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Review Article

Evolution of Two-Dimensional Perovskite Solar Cells: A Bibliometric Analysis of Research Trends and Collaborations

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Abstract

Rapid advancement of two-dimensional perovskite solar cells (2D PSCs) has established them at the forefront of emerging next-generation solar cell technologies. This is primarily due to their exceptional environmental stability, high efficiency, tunable band gap, and versatile optoelectronic properties. This paper presents a comprehensive bibliometric analysis to map the intellectual landscape and evolutionary trajectory of 2D PSC research. Relevant data for the work were obtained from the Scopus database. The analytical capabilities of MetaInfoSci software were used to quantify publication trends, international collaboration networks, and other trends in the research field of 2D PSCs. Analysis of the corresponding results shows exponential growth in annual publications, signaling the research area's emerging significance within the global community of researchers. The results reveal a consistent focus by scientists on lead-free compositions, 2D/3D heterostructures, and interface engineering over the previous decade. This study provides a systematic, data-driven overview of the field's development, serving as a strategic roadmap to identify foundational contributions, current research priorities, and emerging frontiers for researchers and regulators.

Categories: Renewable Energy Systems

Keywords: two-dimensional perovskite solar cells, scopus, bibliometric analysis, publication, collaboration

Introduction And Background

The twin challenges of dwindling fossil fuel reserves and escalating carbon pollution are driving a global move toward renewable energy technologies. Among the various renewable sources, solar energy is one of the most promising solutions due to its abundance, scalability, and minimal environmental footprint. Solar power is now deployed across diverse geographical regions, ranging from technologically advanced metropolitan cities in Europe to arid regions of the Sahara Desert. It is being considered a remedy to the emerging energy crisis, particularly that driven by demand from developing economies such as India and China. In 2022, renewable energy accounted for about 30% of the total electricity generated worldwide, of which the share of solar energy was approximately 4.5% [1-3]. The efficiency of conversion of solar energy into electricity depends on photovoltaic (PV) devices, commonly known as solar cells. They operate on the principle of the PV effect to convert solar radiation into electrical energy [4]. The invention of the first solar cell was reported in 1954 at Bell Labs [5]. It was a silicon (Si)-based solar cell having a power conversion efficiency (PCE) of 6%. The performance of these devices is fundamentally governed by the optoelectronic properties of the photoactive materials employed. In recent years, perovskite materials have emerged as one of the most extensively investigated classes of semiconductors for PV applications. The mineral was initially discovered by Gustavus Rose in 1839 [6]. Since then, this mineral has been widely researched, and various compositions have been synthesized/simulated for developing high-efficiency solar cells.

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Perovskite solar cells (PSCs) have rapidly evolved into a dominant research area in modern PV technologies due to their exceptional optoelectronic properties, defect-tolerant electronic structure, tuneable bandgap, and low-temperature solution fabrication [7]. They are reshaping the future of efficient green technology. Since their first demonstration in 2009, with an efficiency of 3.8% [8], PSC efficiencies have increased continuously and now exceed 26% [9,10], positioning them as strong contenders for next-generation thin-film PVs. The ABX_3 perovskite lattice has special characteristics [3], including high absorption coefficients, low exciton-binding energy, long carrier diffusion lengths, and balanced electron-hole mobility, making it a promising material for single-junction, tandem, and flexible modules [11]. These features enable PSCs to emerge as a highly efficient solar cell technology. Research in this sector has achieved significant progress through compositional engineering, particularly mixed-cation and mixed-halide formulations, which significantly enhance phase stability, moisture tolerance, and thermal robustness [12,13]. Concurrently, solvent engineering, additive engineering, and crystallization control have resulted in high-quality perovskite films with reduced trap densities and improved charge transport characteristics [14].

Conventional three-dimensional (3D) perovskites suffer from various issues such as intrinsic stability challenges, halide segregation, ion migration, electrode corrosion, and degradation under prolonged operational conditions [15]. These drawbacks pose significant barriers to their large-scale commercialization. To resolve these issues, two-dimensional (2D), Ruddlesden-Popper, Dion-Jacobson (DJ), low-dimensional, and quasi-2D perovskite architectures have emerged as transformative alternatives. In 2D perovskites, bulky organic spacer cations are incorporated into the perovskite lattice, forming layered structures that exhibit high hydrophobicity, suppressed ion migration, and improved structural integrity [16]. The integration of 2D perovskites with 3D counterparts has led to the development of 2D/3D heterostructures, which combine the excellent stability of 2D perovskites with the superior charge transport properties of 3D perovskites. These heterostructures effectively passivate surface and grain-boundary defects, reduce non-radiative recombination, and optimize energy-level alignment at interfaces, thereby increasing efficiency and operational stability [17]. As a result, 2D/3D architectures have become the most sought-after research theme in PSC development, particularly for achieving long-term stability for more than 1000 hours of continuous illumination.

The explosive growth, interdisciplinary reach, and expanding diversity of research in the field of 2D PSCs call for an urgent, systematic, and quantitative exploration of the field's scientific terrain. Bibliometric and scientometric analysis provides a data-driven approach to map various publication trends and collaboration networks. Also, data related to influential contributors and emerging research scientists can be analyzed. Through the use of the Scopus database and the advanced analytical toolset present in MetaInfoSci [18] software, current research endeavors can be analyzed to understand not only the intellectual structure but also the evolutionary path taken by research on 2D PSCs. Other analytical tools employed for obtaining deeper insights into the research area of interest are keyword co-occurrence analysis, collaboration mapping, and cluster mapping. Overall, this research aims to reveal and isolate fundamental studies, core research trends, and new research avenues in the field of 2D PSCs. The insights derived from bibliometric and scientometric assessments will serve as a strategic roadmap for researchers, funding agencies, government officials, and policymakers engaged in advancing stable, efficient, and sustainable perovskite PV technologies.

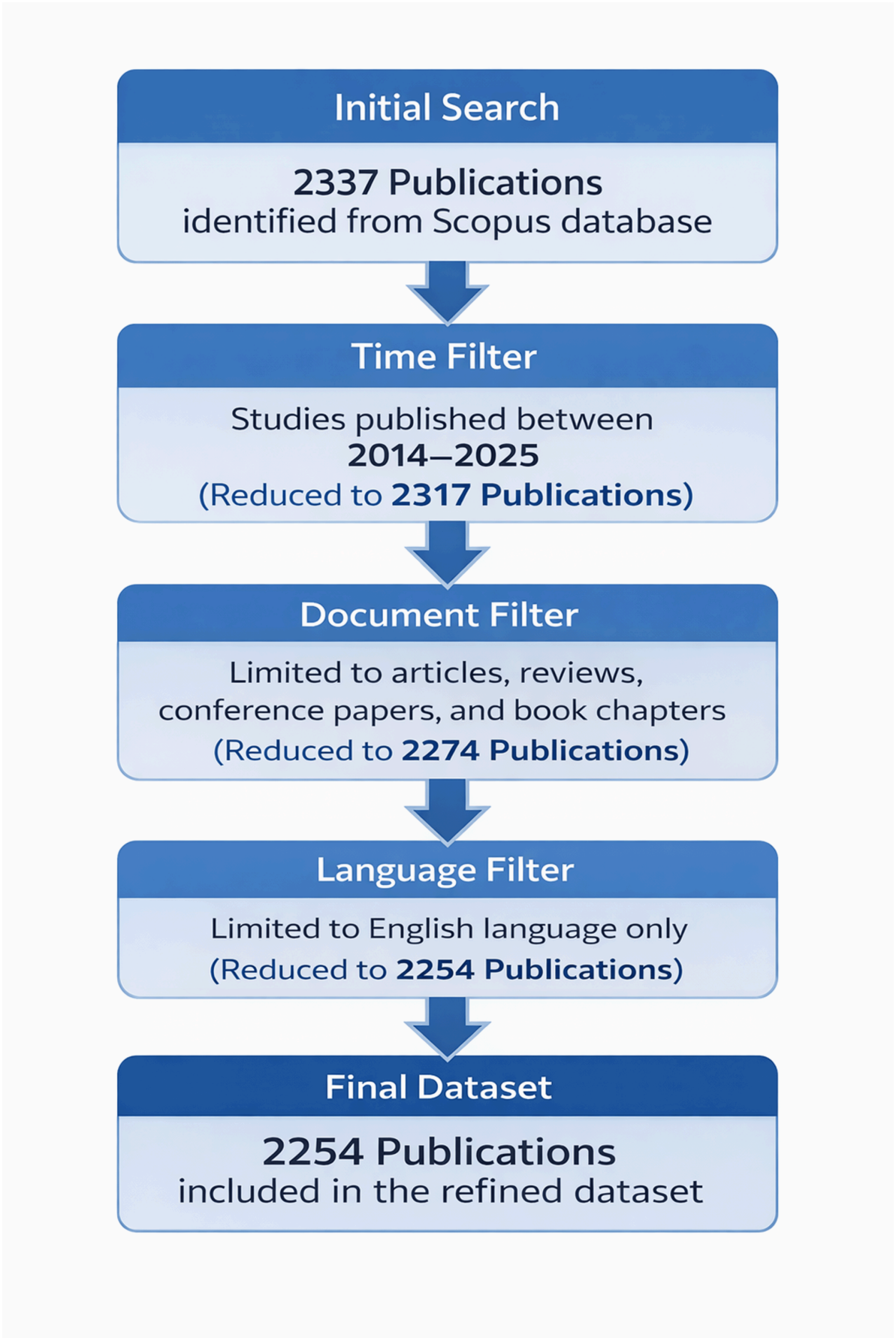
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Methodology

Document Type	Number of Publications		Number of Citations	Number of Publications			
				Open Access Type		Subscription Type	
	Count	%		Count	%	Count	%
Article	1,981	87.89	91,673	630	31.80	1351	68.20
Conference paper	58	2.57	42	10	17.24	48	82.76
Review	198	8.78	15,161	79	39.90	119	60.10
Book chapter	17	0.75	49	2	11.77	15	88.23

TABLE 1: Distribution of publications as per document category

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FIGURE 1: Flowchart showing steps of article filterations used in present work

Bibliometric and scientometric [19] analysis of a research topic of interest requires systematic data collection, which scientists perform through online scholarly databases such as Scopus, Google Scholar, Web of Science, etc. Scopus [20] is one of the biggest interdisciplinary online databases, containing a large collection of academic data. Additionally, it also offers complete and standardized data, which is why it is frequently used by academicians for data collection. The construction of keyword strings for searching databases is the most difficult part of a bibliometric study, as it determines the quantity and correlation of the data with the concerned research field [21]. In this study, the string (TITLE-ABS-KEY(2D perovskiteOR two-dimensional perovskiteOR Ruddlesden-Popper perovskiteOR Dion-Jacobson perovskiteOR quasi-2D perovskiteOR 2D/3D perovskiteOR low-dimensional perovskite) AND TITLE-ABS-KEY(solar cellOR photovoltaic)) AND (LIMIT-TO (DOCTYPE,ar) OR LIMIT-TO (DOCTYPE,re) OR LIMIT-TO (DOCTYPE,cp) OR LIMIT-TO (DOCTYPE,ch)) AND (LIMIT-TO (LANGUAGE,English)) AND PUBYEAR > 2014 AND PUBYEAR < 2025 was used on the Scopus database to extract the data. The total number of publications obtained after implementation of this string was 2,337. A time-based filter was first used to include only studies published between 2014 and 2025. As a result, a few records from 2009 to 2013 and early 2026 were excluded, reducing the dataset to 2,317 documents. Subsequently, the document type was restricted to articles, review papers, conference papers, and book chapters. Finally, limiting the language to English only resulted in a refined dataset comprising 2,254 publications. Figure *1* provides a flowchart showing the steps by which the final articles were identified after various filters. Table *1* provides information about the open-access and subscription status of these publications. Data associated with these publications, including names, titles, abstracts, sources, keywords, and cited references, were exported in CSV format. Finally, the set of 2,254 publications was analyzed to retrieve scientific information and identify research gaps using MetaInfoSci [18]. Gephi [22] software was also used on the collected data for visualization of the author network.

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Review

Publication and citation growth

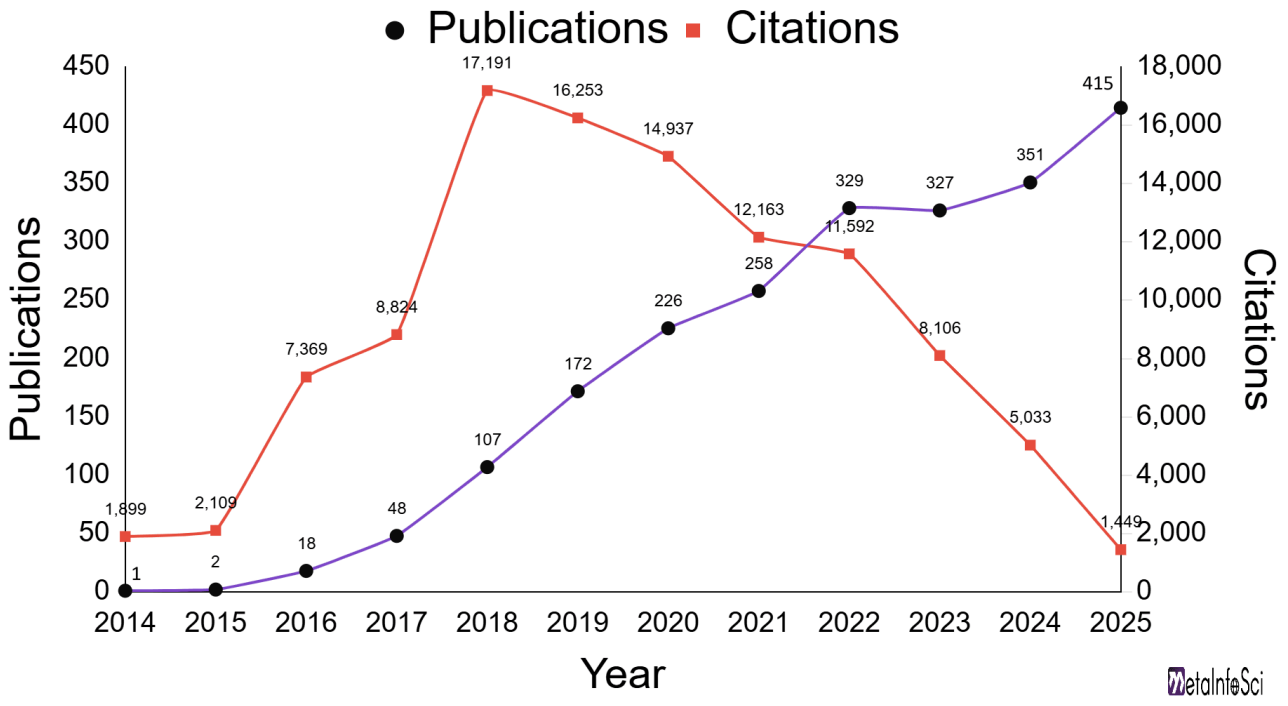


FIGURE 2: Year-wise publications and citations of two-dimensional perovskite solar cells

Figure *2* shows the annual trend in citations and publications for the 12-year period from 2014 to 2025. Initially, no significant work was done before 2015, as the first PSC was discovered in 2009. Publications in this field increased substantially only after 2015. After 2017, there was a significant increase in citations, indicating that many researchers were becoming interested in this research area. The number of publications decreased after 2018, while the number of citations increased as time passed. A total of 2,254 publications were produced, reflecting a sustained and substantial research output. Collectively, these publications have garnered 106,925 citations, indicating a remarkably high level of academic visibility and influence within the research community. The average citation rate of 47.44 citations per publication further underscores the strong impact, quality, and relevance of the individual studies. The previous years have witnessed extensive growth in academic publications in this area, primarily due to the demand for clean and renewable energy across the globe.

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Authors	Title	Year	Journal	Total Citations	Document Type	Journal Quartile
Tsai et al. [23]	High-Efficiency Two-Dimensional Ruddlesden-Popper Perovskite Solar Cells	2016	Nature	3,099	Article	Q1
Cao et al. [16]	2D Homologous Perovskites as Light-Absorbing Materials for Solar Cell Applications	2015	Journal of the American Chemical Society	2,009	Article	Q1
Smith et al. [24]	A Layered Hybrid Perovskite Solar-Cell Absorber with Enhanced Moisture Stability	2014	Angewandte Chemie International Edition	1,899	Article	Q1
Quan et al. [25]	Ligand-Stabilized Reduced-Dimensionality Perovskites	2016	Journal of the American Chemical Society	1,322	Article	Q1
Wang et al. [26]	Efficient Ambient-Air-Stable Solar Cells with 2D-3D Heterostructured Butylammonium-Caesium-Formamidinium Lead Halide Perovskites	2017	Nature Energy	1,316	Article	Q1

Mao et al. [27]	Hybrid Dion-Jacobson 2D Lead Iodide Perovskites	2018	Journal of the American Chemical Society	868	Article	Q1
Grancini et al. [15]	Dimensional Tailoring of Hybrid Perovskites for Photovoltaics	2019	Nature Reviews Materials	847	Review	Q1
Zhao et al. [28]	High-Efficiency Perovskite-Polymer Bulk Heterostructure Light-Emitting Diodes	2018	Nature Photonics	825	Article	Q1
Zhang et al. [29]	Additive Engineering for Efficient and Stable Perovskite Solar Cells	2020	Advanced Energy Materials	727	Review	Q1
Chen et al. [30]	In Situ Growth of 2D Perovskite Capping Layer for Stable and Efficient Perovskite Solar Cells	2018	Advanced Functional Materials	726	Article	Q1

TABLE 2: Top 10 highly cited papers on two-dimensional perovskite solar cells

Journal Name	No. of Publications	Publisher	Impact Factor	Quartile	Open Access Status
Advanced Functional Materials	122	Wiley-VCH Verlag	19	Q1	Hybrid Open Access
ACS Applied Materials and Interfaces	115	American Chemical Society	8.2	Q1	Hybrid Open Access
Advanced Materials	97	Wiley-Blackwell	26.8	Q1	Hybrid Open Access
Solar RRL	88	Wiley-VCH Verlag	4.7	Q1	Hybrid Open Access
Advanced Energy Materials	82	John Wiley and Sons Inc	26	Q1	Hybrid Open Access
Journal of Materials Chemistry A	79	Royal Society of Chemistry	9.5	Q1	Hybrid Open Access
ACS Energy Letters	63	American Chemical Society	18.9	Q1	Hybrid Open Access
Small	62	Wiley-VCH Verlag	12.1	Q1	Hybrid Open Access
ACS Applied Energy Materials	58	American Chemical Society	5.6	Q1	Hybrid Open Access
Chemical Engineering Journal	56	Elsevier B.V.	13.2	Q1	Hybrid Open Access

TABLE 3: Top 10 journals publishing research papers on two-dimensional perovskite solar cells

ACS, American Chemical Society

Publisher Name	No. of Publications		Citations	No. of Journals
	Count	%		
Wiley	531	23.55	15,192	31
American Chemical Society	402	17.83	8,258	18
Elsevier	334	14.81	8,511	49
Royal Society of Chemistry	271	12.02	10,926	16
American Chemical Society	139	6.16	18,521	8
Wiley-VCH Verlag	96	4.60	12,382	9
Nature Research	51	2.26	6,184	5
Springer	44	1.95	613	23
Institute of Electrical and Electronics Engineers	40	1.78	33	5
MDPI	36	1.60	237	7

TABLE 4: Top 10 publishers engaged in publication of research work on two-dimensional perovskite solar cells

Investigation of the distribution of journals from 2014 to 2025 indicates a high preference for the areas of materials science and energy research among the top 10 sources (Table *2*). Table *3* provides the list of the top 10 journals that publish research papers on 2D PSCs. Advanced Functional Materials is at the top with 122 publications, followed closely by ACS Applied Materials and Interfaces (115 publications) and Advanced Materials (97 publications). The journal Solar RRL has a low impact factor but has a good number of publications (88). Advanced Energy Materials has a much higher impact factor than Solar RRL but a lesser number of publications (82). Again, ACS Applied Energy Materials has a low impact factor but a good number of publications (58). Most of the journals have good impact factors, and the scopes of the journals indicate that there is a rising interest in the energy applications of 2D perovskites. One interesting observation was that all journals are Q1, with both open-access and subscription options for publications. The publishers Wiley, American Chemical Society (ACS), and Elsevier have a large number of publications, as shown in Table *4*.

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Author analysis

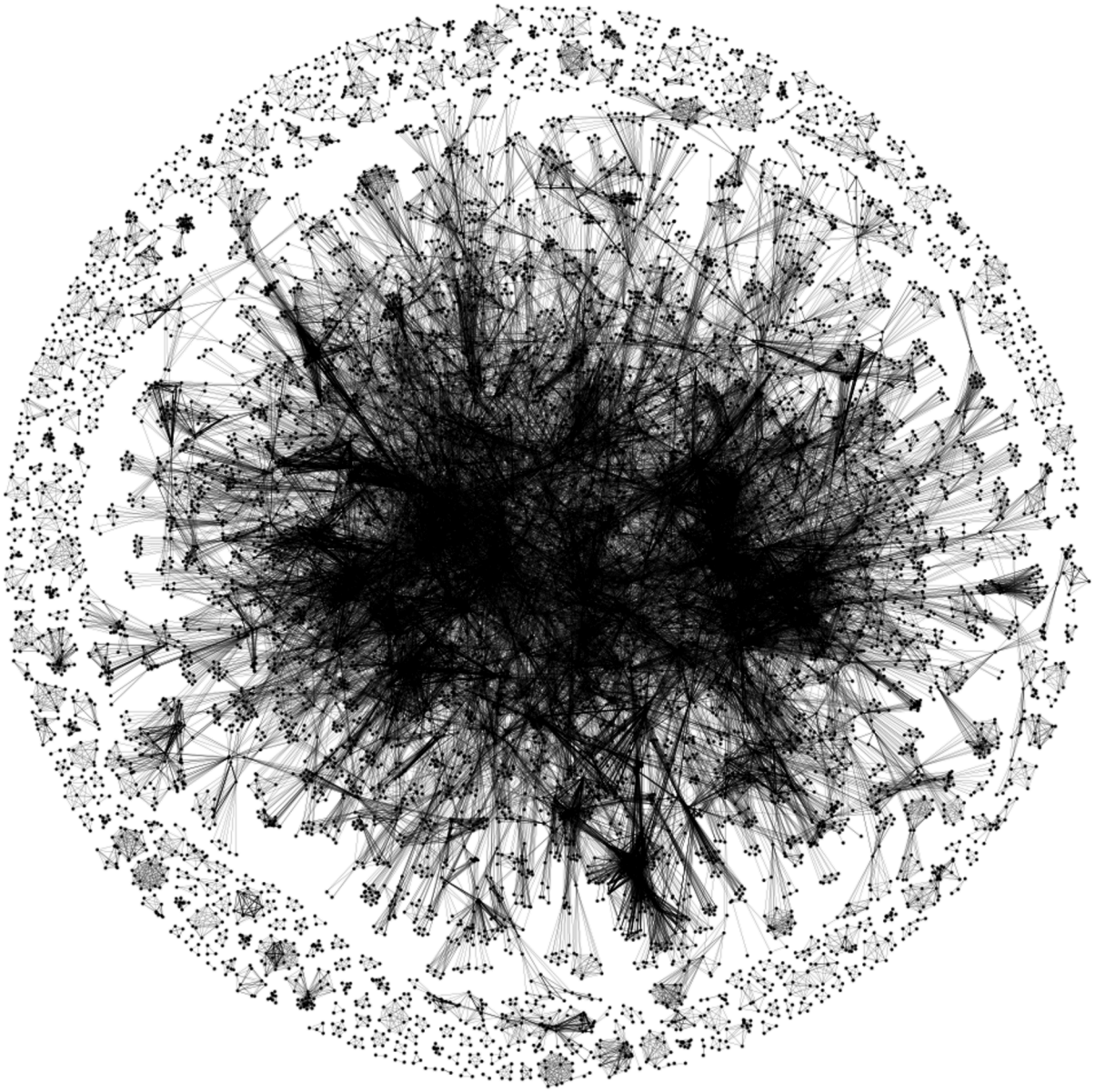


FIGURE 3: Author collaboration network

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Network Statistics	
Total nodes (authors)	10,228
Total edges (collaboration)	89,970
Average degree	14.047
Average weighted degree	17.593
Average clustering coefficient	0.879
Average path length	4.893
Network diameter	13
Modularity	0.877
Connected components	307

TABLE 5: Statistical parameters of author collaboration network

In research, collaboration between different authors plays an important role in improving the overall research quality and impact. The author collaboration network (as shown in Figure *3*) was obtained using Gephi software. The dark connections (in the center) shown in this figure represent the giant component, or the largest connected component (the largest connected part of the network). From Figure *3*, it may be observed that the author collaboration network is highly connected in nature. There are a total of 10,228 authors and 89,970 collaboration links in this figure. Table *5* provides detailed information regarding the parameters obtained after generating the author collaboration network (Figure *3*). A strong tendency toward clustering in co-authorship was observed, with an average clustering coefficient of 0.879. The giant component in the network represents almost 78% of the authors, testifying to intensive knowledge exchange and network cohesion. The moderate average path length (4.893) and diameter (13) indicate an effective flow of information across the field. At the same time, multiple smaller components reflect parallel or emergent research groups. Concomitantly, a few very prolific authors point to the critical role of central hubs that drive collaboration, visibility, and intellectual leadership within the research ecosystem.

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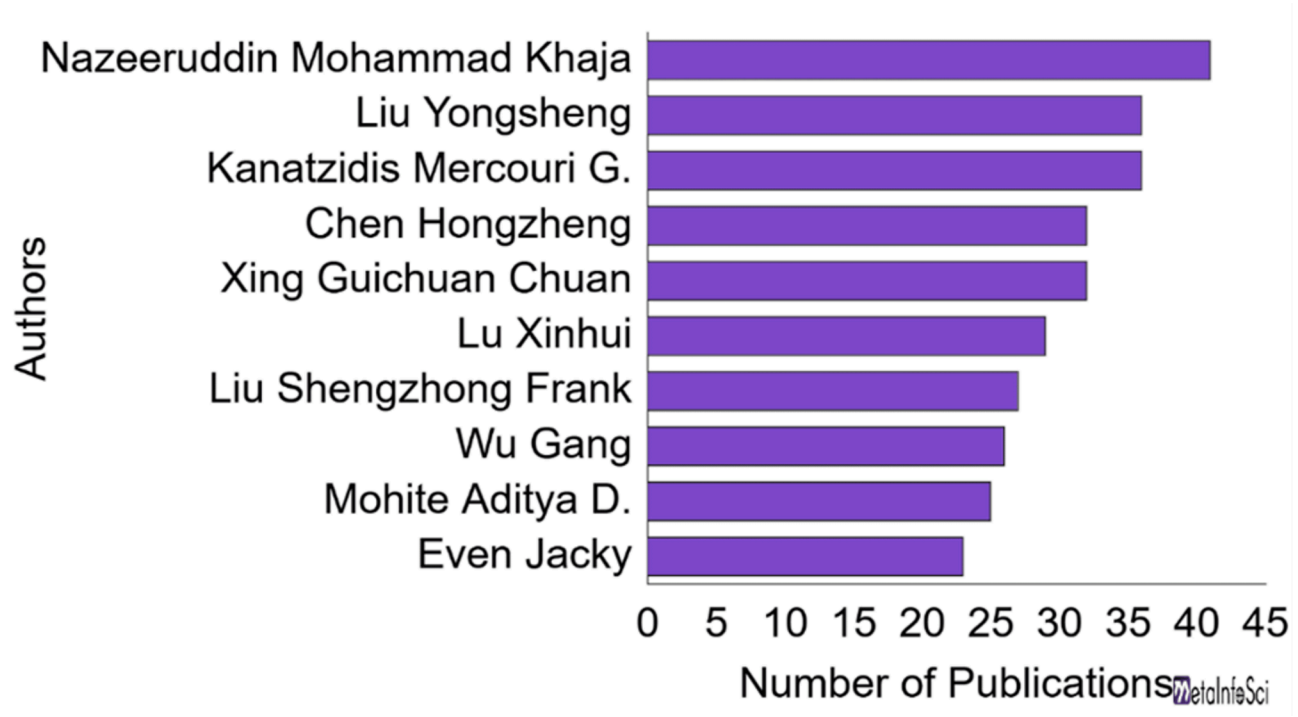


FIGURE 4: Top 10 authors working in the research field of two-dimensional perovskite solar cells

Leading contributors include Nazeeruddin Mohammad Khaja (41 publications), Liu Yongsheng and Mercouri G. Kanatzidis (36 publications combined), and Chen Hongzheng and Xing Guichuan (32 publications each). Remarkably, the top 10 authors (Figure *4*) represent merely 0.1% of the 9,657 total authors and collectively authored 307 publications (1.6% of the 18,748 total publications). The huge volume of papers by this small group places them at the top in this area, where other authors have had a more limited impact.

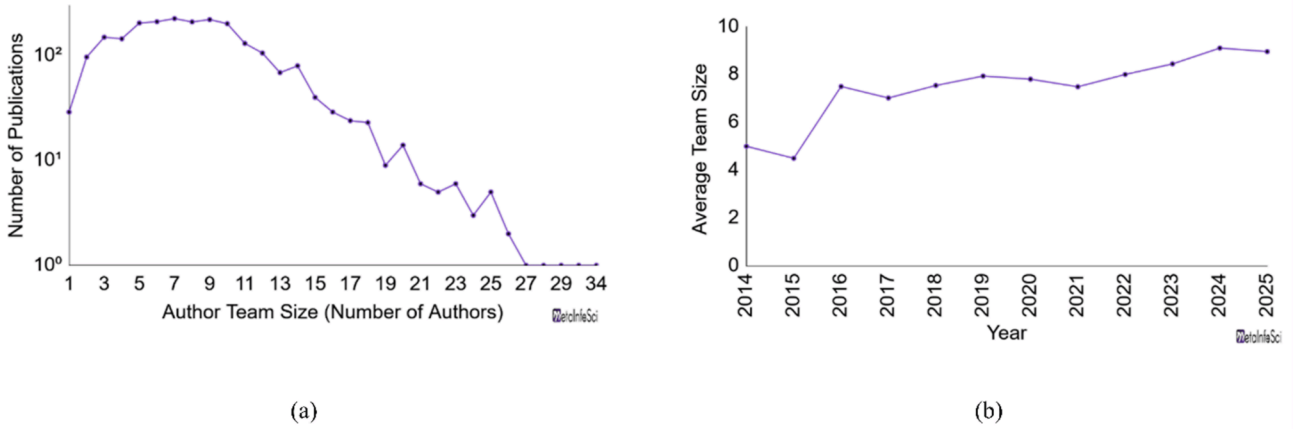


FIGURE 5: Plots depicting variation of (a) number of publications versus team size and (b) average team size versus year in the field of two-dimensional perovskite solar cells

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Figure 5 illustrates collaboration patterns in terms of team size. Team size can be understood as the number of authors involved in a manuscript. Figure 5(a) represents the variation in the number of publications versus team size of authors in publications worldwide. It may be observed that small teams of two to eleven authors have contributed the maximum number of publications. It may be observed from this figure that the number of publications diminishes very rapidly as team size increases further. Figure 5(b) displays a plot showing the variation in the average team size of authors versus year. It indicates that there has been a steady increase in team size from 2014 to 2025. This increase signifies a drift towards greater collaboration in research work, along with rising team sizes over the years. The same can be attributed to the intensification of research in this field.

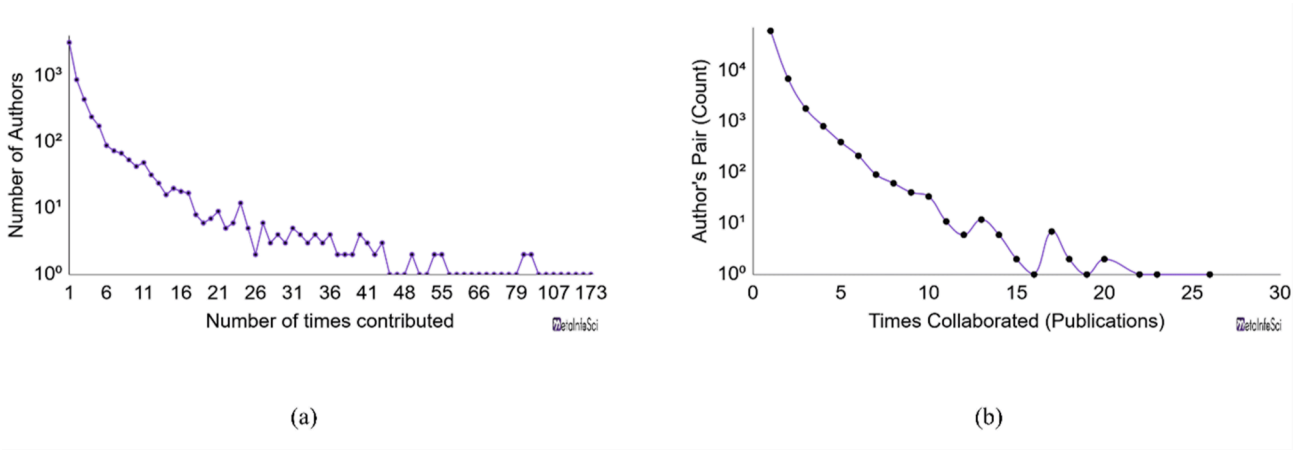


FIGURE 6: Plots depicting (a) author contribution frequency and (b) author collaboration frequency in pairs in the research field of two-dimensional perovskite solar cells

Figure 6 captures the individual productivity and collaborative activities of the authors. The left panel in the figure shows the distribution of contribution frequencies by the authors, and, as has been identified, the distribution exhibits a heavily skewed pattern, meaning that most authors contributed only once or a few times, but very few were highly productive, making numerous contributions. This pattern has largely been identified as characteristic of scientific publishing, meaning that most contributions have come from core contributors. The right-hand plot reveals the frequency of co-authorship between pairs of authors. It is clear that most pairs of authors co-published only once or a few times during their careers. The implications are that the research environment is dominated by a foundation layer of episodic contributors to the literature, a nucleus of very productive individuals with a high number of publications, and a style in which most collaborative partnering is on a short-term or project-specific basis.

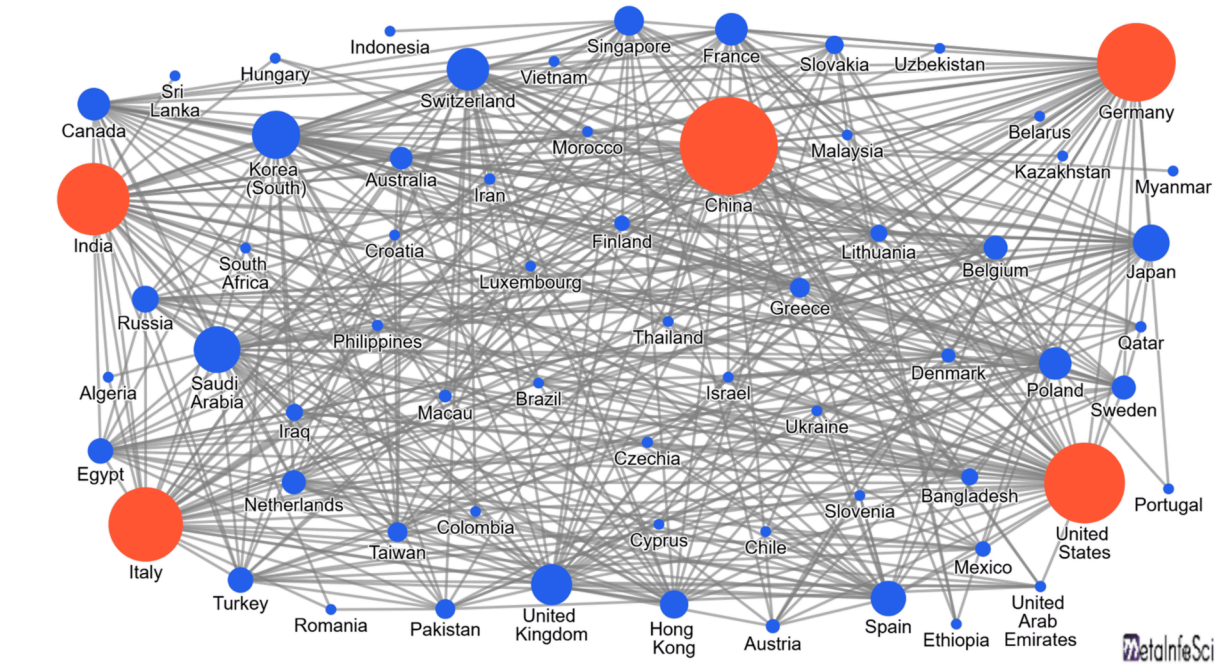
Country collaboration analysis

Figure 7 presents the country-level overview of research productivity and international collaboration in the field of 2D PSCs. Figure 7(a) shows a global collaboration network with 65 nodes and 434 edges. Each node represents a country, and the node size reflects publication volume. Links between different nodes represent co-authorship ties between countries. The average degree of collaboration is 13.35. China, the United States of America, India, Germany, and Italy appear as the most prominent and highly connected top five research hubs in the subject field. These countries play a central role in facilitating and maintaining international research and collaboration. Numerous smaller nodes clustered around these hubs represent widespread cross-border partnerships in a globally interconnected research landscape. Figure 7(b) shows the publication output of different countries. China leads with the highest number of publications, followed by the United States of America and India. South Korea and Hong Kong also exhibit sizeable contributions.

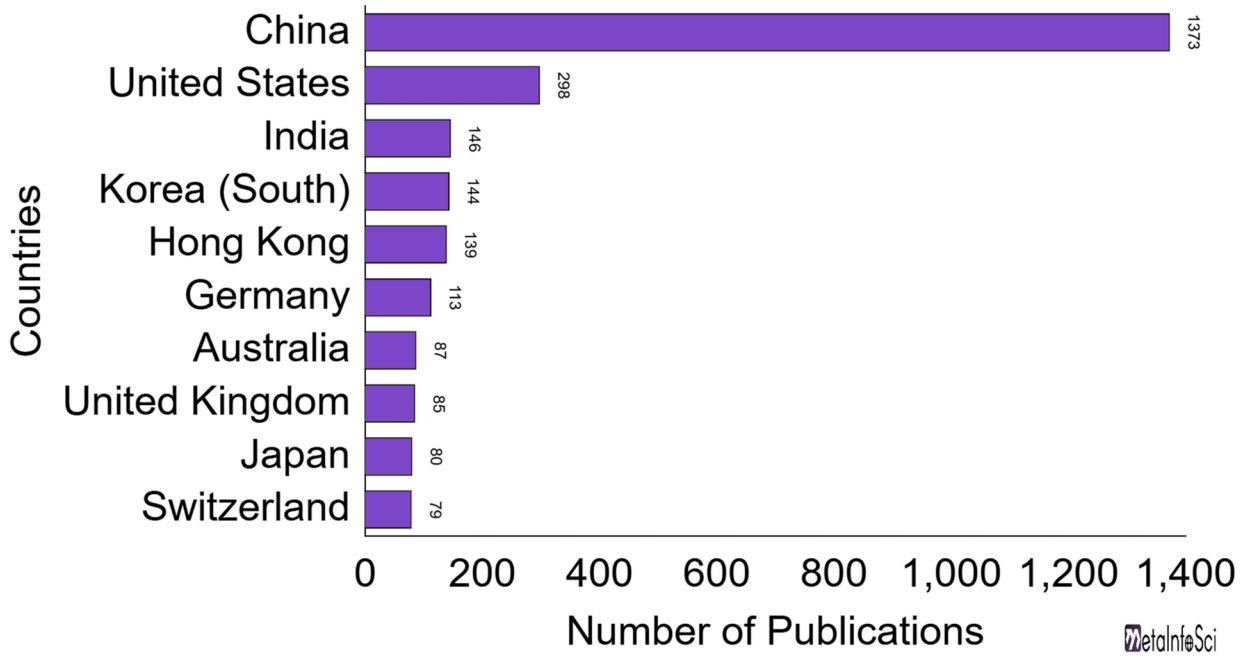
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Asian countries such as India and China demonstrate substantial output but relatively fewer central positions compared to the Western hubs. Overall, the combined visualizations reveal that the subject research field is dominated by a few highly productive countries that act as collaboration anchors, supported by broad international participation.

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United States
Taiwan
Chile
Italy
Mexico
Turkey
United Arab Emirates
Romania
Pakistan
United Kingdom
Hong Kong
Austria
Spain
Ethiopia
MetaInfoSci

(a)


Countries
China
United States
India
Korea (South)
Hong Kong
Germany
Australia
United Kingdom
Japan
Switzerland
1373
298
146
144
139
113
87
85
80
79
0
200
400
600
800
1,000
1,200
1,400
Number of Publications
MetaInfoSci

(b)

FIGURE 7: (a) Countries collaboration network, and (b) top 10 countries working in the research field of two-dimensional perovskite solar cells

As shown in Figure *8*(a), the largest number of publications are produced by small teams. Publications having authors from a single country (1,511 papers) account for over 67% of the total documents. Publications containing authors from two (491 papers) and three (172 papers) countries represent a major part of the remaining documents. As team size increases beyond four countries, the number of publications drops sharply, indicating that the field is largely driven by researchers from individual countries or small collaborative groups rather than large consortia. Figure *8*(b) shows the publication output of the top 10 country collaborations.

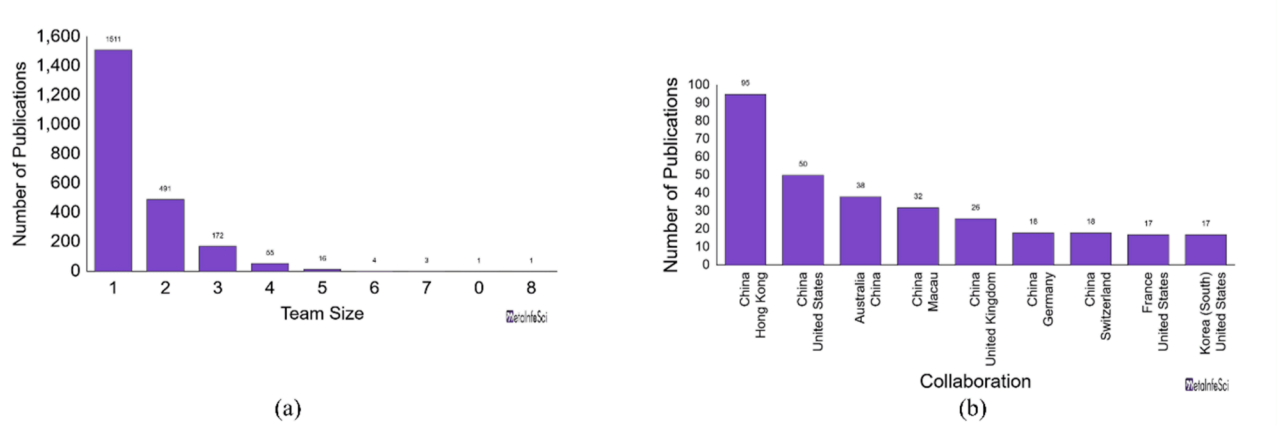


FIGURE 8: (a) Plot of number of publications versus team size. (b) Publication output of top 10 country collaborations

From an international collaboration perspective, the network is centered around a limited set of highly connected country pairs. The China-Hong Kong pair has emerged as the strongest collaboration (95 publications), followed by the China-USA and Australia-China pairs, reflecting the central role played by China as a global research collaboration hub. Other links, such as China with Macau, the United Kingdom, and Germany, show moderate but consistent activity. Overall, the network reflects a moderately dense collaboration structure. The distribution clearly indicates that China and the USA are the primary hubs for scientific collaboration within the specified time period. Overall, the trend indicates that there is strong domestic collaboration, as reflected in the dominance of small, local research teams, whereas international collaboration is more selective and concentrated among a few leading countries. This suggests that global partnerships exist but are driven by specific research hubs rather than being broadly distributed across the worldwide research community.

Thematic analysis

A word cloud provides a broader perspective of a research field using prominent and most frequently used keywords corresponding to that area. Analysis of the word cloud in the current study (Figure *9*) provides a distinct and precise overview, offering an opportunity to discover relevant trends. Major terms brought forward through the weightage calculations are 'perovskites', 'solar cells', and '2D'. The analysis leaves little ambiguity about the most focused topics of researchers in the field. A distinct and recurring concept within the subject research field is the prominent engagement with the terms 2D and quasi-2D perovskite. The presence of terms such as 2D perovskite, 2D, and quasi-2D perovskite reveals a major interest amongst researchers in exploring these particular structures.

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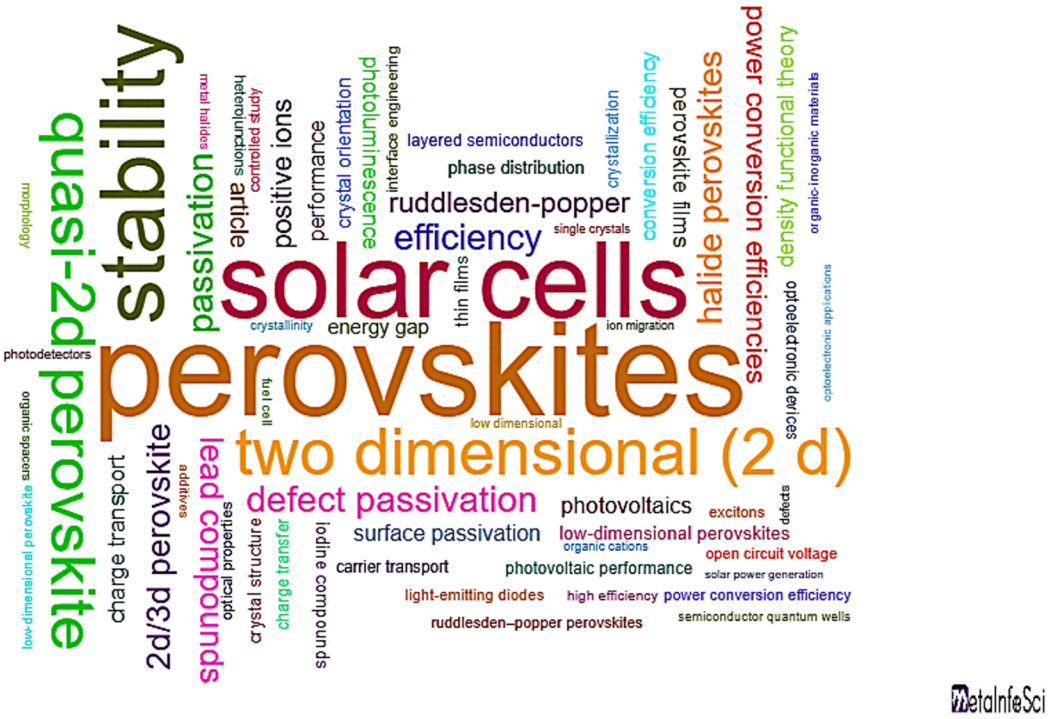


FIGURE 9: Word cloud representing keywords from publications with size of each word indicating its frequency

In addition, important challenges and goals of the subject research field are also revealed in Figure *9*. 'Stability' appears to be one of the major concerns for PSCs, for which further work is required. Another prominent keyword is 'defect passivation', which is used to suppress electrically active defects in perovskites to achieve better charge transport and higher efficiency [31]. Wide usage of this keyword by scientists indicates that this technique helps improve the overall functioning of PSCs, which future workers can also utilize to obtain better results. The word cloud presents an image describing a highly dynamic area of interest amongst workers engaged in the advancement of 2D PSCs. Their efforts are largely focused on enhancing stability and increasing the efficiency of the devices. Table *6* provides comparative data regarding composition, stability, efficiency, and other parameters of selected published papers.

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Perovskite Composition	Device Structure	Voc (V)	Jsc (mA/cm²)	FF (%)	PCE (%)	Stability	Reference
$(FAPbI_3)_{1-x}(MAPbBr_{3-y}Cl_y)_x$	Glass/ITO/SnO_2/PVSK/Spiro-OMeTAD/Au[1]	1.18	25.04	77.79	22.98	Under continuous white LED illumination (100 mW/cm²) in a nitrogen glovebox, the device retains 89% of its initial PCE after 300 hours	[32]
$(MAPbI_3)_{1-x}[(PEI)_2PbI_4]_x$ (x = 2%)	Glass/ITO/PEDOT:PSS/PVSK/$PC_{61}BM$/LiF/Ag	1.08	19.30	72.90	15.2	Device performance decreased by 16% on 14th day under ambient exposure conditions with a humidity of approximately 50%	[33]
$(PEA)_2(MA)_4Pb_5I_{16}$[1]	Glass/ITO/PEDOT:PSS/PVSK/$PC_{61}BM$/BCP/Ag	1.11	15.01	67.00	11.01	78.5% of original PCE was retained by device after keeping it in air for 160 hours	[34]
$(FAPbI_3)_{1-x}(MAPbBr_{3-y}Cl_y)_x$[2]	Glass/ITO/SnO_2/PVSK/Spiro-OMeTAD/Au	~1.1	~24.00	~78	21.05	Retained 98% PCE after 528 hours of storage in ambient conditions	[35]
$(BA)_2(MA)_3Pb_4I_{13}$[3]	Glass/FTO/TiO_2/PVSK/Spir	1.08	19.95	63.47	13.68	Retained 89% PCE after 1,400 hours of storage in	[36]

	o-OMeTAD/Au					air at room temperature (in dark)	
$(PEI)_2(MA)_6Pb_7I_{22}$	Glass/ITO/PEDOT:PSS/PVSK/$PC_{61}BM$/LiF/Ag	~1.10	~13.12	~65	10.08	Retained 90% PCE after 500 hours of light illumination	[37]
$BA_{0.09}(FA_{0.83}Cs_{0.17})_{0.91}Pb(I_{0.6}Br_{0.4})_3$	Glass/FTO/SnO_2/($PC_{61}BM$/C_{60})/PVSK/Spiro-OMeTAD/Au	1.18	19.8	73	17.2	The time required for 80% of the post burn-in decay (normal PCE) of champion device was 1,005 hours	[26]
$[(Cs_{0.04}FA_{0.85}MA_{0.11})Pb(I_{0.96}Br_{0.01}Cl_{0.03})_3]_4$	Glass/FTO/c-TiO_2/m-TiO_2/SnO_2/PVSK/XPMAI-based salts/Spiro-OMeTAD/Au	1.13	25.67	80.70	23.15	PCE reduced to 98% of initial value after 1,250 hours of continuous illumination	[38]
n-Butylamine (BA) treated $MAPbI_3$	Glass/ITO/PTAA/PVSK/$PC_{61}BM$/C_{60}/BCP/Cu	1.11	22.49	78.00	19.56	Retained 96.5% of initial efficiency after 100 hours of continuous heating	[39]
$FA_{0.9}MA_{0.05}Cs_{0.05}PbI_3$/$FA_{0.88}MA_{0.07}Cs_{0.05}PbI_{2.89}Br_{0.11}$	Glass/ITO/SnO_2/PVSK/PTAA/Au	1.125	25.96	84.32	24.63	Retained 80% of initial efficiency after 2,220 hours of heating	[40]
$Rb_{0.05}Cs_{0.05}MA_{0.05}FA_{0.85}Pb(I_{0.95}Br_{0.05})_3$	Glass/ITO/MeO-2PACz/PVSK/C_{60}/SnO_2/Ag	1.18	25.58	84.90	25.58	Retained >93% of their maximum PCEs after ~5,030 hours of continuous	[41]

						operation (1.2-sun)	

TABLE 6: Composition, device structure, and associated parameters of perovskite-based solar devices obtained from selected published papers

Spiro-OMeTAD, PEDOT:PSS, and $PC_{61}BM$ are used as charge transport layers in perovskite solar cells. Selected results for best-performing devices are provided in the table. Details of devices can be obtained from the reference.
BA, Bathocuproine; BCP, Butylammonium; FA, Formamidinium; FF, Fill Factor; MA, Methylammonium; PCE, Power Conversion Efficiency; PEA, Phenylethylammonium butylammonium; PEI, Polyethylenimine; PTAA, Poly(bis(4-phenyl)(2,4,6-trimethylphenyl)amine); PVSK, Perovskite

[1] The additive ammonium thiocyanate (NH_4SCN) was used.

[2] Passivation layer was developed onto the perovskite films.

[3] Cs^+ doping was performed.

[4] Passivated by (4-(thiophen-2-yl)phenyl)methanaminium iodide (TPMAI).

A Sankey diagram is exhibited in Figure *10*, which illustrates 45 nodes and 66 links. It reflects the structural level of concentration in the research community in terms of 30 keywords, 5 themes, and 10 countries. The major nodes indicate a significant focus on perovskite materials, especially regarding device-level issues and optimization of device-level efficiencies, effectively capturing the main sources of knowledge and research work being pursued. The thematic landscape of the field is organized around several prominent intellectual anchors, notably 2D/3D perovskite architectures, Dion-Jacobson (DJ) perovskites, and efficiency-driven design strategies. DJ perovskite is a type of 2D perovskite in which inorganic layers are connected by divalent organic spacer cations [42-44]. Unlike Ruddlesden-Popper perovskites [45,46], they do not contain van der Waals gaps between layers. DJ perovskites show stronger interlayer interaction, better charge transport, and improved thermal and moisture stability. It may be observed from Figure *10* that the central themes actively encompass critical physical mechanisms and device-level strategies. Examples are charge carrier transport, electron-phonon interactions, energy funneling, energy-level alignment, grain boundary engineering, and fluorination. The disproportionate concentration of research activity within these advanced subdomains, relative to broader thematic categories, reflects the field's progression toward maturity, characterized by mechanism-oriented insights and precision-driven device engineering in perovskite materials and PV technologies.

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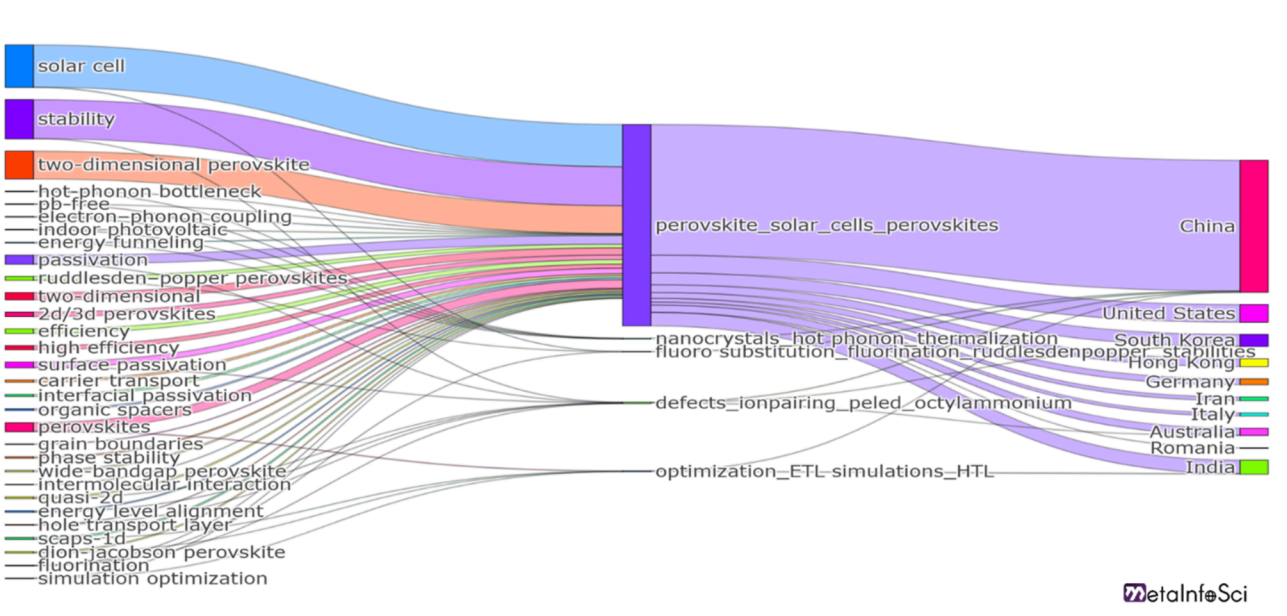


FIGURE 10: Sankey diagram of top 30 keywords and 5 thematic areas and 10 top countries

Conclusions

PSCs have achieved efficiencies comparable to or higher than those of traditional silicon-based solar cells. They represent the next-generation solar cell technology, although the challenge of stability remains. In the present review, bibliometric analysis has been carried out on the literature related to the research and development of 2D PSCs during the period 2014-2024. This research area is rapidly growing and has the capability to meet future energy challenges worldwide. Despite the progress, gaps still exist in the research that need to be explored for predicting future directions. The present work tries to identify these gaps and present possible future research directions. Progress in PSC research may be mainly attributed to the collaborative and cumulative research efforts of China, the USA, and India. They have been found to lead the world in terms of publications and citations. Other countries involved in PSC research have fewer publications, and the corresponding data provide researchers (in this research field) from these countries with more opportunities to further strengthen and expand their work. Research collaboration opportunities may be more readily available with scientists from such countries. The major trends in research involve experimenting with new configurations and precursors, increasing material stability, and optimizing bandgap combinations to enhance efficiency and scalability. This paper also points out the importance of top-tier journals in determining the direction of progress in the field. Through the identification of existing research gaps and the promotion of interdisciplinary collaboration, 2D PSC research can revolutionize the photovoltaic industry.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Tabish Rasheed, Mohammad Aamir

Acquisition, analysis, or interpretation of data: Tabish Rasheed, Mohammad Aamir, Amanat Ali

Drafting of the manuscript: Tabish Rasheed, Mohammad Aamir, Amanat Ali

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Conflicts of interest: In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

Data Availability Statements

Data sharing is not applicable. This work is theoretical; no datasets were generated or analyzed.

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