) solar cells during the period 2015-2025. The first presents the countries of corresponding authors, distinguishing between national publications (SCP: Single Country Publications) and international collaborations (MCP: Multiple Country

Publications). The second represents a global map of the volume of scientific output on the subject, categorized into five levels based on the number of publications. The analysis highlights a marked predominance of Asia in this field. China stands out for its high scientific output, leading the ranking in terms of the number of documents published, the majority of which were produced without international collaboration (SCP). It is followed by India and South Korea, which also demonstrate strong commitment, combining local efforts and international partnerships. Bangladesh holds a remarkable position despite more limited resources, reflecting its growing involvement in SnS-based photovoltaic research. In the West, the United States, Germany, the United Kingdom, France, and Spain are active contributors, although their publication volume is relatively lower than that of the Asian leaders. Their high participation in international co-authored publications (MCPs) reflects a strategy focused on global academic collaborations, often within the framework of transnational research projects. The global scientific collaboration map (Fig. 10) clearly illustrates the dynamics of research on SnS-based solar cells. It highlights a concentration of activities around countries such as China, India, the United States, South Korea and the United Kingdom, which dominate both in terms of publication volume and number of international collaborations. These countries play a leading role in the development of the research area, structuring co-publication networks on a worldwide scale. At the same time, the figure also shows the gradual emergence of other regions, notably North Africa (Morocco, Algeria), Southern Africa (South Africa) and South Asia (Bangladesh), although their contribution remains limited. The dark blue areas correspond to countries with high scientific output, while the lighter shades reflect potential for development. These results reveal a significant geographical imbalance in scientific output, prompting further promotion of South-South and North-South cooperation. Such collaborations are essential for strengthening local capacities, sharing knowledge and accelerating the adoption of SnS-based photovoltaic technologies in regions with a strong need for sustainable energy solutions. However, it is also important to consider the potential consequences of this geographical concentration. While it creates powerful and efficient research hubs, it may also lead to a narrowing of research perspectives, focusing on challenges or materials uniquely relevant to those regions. Fostering broader North-South and South-South cooperation is therefore a strategic imperative, not only to balance scientific output but also to diversify research approaches and ensure that innovations in SnS technology are globally applicable and accessible.

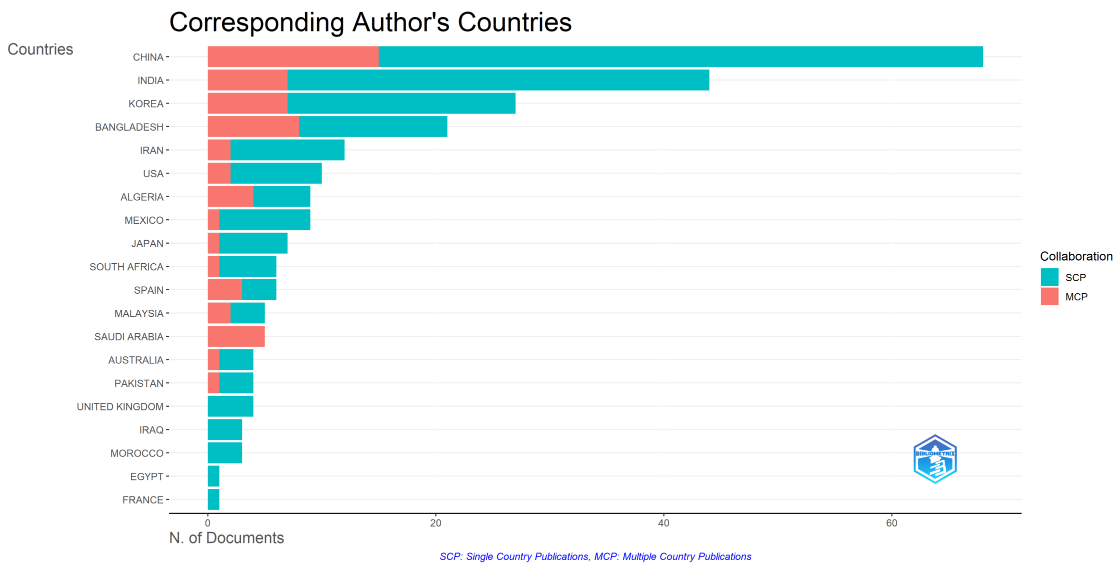


Fig. 10. Geographic Spreading of Corresponding Authors and Types of Collaboration.

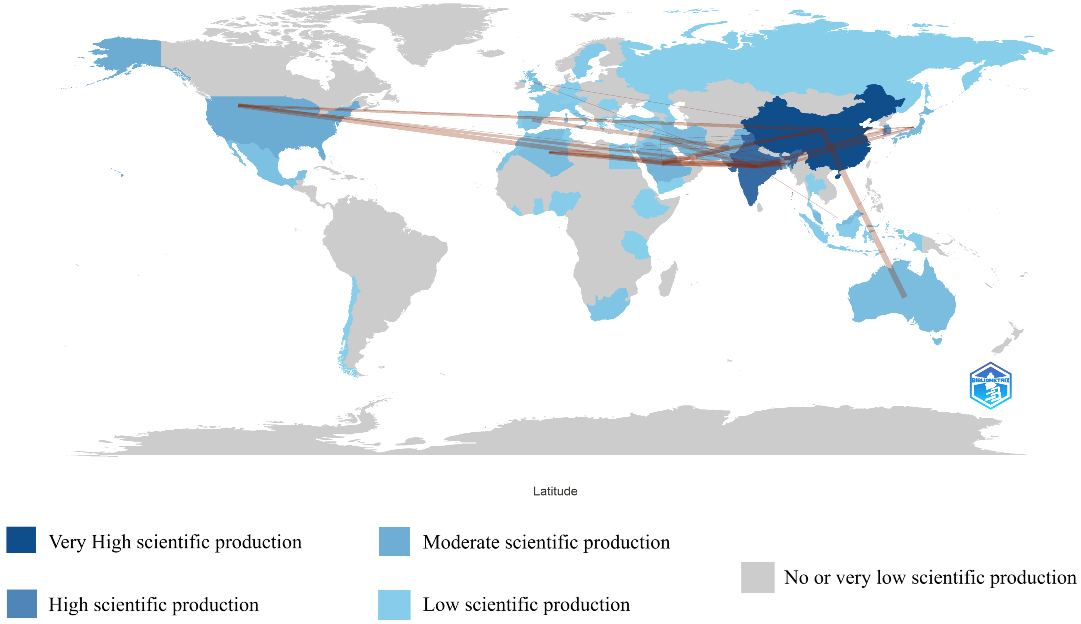


Fig. 11. Geographic spreading of scientific production and collaborations on SnS-based solar cells.

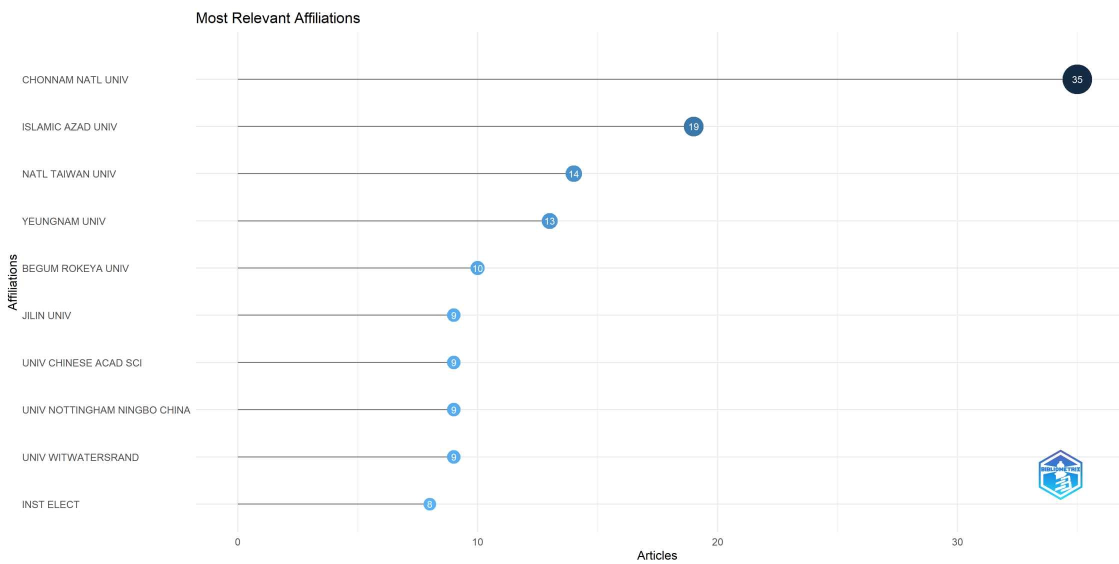


Fig. 12. Top 10 most productive institutions affiliation on the topic of SnS-based solar cells.

4.3.3 Most Productive Institutions

Analysis of institutional affiliations reveals the universities and research centers most active in the field of tin sulfide (SnS) solar cells (Fig. 12). Chonnam National University (South Korea) leads the way with 35 publications, followed by Islamic Azad University (18 articles) and National Taiwan University (14 articles). The majority of the most productive institutions are located in Asia, reflecting the strategic interest of this region in the development of low-cost, low-environmental-impact photovoltaic technologies. Some African institutions, such as the University of the Witwatersrand (South Africa) and the University of Algiers (Algeria), also appear in the ranking. These contributions indicate a growing involvement of developing countries in renewable energy research. Several Asian and international universities are actively collaborating within co-publication networks, as shown by the visible connections between the different nodes of the affiliation graph. This network reflects a dynamic of collaborative research on a global scale in the field of SnS solar cells.

4.4. Keywords analysis

4.4.1 Most frequent keywords

Analysis of institutional affiliations reveals the universities and research centers most active in the field of tin sulfide (SnS) solar cells (Fig. 12). Chonnam National University (South Korea) leads the way with 35 publications, followed by Islamic Azad University (18 articles) and National Taiwan University (14 articles). The majority of the most productive institutions are located in Asia, reflecting the strategic interest of this region in the development of low-cost, low-environmental-impact photovoltaic technologies. Some African institutions, such as the University of the Witwatersrand (South Africa) and the University of Algiers (Algeria), also appear in the ranking. These contributions indicate a growing involvement of developing countries in renewable energy research. Several Asian and international universities are actively collaborating within co-publication networks, as shown by the visible connections between the different nodes of the affiliation graph. This network reflects a dynamic of collaborative research on a global scale in the field of SnS solar cells.

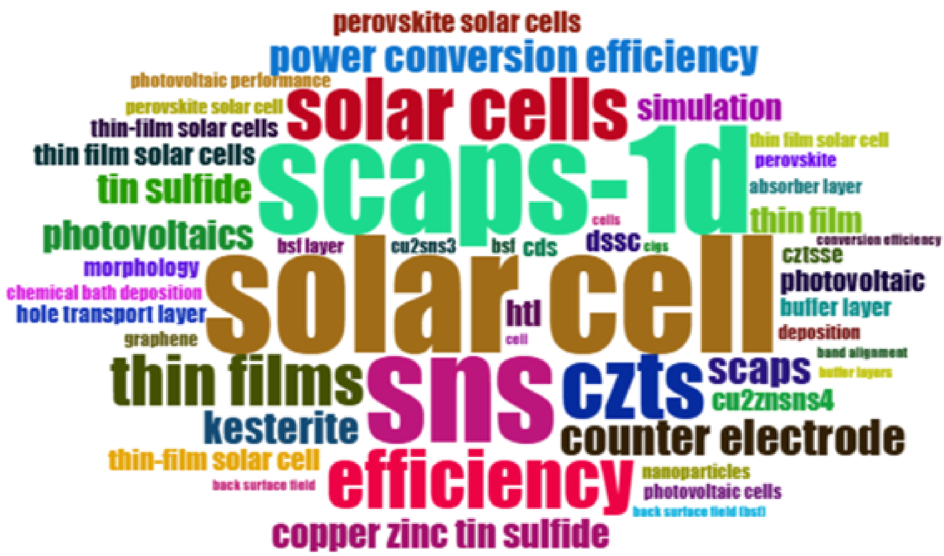


Fig. 13. word cloud including the 50 most common words

4.4.2 Keyword co-occurrence network author keywords

This co-occurrence map highlights the conceptual structure of research on SnS-based solar cells. The most central keywords are SnS, solar cell and scaps-1d, reflecting their importance in recent scientific literature. The red cluster, strongly connected to scaps-1d, groups together technical terms related to numerical simulation and heterojunction engineering (back surface field, perovskite, HTL, CIGS). The purple cluster, centred on SnS and solar cell, reflects general experimental approaches. Other distinct groups (orange, green, blue) address specific aspects such as buffer materials (CdS, ZnS, Cu_2ZnSnS_4), the morphology of active layers, and stability (graphene, dssc). This network highlights the multidisciplinary nature of the field, the growing importance of simulation tools,

Table 3. 15 most frequently used keywords in the last 10 years

Rank	Author Keywords (Occurrences)	Keywords Plus (Occurrences)	Abstract Keywords (Occurrences)	Title Keywords (Occurrences)
1	solar cell (32)	performance (54)	solar (677)	solar (213)
2	scaps-1d (29)	efficiency (52)	sns (441)	cells (137)
3	SnS (28)	thin-films (37)	efficiency (430)	cell (75)
4	czts (19)	tin compounds (32)	cells (394)	performance (74)
5	solar cells (17)	iv-vi semiconductors (31)	layer (394)	sns (65)
6	efficiency (16)	layered semiconductors (31)	cell (352)	layer (50)
7	thin films(14)	sulfur compounds (27)	performance (256)	thin (50)
8	counter electrode (10)	deposition (25)	films (245)	efficiency (46)
9	kesterite (9)	temperature (24)	conversion (237)	photovoltaic (45)
10	power conversion efficiency (9)	fabrication (9)	czts (231)	tin (39)
11	scaps (9)	optical-properties (23)	power (213)	film (36)
12	copper zinc tin sulfide (8)	solar cells (23)	thin (201)	sulfide (33)
13	photovoltaics (8)	thin films (23)	photovoltaic (189)	based (29)
14	tin sulfide (8)	growth (22)	tin(184)	films (28)
15	htl (7)	copper compounds (21)	absorber (183)	perovskite (28)

and the diversification of architectures and materials used to ienhance the efficiency of SnS-based photovoltaic devices.

It is important to note that the appearance of terms such as CZTS and perovskite within the keyword and co-occurrence analysis does not indicate a move away from the dominant SnS focus of the dataset, but rather they appear as a natural neighbor to SnS because they are discussed within a comparative architecture, transport layer, or broader heterojunction engineering context. Their bibliometric presence therefore reflects thematic adjacency within the literature, not a redefinition of the corpus itself.

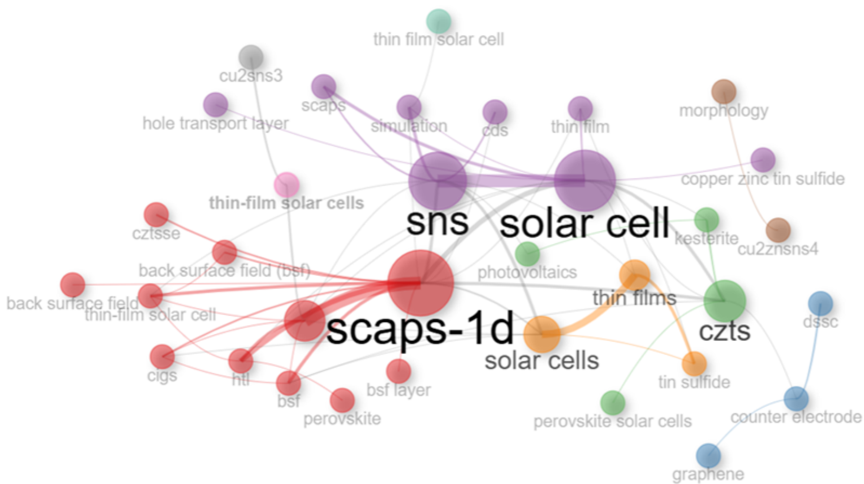
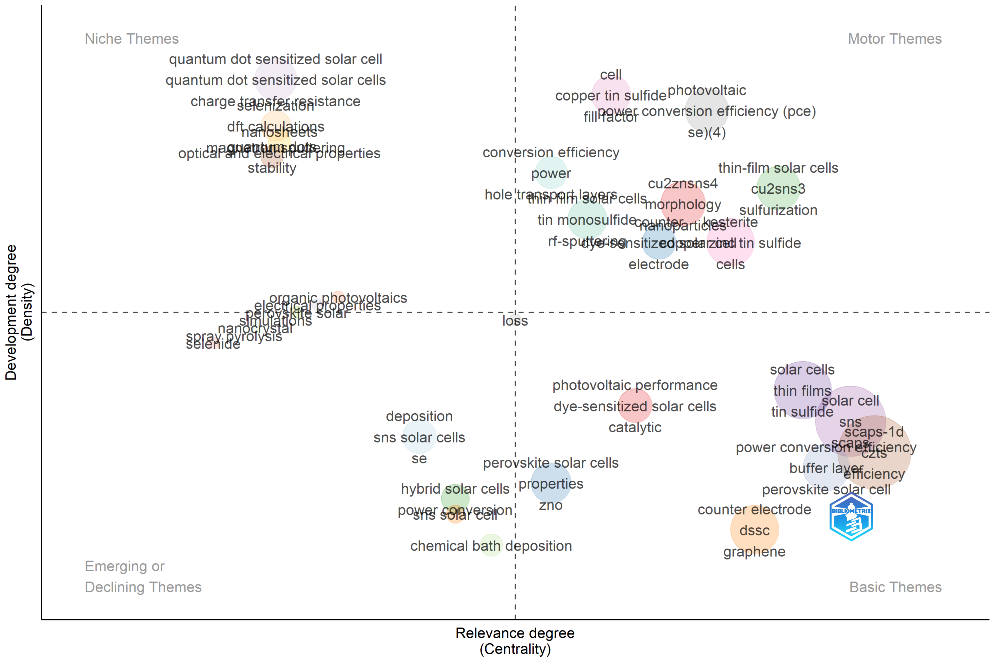


Fig. 14. Co-occurrence map of author keywords in research on SnS-based solar cells

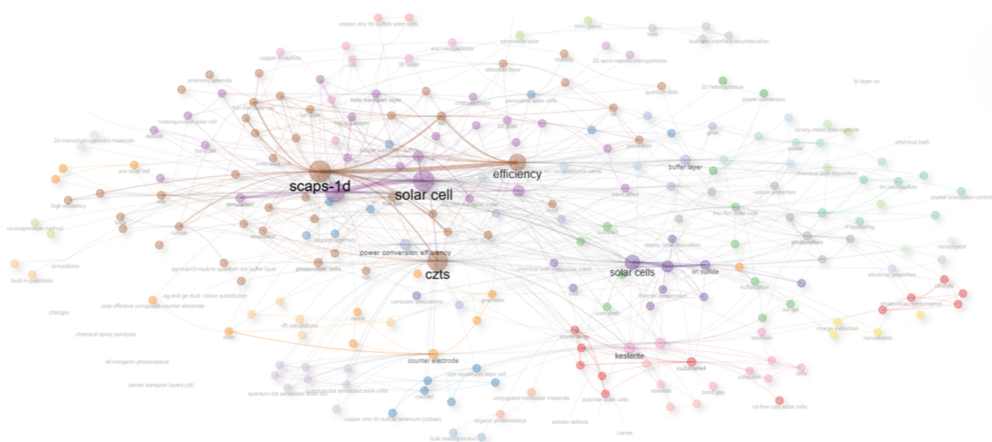
4.4.3 Thematic evolution

Thematic analysis enables the mapping and monitoring of research trends in the research area of SnS-based solar cells over the period 2015-2025. This study is based on two approaches: thematic mapping and temporal analysis of author keywords (trend topics).

Thematic mapping The Fig. 15. below show two complementary visualizations resulting from the analysis of keyword co-occurrences: a thematic map (a) and a thematic network (b). These representations were generated from metadata extracted from Scopus and Web of Science databases, processed using the Bibliometrix-R tool and visualised using VOSviewer. The thematic map is constructed on two main axes: Centrality (horizontal axis) indicates the importance of a theme within the overall network (linked to other themes).and Density (vertical axis) reflects the level of internal growth of the theme (maturity of the associated scientific content).



(a) Thematic map



(b) Keyword network map

Fig. 15. Thematic map (a) and keyword network map (b) illustrating the structure of research topics on SnS-based solar cells.

The thematic analysis highlights four main categories. Motor Themes bring together well-established and central topics such as scaps-1d, conversion efficiency and hole transport layer. These themes structure current advances, particularly in the simulation and optimization of SnS cells. Basic Themes, such as SnS, thin film solar cells and photovoltaic performance, are widely explored but remain general in their specialization. Niche Themes, including quantum dot sensitised solar cells and charge transport, are more targeted areas but are not closely connected to the rest of the field, and may either evolve in depth or remain marginal. Finally, Emerging or Declining Themes, such as chemical bath deposition and hybrid solar cells, appear to be less developed, indicating either a recent start or a loss of interest.

In addition, the network map highlights the direct links between keywords. The main cluster revolves around scaps-1d, solar cell, efficiency and SnS, reflecting the core of current research[19]. Other thematic clusters emerge around terms such as CZTS, counter electrode and graphene, reflecting the diversity of approaches and the wealth of avenues explored[20]. Taken together, this suggests a strong interconnection between concepts and a growing interdisciplinary dynamic in the SnS-based solar cell field.

Temporal analysis of themes (Trend Topics) The temporal analysis (Fig. 16) allows us to visualize the emergence and evolution of research topics over the years.

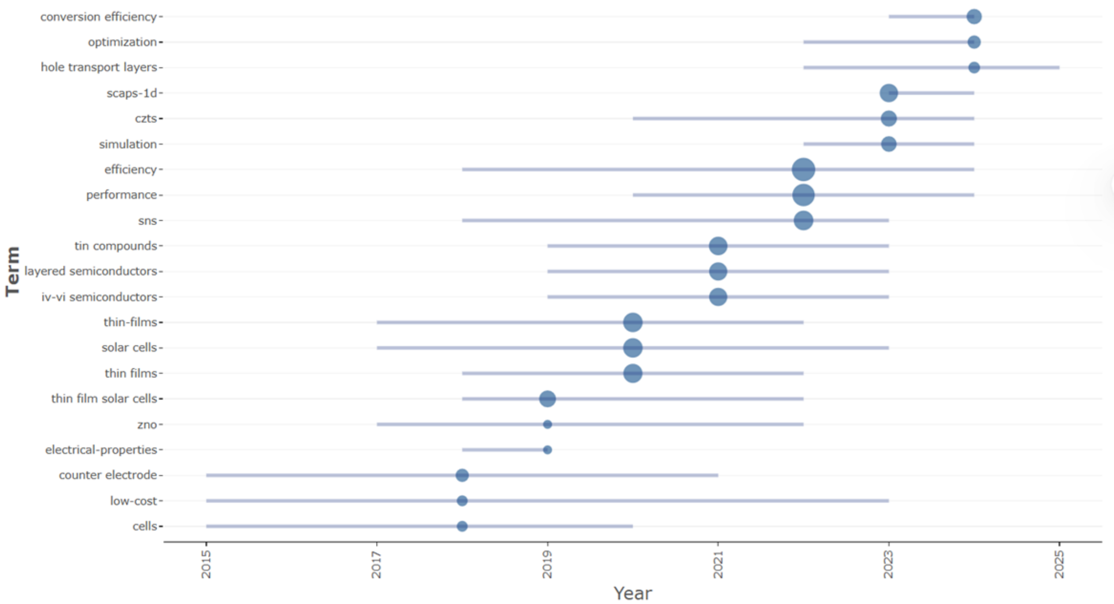


Fig. 16. Trend Topics showing the temporal evolution of major keywords in the last 10 years.

- 2015–2018: exploratory phase dominated by generic terms such as thin films, solar cells, low-cost, and electrical properties, reflecting a desire for broad, unspecialized exploration.
- 2019–2021: structuring period marked by the appearance of more specific keywords such as simulation, performance, tin compounds, and IV-VI semiconductors, directing work towards materials issues and advanced modelling.
- 2022–2025: phase of technological intensification. The keywords conversion efficiency, hole transport layers, scaps-1d, and czts dominate, highlighting efforts to optimise performance and the increased use of numerical simulations to guide device design.The notable rise of 'scaps-1d' as a motor theme during this period, for instance, can be partly attributed to the influence of highly cited simulation studies, such as the work by Minbashi et al. (2018) referenced in Table 3, which demonstrated the power of the SCAPS software in designing high-efficiency SnS device architectures and set a benchmark for subsequent modeling efforts.

These trends confirm the rise of research focused on the efficiency, stability, and integration of new SnS-based optoelectronic architectures.

If the entirety of the thematic evolution is considered, a clear pattern of maturation in the field is seen. The initial period (2015-2018) saw general keywords such as thin films, solar cells, and electrical properties, which is consistent with a foundational period of material discovery. The second period (2019-2021) saw a more structured set of keywords such as simulation, performance, tin compounds, and IV-VI semiconductors, which is consistent with a mechanistic level of understanding and device modeling. The most recent period (2022-2025) saw a strong presence of keywords such as conversion efficiency, hole transport layers, SCAPS-1D, and CZTS, which is consistent with a performance-based engineering approach. In other words, the field has moved from an exploration of the nature and properties of SnS to an exploration of how to improve SnS devices and, most recently, to an exploration of how to improve device performance by architectural design.This trajectory also helps explain why SCAPS-1D now appears as a motor theme: it has become a central tool for accelerating device-level optimization.

4.5. Journal analysis

4.5.1 Most cited journals

The table above exhibits the ten most active journals in the research area of SnS-based solar cells between 2015 and 2025. These journals stand out not only for the number of publications (TP) but also for their impact as measured by total citations (TC), the h-index, the CiteScore 2024, and the most influential article published.

Journal	h_index	TP	TC	Cite Score (2024)	The most cited article (reference)	Times cited	publisher
SOLAR ENERGY	12	16	619	12.6	Simulation of high efficiency SnS based solar cells with SCAPS (Minbashi, M. et al., 2018)	121	Elsevier
THIN SOLID FILMS	6	11	152	3.9	Sol-gel processed CZTS thin film solar cell on flexible molybdenum foil (Dong, L. et al., 2017)	44	Elsevier
JOURNAL OF ALLOYS AND COMPOUNDS	9	9	275	11.8	Performance analysis of SnS solar cell with a hole transport layer based on experimentally extracted device parameters (Hosen, A. et al., 2022)	54	Elsevier
OPTICAL MATERIALS	4	9	92	6.8	Simulation of high-efficiency SnS-based dual-heterojunction thin film solar cells using SCAPS (Kuddus, A. et al., 2021)	47	Elsevier
JOURNAL OF ELECTRONIC MATERIALS	7	8	420	3.6	Performance Analysis for SnS and Sn_2S_3-Based Back Surface Field CZTSSe Solar Cell: A Simulation Study (Gohri, S. et al., 2021)	61	SPRINGER
JOURNAL OF MATERIALS SCIENCE-MATERIALS IN ELECTRONICS	5	8	93	4.2	Facile synthesis of SnS nanostructures with different morphologies for supercapacitor and dye sensitized solar cell applications (Dar, M. A. et al., 2021)	55	SPRINGER
SOLAR ENERGY MATERIALS AND SOLAR CELLS	5	8	99	12.4	Impact of Urbach energy on open-circuit voltage deficit of thin-film solar cells (Chantana, J. et al., 2020)	164	Elsevier
APPLIED SURFACE SCIENCE	6	7	89	13.4	Tin sulfide (SnS) nanostructured films deposited by continuous spray pyrolysis (CoSP) technique for dye sensitized solar cells applications (Alam, F. et al., 2015)	36	Elsevier
ACS APPLIED ENERGY MATERIALS	5	6	89	10.2	SnS Quantum Dots as Hole Transporter of Perovskite Solar Cells (Li, Y. et al., 2019)	30	ACS Publications
JOURNAL OF MATERIALS CHEMISTRY A	5	6	338	21	All-inorganic CsPbBr3 perovskite solar cell with 10.26% efficiency by spectra engineering (Yuan, H. et al., 2018)	210	ROYAL SOC CHEMISTRY

Among them, Solar Energy stands out for its high productivity and number of citations, while Journal of Materials Chemistry A has the highest CiteScore and the most cited article. There is also a clear dominance of the publisher Elsevier, followed by Springer, ACS Publications and RSC.

The flagship articles published mainly address simulation (SCAPS), active layer optimization, SnS nanostructure synthesis and optical loss reduction. These results confirm the growing interest in SnS in the development of sustainable and low-cost photovoltaic technologies.

4.5.2 Journal co-citation network

The Fig. 17 shows the co-citation network of the main journals publishing on SnS-based solar cells. Solar Energy occupies a central position, strongly connected to journals such as Thin Solid Films, Applied Surface Science and Journal of Alloys and Compounds. This centrality highlights its key role in disseminating and structuring knowledge in this field. The network also reveals the existence of a core group of specialised journals forming a coherent and influential publication space for SnS research. This type of analysis helps to identify the most relevant journals for publication and scientific monitoring.

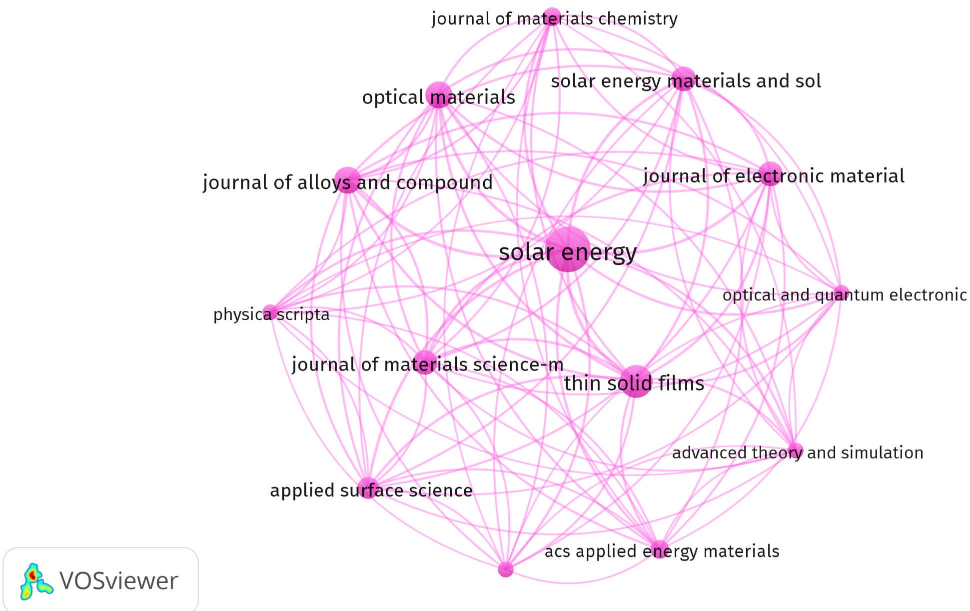


Fig. 17. Co-citation network among leading scientific journals in the field of SnS-based solar cells.

5. Conclusion

This bibliometric study provided an in-depth exploration of recent advances in improving the efficiency of tin sulfide (SnS) solar cells over the period 2015-2025, using data from the Scopus and Web of Science databases. Using the Bibliometrix-R tool, the data were analyzed along several axes: author productivity, international collaborations, and keyword analysis. A total of 266 articles were reviewed, revealing a significant growth in scientific output and growing community interest in SnS, a promising material for thinfilm solar cells due to its abundance, non-toxicity, and favorable optoelectronic properties.

The study highlighted the leading countries and institutions (including China, India, Korea, and Bangladesh), the most influential researchers, and the collaborative networks structuring this field of research. Keyword analysis identified major themes such as deposition method optimization, SCAPS-1D simulation, heterojunction engineering, defect passivation, and active layer architecture. Emerging topics such as stability improvement, recombination loss reduction, and SnS integration into novel tandem architectures were also identified, highlighting both persistent challenges and future research directions.

5.1. Implications and Actionable Recommendations

The findings of this bibliometric analysis offer several concrete implications and actionable recommendations for key stakeholders in the SnS solar cell ecosystem.

a. For Researchers:

- **Prioritize Research on Critical Gaps**: Our analysis highlights that while research on ”conversion efficiency” is a mature motor theme, topics like long-term stability and scalability are significant and persistent research gaps. To validate this, a quantitative keyword search of the abstracts in our final dataset was conducted. This revealed that terms related to ’stability,’ ’degradation,’ or ’longevity’ appeared in less than 15% of the articles, while terms related to ’scalability,’ ’large-area,’ or ’industrial production’ were present in fewer than 5%. This stark quantitative gap underscores the urgent need for future experimental work to prioritize these areas to move SnS technology closer to commercial viability.
- **Explore Emerging Thematic Intersections**: The thematic map (Fig. 15) shows strong clusters around simulation (”scaps-1d”) and specific materials (”czts,” ”perovskite”). A promising and underexplored research direction lies at the intersection of these themes—for example, using advanced numerical modeling to design and optimize novel SnS-based tandem architectures with materials like perovskites.
- **Revitalize Niche Areas**: Themes such as ”quantum dot sensitized solar cells” and ”charge transport” were identified as niche topics. Integrating these concepts with mainstream device architectures could unlock novel pathways for efficiency enhancement.

b. For Policymakers and Funding Agencies:

- **Target Funding to Overcome Key Hurdles**: To accelerate progress, funding priorities should be strategically directed towards the critical gaps identified, specifically programs focused on improving the operational stability of SnS devices and developing cost-effective, large-scale deposition techniques.
- **Foster International and Interdisciplinary Collaboration**: The geographical concentration of research, primarily in Asia (Fig. 9, 11), presents both a strength and a risk. We recommend launching targeted funding initiatives that incentivize North-South and South-South collaborative projects. This will not only balance the global research landscape but also diversify approaches to solving shared scientific challenges.
- **Support Simulation-Driven Research**: The prominence of ”SCAPS-1D” confirms the critical role of simulation in modern materials science. Funding programs should continue to support research that combines experimental work with robust theoretical modeling, as this dual approach is clearly a cornerstone of high-impact research in this field.

c. For Industry:

- **Focus R&D on High-Impact Technologies**: The frequent appearance of keywords like ”heterojunction engineering,” ”hole transport layer,” and ”buffer layer” in high-impact journals (Table 3) suggests these are the most promising avenues for achieving certifiable efficiency gains. Industrial R&D investment could be strategically focused on optimizing these device components.
- **Identify Strategic Academic Partners**: The list of the most productive institutions and influential authors (Fig. 5, 12) serves as a clear map for industry to identify key opinion leaders and potential academic partners for collaborative research, technology licensing, and talent recruitment.
- **Monitor Tandem Architecture Developments**: The emergence of ”CZTS” and ”perovskite” as key themes indicates a strong trend towards tandem and multi-junction architectures. Industry players should closely monitor these developments, as they represent the most likely path to surpassing the efficiency limits of single-junction SnS cells.

5.2. Methodological Limitations and Biases

However, this study has certain limitations that must be critically acknowledged. The Scopus and Web of Science databases, while comprehensive, do not cover all of the world's scientific literature, and our search was restricted to English-language publications, potentially underrepresenting valuable contributions from other linguistic regions. Furthermore, the precision of our results is dependent on the metadata provided by authors and publishers. The search query itself, while carefully constructed, introduces a potential bias; studies on SnS solar cells using alternative terminology may have been inadvertently excluded, shaping the resulting dataset. Finally, our focus on academic journal articles means that innovations captured in patents, industry reports, or conference proceedings are not reflected in this analysis. These factors suggest that our study provides a robust map of the academic research landscape, but not a complete picture of all innovation occurring in the field of SnS solar cells.

In addition, the robustness of bibliometric results is subject to the reliability of the metadata. Variations in keyword allocation, naming conventions for authors, formatting of institutional information, indexing schemes, and citation recording between databases can influence the results on co-occurrence maps, citation-based measures, and collaboration networks. Therefore, the present results must be viewed as an organized representation of the indexed literature rather than an entirely flawless or comprehensive reconstruction of the entire research landscape.

This bibliometric analysis reveals that SnS-based solar cell research has progressed from a stage of emphasis on material exploration to more emphasis on device optimization, in which simulation tools such as SCAPS-1D have been found to play a major catalytic role. However, the pace of research on simulation has not been matched by a corresponding increase in research on the issues of long-term stability and manufacturability, which are major hurdles for the practical use of SnS-based solar cells. Thus, there has been rapid progress in the conceptual and design aspects of SnS-based solar cells, but there is a definite imbalance in the pace of progress.

5.3. Future Directions

Future research should build directly on the bibliometric patterns identified in this study. Given the emergence of SCAPS-1D as a motor theme and the strong concentration of recent work around conversion efficiency and device architecture, the next step should be to use validated simulation frameworks not only to maximize efficiency, but also to predict defect sensitivity, operational stability, and the performance of larger-area devices under realistic conditions. At the same time, the relatively small emphasis on topics related to scalability and long-term durability suggests that these topics are not adequately addressed, in spite of their central importance for technological translation. An avenue for future bibliometric research consists in combining manual thematic analysis with statistical comparisons of subdomains such as efficiency enhancement, durability, scalability, and defects.

To further elevate the analytical rigor of bibliometric studies in this field, future reviews should move beyond descriptive mapping toward statistical gap analysis. We recommend that subsequent inquiries employ manual thematic coding to categorize publications into precise sub-domains (e.g., stability, scalability, defect engineering). Applying inferential statistical methods, such as Chi-square tests, to these categories would allow researchers to quantitatively compare thematic distributions across time periods. This approach would verify the statistical significance of the disparities between efficiency-focused studies and those addressing practical deployment challenges, thereby providing a robust evidence base to guide future funding and strategic research priorities.

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