A bibliometric analysis of trends in solar cooling technology

Kangkana Saikia, Manel Vallès, Alexandre Fabregat Tomàs, Raúl Saez, Dieter Boer*

Departament d'Enginyeria Mecànica, Universitat Rovira i Virgili, Av. Paisos Catalans 26, 43007 Tarragona, Spain

Email: dieter.boer@urv.cat

* Corresponding author

Highlights

- Scientific literature on solar cooling technologies is obtained from the Web of Science Database.
- The statistical trends in the number of publications pertaining to countries, authors, journals, and research institutions are analyzed.
- Collaboration between authors, institutions, and countries in this field of research is visualized.
- Co-occurrence network of most frequent keywords is used to identify hot topics of research.
- The evolution of various solar cooling technologies is discussed.

Abstract

With the increasing demand for air-conditioning and refrigeration and depleting fossil fuel resources, countries across the globe have been exploring sustainable alternatives to supply cooling loads. While solar cooling technology has been investigated and demonstrated in recent decades, it has not yet been able to take over traditional cooling systems due to the technical and financial constraints. Understanding the state of the art in this emerging research field is crucial in planning future research efforts. In light of this motivation, this study uses bibliometric analysis to identify hot topics, trends, and research clusters in solar cooling. A dataset of 3639 publications on solar cooling obtained from Web of Science has been analyzed using (i) the open source tool VOSviewer, (ii) the R package Bibliometrix and (iii) an in-house bibliometric tool. This analysis allowed us to determine the annual publication rate both total and segregated by country, author, journal, and research institution. With an overall increasing trend in the total number of publications, China was identified as the leading country in solar cooling research followed by the USA, and Southern European countries. Keyword analysis and time evolution of various key solar cooling technologies have shown that the focus has so far been on solar thermal cooling technology. Nonetheless, as solar photovoltaic prices drop significantly, researchers are expected to focus more closely on photovoltaic driven cooling systems in the near future as a step towards reducing fossil fuel dependence and mitigating climate change.

Keywords: Solar cooling, Solar energy, Renewable heating and cooling, Bibliometrics, Keyword analysis

1. Introduction

Solar energy is one of the most widely used renewable energy sources that has come into force in the 21st century to generate renewable electricity and reduce carbon dioxide emissions. Another prospect that has caught attention is the utilization of solar energy for renewable heating and cooling systems. It is worth to mention that these systems account for a huge share of total energy consumption, which can reach up to 30% in the case of developing countries (Wang et al., 2016). In Europe, the potential space cooling demand is projected at 466 TWh in an average year, taking into account both residential and service sectors (Jakubcionis and Carlsson, 2018; Jakubcionis and Carlsson, 2017). After the energy crisis of the 1970s, researchers began exploring solar energy for cooling purposes for the first time, and a few pilot plants emerged within a short timeframe (Lazzarin, 2014). Over the next four decades, many works have been carried out on solar cooling technologies for refrigeration and air-conditioning all over the world. However, such developments have been overshadowed by the research on solar energy assisted heating because of its higher demand. In the meantime, the demand for cooling systems in the building sector was increasing gradually. A reflection of this increment can be seen by the increase in annual electricity consumption from 7300 TWh to 22,100 TWh between 1980 and 2013 (Liu, 2015). According to the latest reports, between 2010 and 2017, global energy consumption for space cooling in buildings has increased by more than 20% (IEA, 2018). This is a clear consequence of rising summer temperatures due to climate change and increased demand for indoor comfort due to population and economic growth. Under these circumstances, using solar energy for cooling is a promising step towards the mitigation of energy and climate emergencies for a sustainable future (Papadopoulos et al., 2003; Al-Alili et al., 2014; Anand et al., 2015). It is an indisputable fact that solar radiation is adequately available during the hours when the demand for cooling is extreme. This makes solar cooling an ideal option for the renewable cooling system. The current availability of highly efficient and cost-effective solar thermal collectors and photovoltaic (PV) panels have encouraged this technology to emerge as an alternative for conventional cooling systems.

The growing interest in solar cooling technologies from the scientific community and the market has increased the amount of literature related to this filed markedly. Therefore a bibliometric review of the published works in this field seems timely. Although it is by no means a substitute for traditional reviews, analyzing the corpus of scientific publications on a given research topic has demonstrated its ability to explain the development patterns for past and present as well as future research scope. Dated back to the 1950s, bibliometrics has been used as a standard statistical tool across various disciplines to quantify and evaluate the trend of a particular subject of interest (Godin, 2006). Recently, a lot of bibliometric analysis has been performed in energy-related research fields to get a structured update as a huge volume of data has been generated in energy research for the last couple of decades. Calderon et al. (2019) conducted a bibliometric analysis of thermal energy storage research to provide an overview of the history and developments in this field, covering more than 14,000 publications. Park and Nagy (2018) performed a data-driven systematic review analyzing the relationship between thermal comfort and building control research with the help of a citation network. They also used keyword analysis to describe the past and present scientific landscape. Wang, L. et al. (2017) studied the global transition to low-carbon electricity both quantitatively and qualitatively, wrapping 13,767 documents over a quarter-century. As per the knowledge of the authors, there has been no systematic review on solar assisted cooling systems available to date. Therefore, in this work, a bibliometric review is carried out by examining the available scientific literature on solar cooling technologies with the primary aim of gaining a clear understanding of this research field's growth over time. This is accomplished by measuring the contributions of different aspects to solar cooling technologies, both in terms of quantity and quality of research.

2. Methodology

This section explains the methodological approaches and software tools considered in this study. To generate various bibliometric results and technology trends, a set of publications related to solar cooling research has been collected, refined, processed, and analyzed employing advanced software tools.

2.1 Bibliometric analysis

By analyzing the data in the corpus of scientific publications on solar cooling, bibliometric analysis extracts quantitative information about publication metrics, geographical attributes, author collaboration via co-authorship, research institution relevance, etc. The results of this analysis are used to reveal the latest status of solar cooling research.

In this bibliometric study, analyses were performed using specialized software, namely Bibliometrix, VOSviewer (version 1.6.11), and in-house bibliometric tool written in Python 3.7. Bibliometrix is one of the latest open-source software developed in the R environment to carry out systematic scientific-literature mapping (Aria and Cuccurullo, 2017). VOSviewer is another freely available software tool developed by Van Eck and Waltman that can be employed for creating and visualizing bibliometric maps of scientific publications, authors, journals, countries, institutions, and keywords (van Eck and Waltman, 2010). The use of Python language for bibliometric analysis is a new approach that could facilitate a more in-depth analysis of the research community and the evolution of technology in a particular research field (Calderon et al., 2019; Park and Nagy, 2018). The in-house tool can be readily custom-tailored to extract and analyze information that is not possible in VOSviewer or Bibliometrix.

2.2 Data Source

The data was collected on 22nd October 2019, from Web of Science (WOS) Core Collection. The WOS database maintained by Clarivate Analytics has been accepted as a source of high-quality data for a significant number of bibliometric analysis in different fields (de Paulo and Porto, 2017). Li et al. (2018) have shown that during the last 20 years, the WOS has evolved significantly to become one of the leading tools for answering scientific queries and analysis. To develop our database in solar cooling, we used a combination of keywords along with logical operators AND, OR, and NOT (as shown in fig.1) in the topic field of WOS database which includes the title, abstract, author keywords, and keywords plus® sections of the records. The selection of keywords to build a meaningful database covering all the relevant publications on one subject matter is a critical step. In our case, rigorous work has been done to identify keywords for the search as appropriate as possible to maximize the number of relevant documents on solar cooling research. At first, several review articles were extracted from WOS by using the keyword “solar cooling” in the search. These articles were analyzed to identify other important keywords in this field. Based on this, a query relating all the relevant solar cooling technologies was framed step by step to extract data from WOS. Initial search results revealed that many records that are irrelevant to our topic of interest had been included in our database. For example, one of the critical keywords was “absorption”, which resulted in the inclusion of a large number of non-relevant documents in our database from astrophysics, astronomy, geophysics, climate research, and solar energy materials. Following this situation, a number of exclusions phrases were also introduced in the search criteria to refine the database. The search resulted in 3931 documents, as shown in fig. 1 covering all records in English published till 2019 in various forms of publications, including articles, reviews, conference proceedings, book chapters, and books and editorials. We have considered documents published only in the English language here since it contains more than 90% of the total documents. After carefully screening these documents through their titles and abstracts, we manually omitted several publishing sources and topic categories in WOS irrelevant to the subject of the utilization of solar energy for cooling purposes. For instance, publication sources such as the Journal of Physical Chemistry, Journal of the Atmospheric Sciences, etc. have contributed to our solar cooling database because there are documents published in these journals using a few keywords from our search criteria.

Nevertheless, these documents can be considered as irrelevant in our context since they do not add any value to the solar cooling database. Finally, 3639 documents with full records and citations were downloaded in plain text format for further analysis purposes.

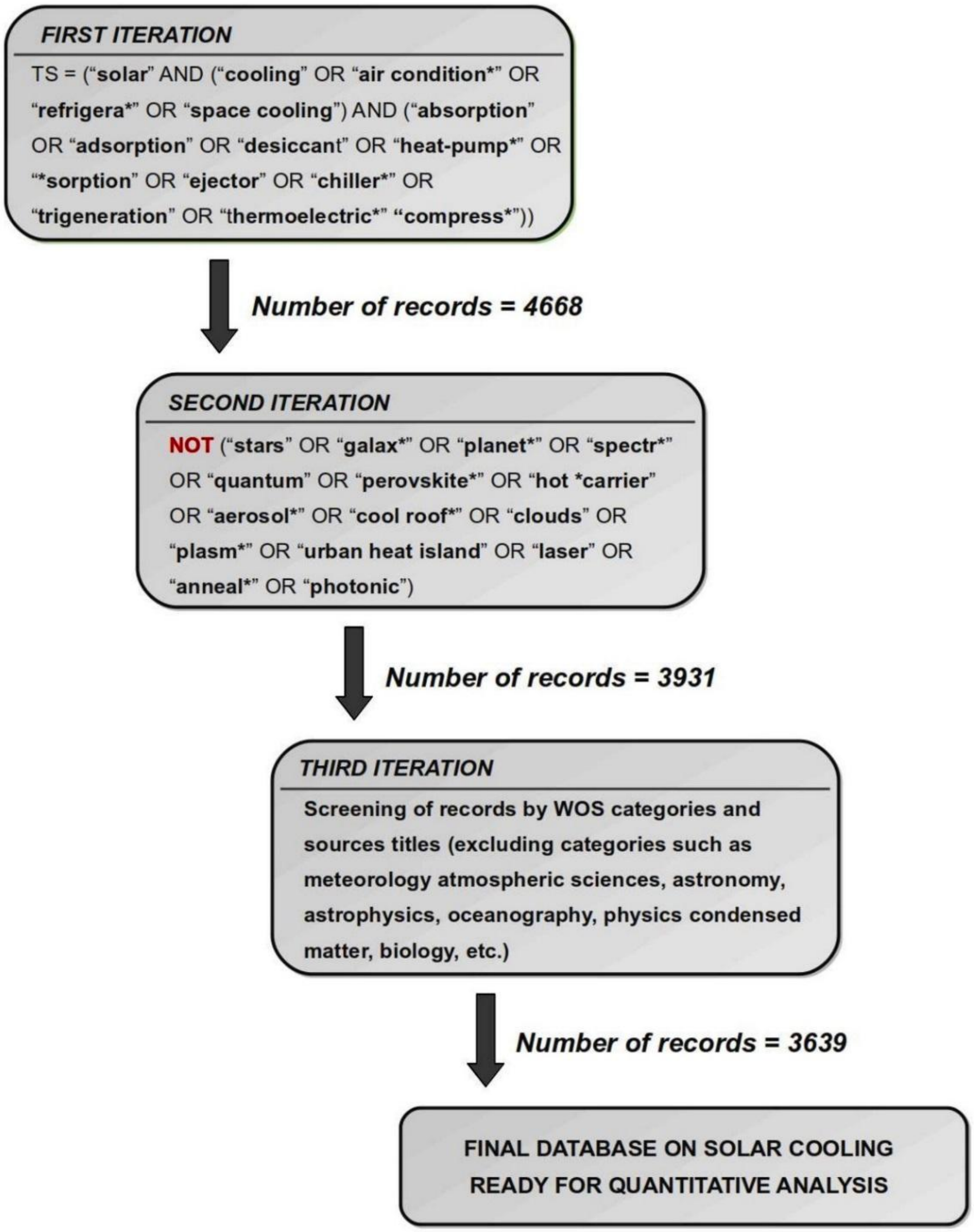

Fig. 1: Flow chart showing data collection and refinement. Note: The quotation marks were used to look for exact phrases. The wildcard * was used to find plural and other forms of the words.

2.3 Impact factor and h-index

To measure the impact of research by a publication source, an author, an institution, or a country, the impact factor and h-index were chosen as the indicators in this study. These two indexes have been used as popular standards to evaluate the influence of research in several bibliometric studies in energy-related fields (Geng et al., 2017; Mao et al. 2015). The impact factors of the publication sources are obtained from the Journal Citation Reports 2019 (JCR) published by Clarivate Analytics (Clarivate Analytics, 2019). Invented by Eugene Garfield, the impact factor of a journal is a ratio of the current year citations to the source items published in that journal during the previous two years (Garfield, 1994). The h-index, introduced by J. E. Hirsch in 2005, takes into account both the number of publications and their citation count of an individual (Hirsch, 2005). An author's h-index is equal to X if she/he has X publications which have been cited by other authors at least X times (Kamdem et al., 2019). In our bibliometric study, h-index is used to assess the impact of research by the authors, journals, and countries in the solar cooling field. This is a recent development for h-index whereby it can be used to evaluate the research output by considering any collection of papers affiliated to a journal, country, institutions, or any particular field of study (Díaz et al., 2016).

2.4 Keyword analysis

It is a common bibliometric methodology for content analysis where keywords are extracted and examined based on their frequency. Generally, researchers rely on the author-defined keywords and titles of publication to represent the vital takeaway points of research so that progress can be monitored of a particular research field (Mao et al., 2015; Du et al., 2014). For our analysis, we have extracted all of the author-defined keywords from the solar cooling database using VOSviewer. We used the author's keywords as the unit of analysis because we found that they are much more comprehensive than Keywords Plus while representing the content of the literature (Zhang et al., 2016). Since there were keywords such as regional names, repetitive words with singular and plural forms, and abbreviations, we constructed a thesaurus file to merge these keywords. The thesaurus file was applied along with the VOSviewer text mining function for generating a map of keyword co-occurrence to examine the various subject domains. In addition, to see the temporal evolution of different solar cooling technologies, the author's keywords are mapped into different technology clusters using Python programming.

3. Results and discussion

3.1 Publication overview

By following the methodology, as described in section 2, we developed a database on solar cooling consisted of 3639 publications for further analyses. A piece of detailed information about this database is provided in table 1. The frequency of the publication and average citations linked to solar cooling is shown in fig. 2 as a function of year. The results show that the number of publications over the years from the 1970s up to now has increased. This rise can be explained by increasing global concern over the depletion of fossil fuel reserves and the quest for sustainable energy solutions. The oil crisis in 1973 and 1979 are significant in this regard because this led to a series of initiatives and policies to accelerate renewable energy innovation and research. In 1977, the International Energy Agency (IEA) initiated the Solar Heating and Cooling Technology Collaboration Programme (SHC TCP), which was one of the first programs to focus on the utilization of solar thermal energy in all possible aspects (Montagnino, 2017). In addition, the Montreal Protocol in 1988 called for a reduction in ozone-depleting refrigerants, which brought more attention to solar cooling technology. The overall period of development in solar cooling can be split into two phases, before and after 2005. As shown in Fig. 2, growth was slower until 2005, followed by a rapid increase in the number of studies in the last decade. This may be attributed to the availability of new solar collectors such as compound parabolic collectors (CPC) along with the significant fall in the cost of solar PV (Lazzarin and Noro, 2018). The annual distribution of average citations follows the publication trend with a sharp rise around the year 2000, and it is currently going downwards since citations require time to collect, particularly for more recent publications. Continuation of efforts in research and developments in the solar cooling sector demonstrate that both the industry and research community acknowledge its high potential.

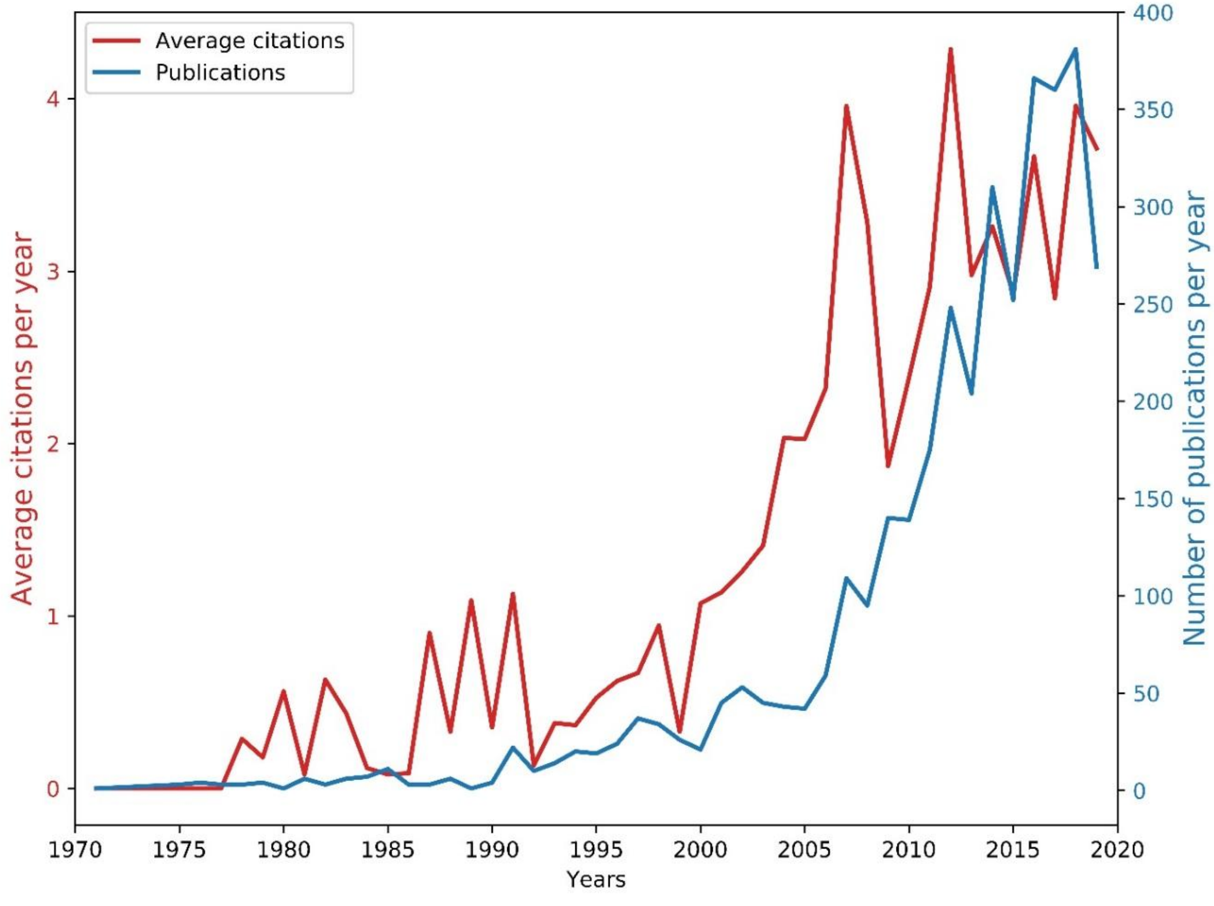

Fig. 2: Publication and citation trend in solar cooling during 1971-2019.

Table 1: Main information regarding the collection of metadata on solar cooling.

Description	Results
Documents	3639
Sources (Journals, Books, etc.)	748
Time period	1971 - 2019
Annual growth rate of publications	13.24%
Keywords Plus	2411
Author's Keywords	5254
Average citations per documents	17.38
Authors	6643
Single-authored documents	263
Co-Authors per Documents	3.43
Document types	
Article	2124
Proceedings paper	1004
Review	244
Article; proceedings paper	182
Article; book chapter	44
Meeting abstract	9
Note	9
Article; early access	8
Correction	4
Editorial material	2
Editorial material; book chapter	2
Letter	2
Article; data paper, Book, Correction, addition, reprint, Review; book chapter	1 each

3.2 Country statistics

With the help of VOSviewer, we found that organizations from 95 countries have published scientific articles on solar cooling, out of which 14 number of countries have contributed with only one article each. Table 2 represents the top 20 most productive countries by taking account of the total number of publications and citations. Amongst them, China is the leading country concerning total publications counted by the corresponding author's country, publications with and without international collaboration, total citations, and h-index. This is primarily because of the conscious and long-term industrial policies by the Chinese government, which has propelled it to become the leader in the solar energy sector. Alongside the rapid development of the economy and society, China is also the biggest emitter of carbon dioxide. In the building sector in China, there has been a rapid increase in space cooling demands in the last two decades, and it is growing at a rate of 13% every year since 2000 (IEA, 2019). This can justify the increased interest and investment by China to utilize solar energy for developing sustainable cooling practices and cleaning up the electricity mix. The other countries, such as the USA, India, Canada, Australia, Mexico, and Japan are productive, too, as shown in table 2. While Turkey has been ranked lower based on the total number of publications, but it is one of the highly cited countries with a high value of h-index. Table 2 also reflects that importance has been given to research on solar-driven cooling in European nations, particularly in Italy, Spain, Germany, UK, France, and Greece. Southern Europe can be seen heavily invested in this field as the demand for air-conditioning increases during the summer season, and utilizing solar energy to supply cooling loads can save primary energy consumption up to 50% (Koroneos et al., 2010; Balaras et al., 2007). Many countries like Iran, Saudi Arabia, Egypt, Tunisia, and Algeria from the Middle East and North Africa (MENA) region have focused on solar cooling due to the growing awareness of the solar cooling potential and a thriving market (Iqbal and Al-Alili, 2019).

Table 2: Top 20 publishing countries in the solar cooling field.

Country	TPC	SCP	MCP	TC	*h*-index*
China	745	660	85	12150	54
USA	251	187	64	3383	34
Italy	241	210	31	3372	32
India	199	162	37	2697	26
Spain	140	111	29	2615	27
Germany	126	99	27	3303	29
Iran	118	102	16	1228	19
Canada	104	76	28	1793	26
UK	100	61	39	2703	25
Turkey	95	77	18	3056	30
Australia	94	72	22	1353	22
Mexico	85	63	22	1067	16
France	83	59	24	1862	23
Saudi Arabia	76	41	35	1234	17
Japan	75	46	29	1706	19
Greece	70	58	12	1216	19
Malaysia	62	46	16	1869	20
Tunisia	59	40	19	493	14
Egypt	51	39	12	687	16
Algeria	41	24	17	308	8

Note: TPC= Total number of publications by the corresponding author's country, SCP= Single country publications, MCP= Multiple country publications, TC= Total citations. **h*-index for the entire period (1971-2019) calculated with the aid of Python in-house tool.

Furthermore, the evolution of publications over time in the case of the top publishing countries is shown in fig. 3 using Python in-house tool. The European Union (EU) as a whole shows a remarkable increment when publications are grouped, followed by China. In the last 20 years, the EU has funded the research and development generously in the field of solar heating and cooling, aimed at reducing costs, improving technology, and encouraging market adoption (Hoogland et al., 2019). This is reflected by its strong global position in fig. 3. The Chinese government has a target to add 16 GWth/yr, 41 GWth/yr, and 109 GWth/yr solar cooling capacity in buildings by the year 2020, 2030, and 2050, respectively (Zheng et al., 2014). In comparison, the growth in the USA has dimmed more recently. On the other hand, Iran and India can be seen with an increment in the number of published research works, which implies that they can become key players in this research field in the following years.

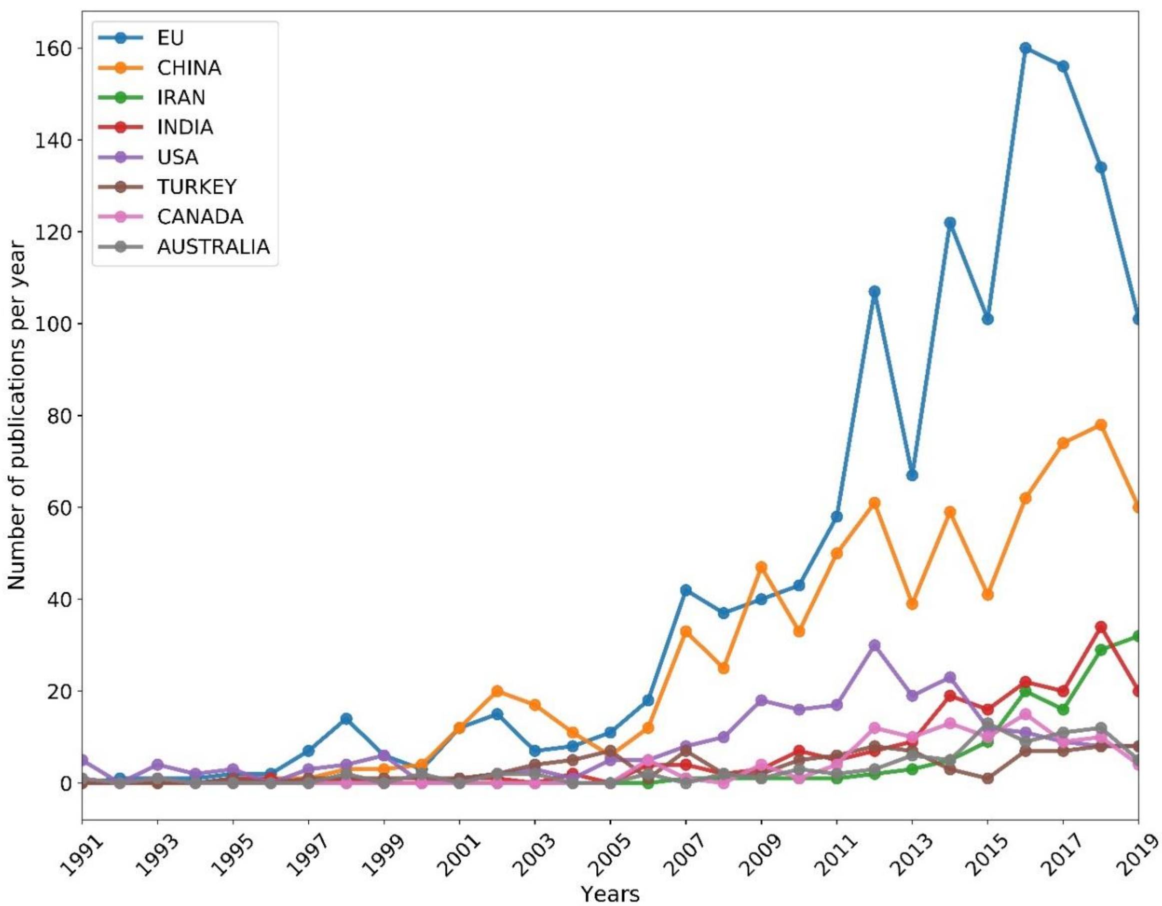

Fig. 3: Time evolution of most productive countries in solar cooling research.

The academic interaction among the top 30 countries with respect to solar cooling research is shown in fig. 4. The minimum number of publications by each country is considered to be 35 to construct a co-authorship network through the VOSviewer. In this network, every node represents a country. The size of the node corresponds to the number of publications generated by a country, whereas the thickness of the lines between the two countries represents the extent of the academic collaboration. It can be seen from fig. 4 that China has a strong collaboration with the USA, UK, and Japan. Another noteworthy collaboration exists between European nations such as Germany, Italy, Spain, Austria, and France. Furthermore, there is a remarkable interaction between Canada and Saudi Arabia, along with Turkey and Egypt.

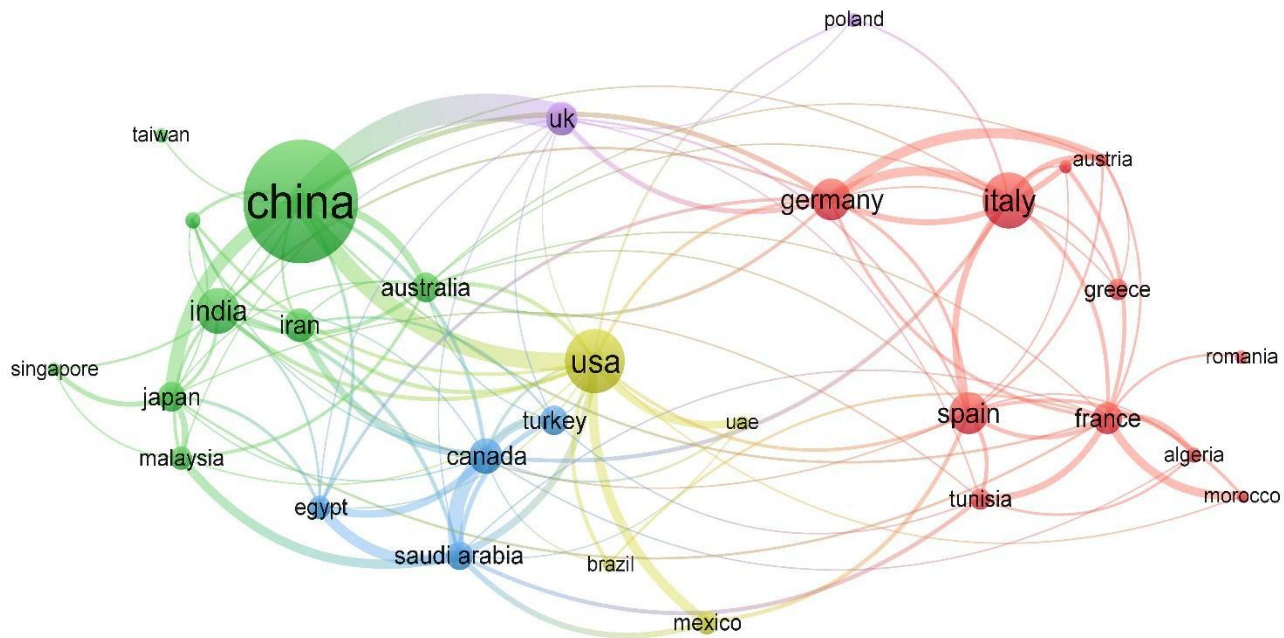

Fig. 4: Collaboration network among the top 30 countries in the field of solar cooling.

3.3 Author statistics

According to the results, 6643 authors are contributing to our solar cooling database. Out of these, 4579 (68.9 %) authors have only one publication. Table 3 shows the top 20 most productive authors on solar cooling research who has published more than 20 documents, including the h-index, total citations, starting publication year, and their respective affiliation extracted from WOS. Efforts have been made to remove duplicate author profiles from the database, which are very prominent in the case of authors from China. The most productive author is found to be R.Z. Wang from Shanghai Jiao Tong University, China. He is followed by other Chinese authors Y.J. Dai and X. S. Zhang in the top five places. The list includes more authors from China. Top authors from other countries within the top five spots are I. Dincer and F. Calise from Canada and Italy, respectively. Table 4 also shows each author's local h-index, which is considered as a significant indicator that characterizes the cumulative impact of a researcher (Hirsch, 2005; Butson and Yu, 2010). Again, R.Z. Wang tops the list with an h-index of 39 in the solar cooling research field, followed by Y.J. Dai and F. Calise. The reason behind increasing citations of Chinese authors has been explained by various factors such as improved quality of research, strong competition among Chinese researchers, more international collaboration, higher visibility of research by publishing more work in English, and plenty of local citations (Tang et al., 2015).

Table 3: Top 20 authors in the solar cooling field.

Author	Affiliation	NP	TC	H_index	PY_start
Wang, R.Z.	Shanghai Jiao Tong University, China	160	4594	39	2000
Dai, Y.J.	Shanghai Jiao Tong University, China	59	1817	25	2002
Dincer, I.	University of Ontario Institute of Technology, Canada	46	1161	19	1995
Calise, F.	University of Naples Federico II, Italy	40	1187	22	2009
Zhang, X.S.	Southeast University, China	39	566	13	2000
Saha, B.B.	Kyushu University, Japan	34	1010	17	2001
Li, M.	Yunnan Normal University, China	30	544	12	2000
Sopian, K.	Universiti Kebangsaan Malaysia, Malaysia	29	673	13	2005
Wang, L.W.	Shanghai Jiao Tong University, China	26	482	11	2004
Li, Y.	Shanghai Jiao Tong University, China	23	616	13	2008
Rivera, W.	Universidad Nacional Autónoma de México, Mexico	23	364	12	2000
Best, R.	Universidad Nacional Autónoma de México, Mexico	22	344	11	1991
Riffat, S.B.	University of Nottingham, UK	21	478	11	1996
Tzivanidis, C.	National Technical University of Athens, Greece	21	283	11	1998
Wu, J.Y.	Shanghai Jiao Tong University, China	21	827	14	2000
Zhai, X.Q.	Shanghai Jiao Tong University, China	21	662	13	2004
Fong, K.F.	City University of Hong Kong, Hong Kong, China	20	577	12	2010
Ge, T.S.	Shanghai Jiao Tong Univ, China	20	765	14	2009
Goswami, D.Y.	University of South Florida, USA	20	884	16	1999
Qu, M.	Purdue University, USA	20	373	8	2007

Note: NP = Number of publications, TC = Total citations, PY_start = Publication year starting

Fig. 5 depicts these top authors' productivity in solar cooling over the years. From this, it is seen that the authors from China (R.Z. Wang, Y. J. Dai, X.S. Zhang, M. Li, and Y. Li) are working in this field actively since last two decades. Recently, the research output from the authors I. Dincer and F. Calise has been very high in this field. Meanwhile, R. Best from Mexico is one of the pioneering authors in solar cooling research starting from the year 1991.

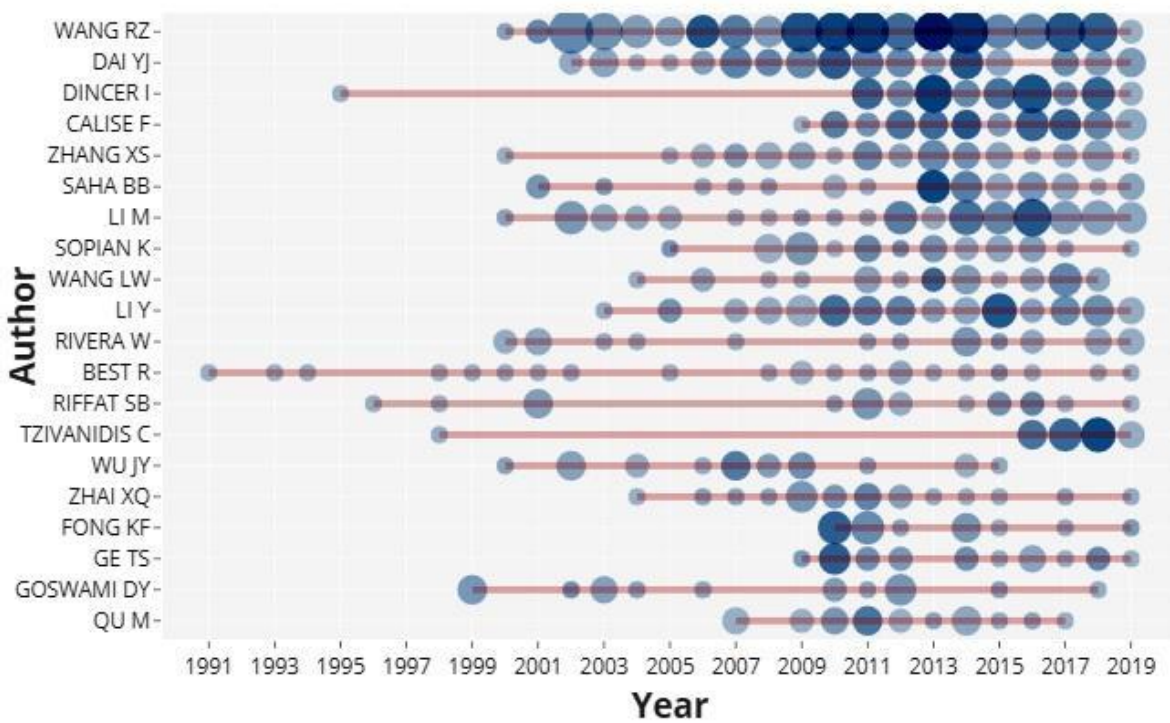

Fig. 5: Time evolution of the top 20 authors in solar cooling.

In addition, the collaboration network among authors in solar cooling is presented in fig. 6, which includes 130 co-authors following the minimum number of publications to be seven in VOSviewer. It shows the main author communities in clusters of different colors that can be helpful in identifying academic cooperation. The prominent authors are represented with larger nodes as their publication count is high. The smaller nodes are authors with low publication count.

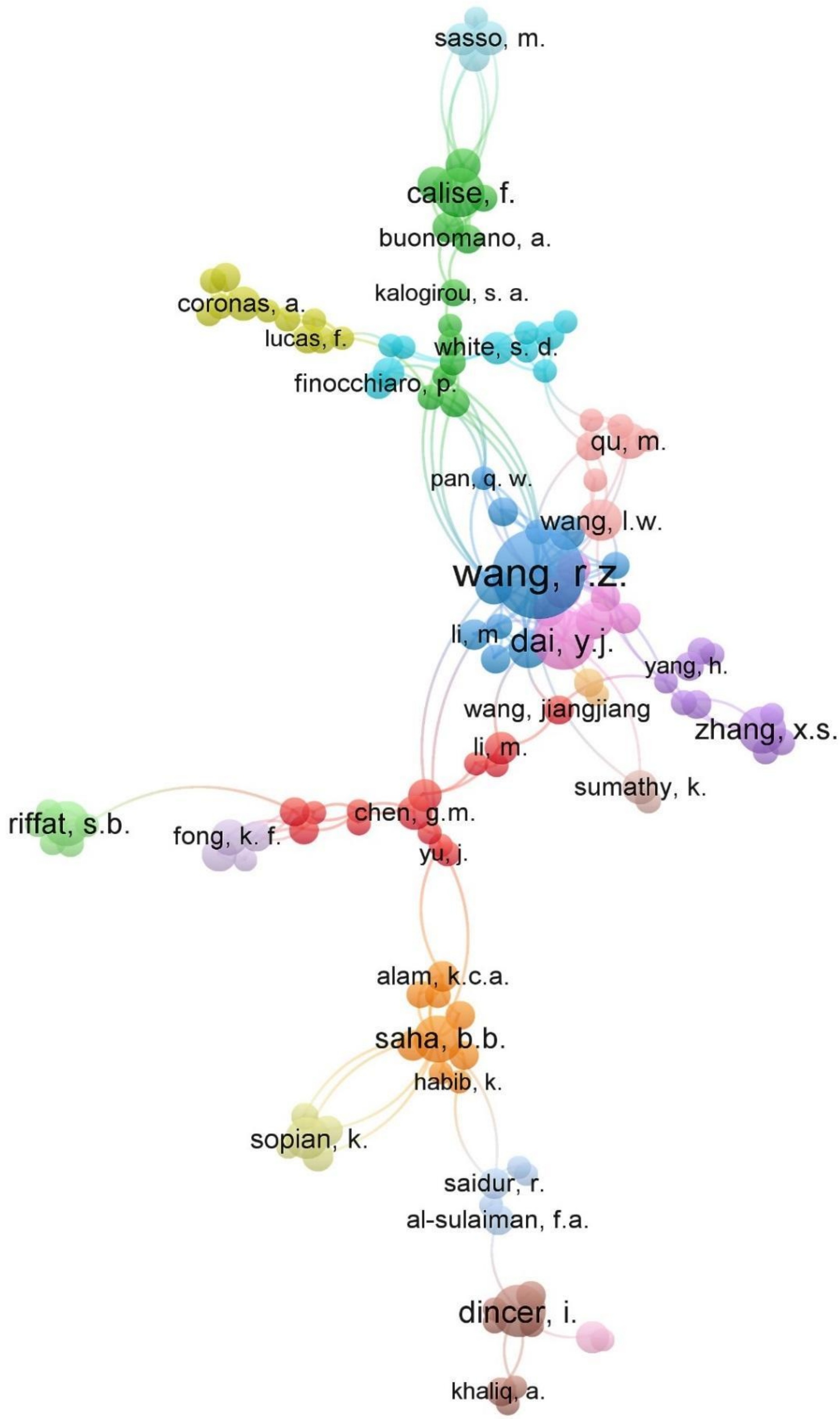

Fig. 6: Co-authorship network among authors by applying a threshold of 7 or more papers.

3.4 Journal statistics

The findings show that there are 748 sources relevant to solar cooling in our database for the entire period. Table 4 lists the top ten sources based on the number of publications contributed by each of them, along with the latest impact factor (for 2018) and h-index. These top 10 journals account for approximately 50% (1800) of the total publications. The most relevant journal is Applied Thermal Engineering, followed by Energy Conversion and Management and Solar Energy in second and third positions, respectively. The journal with the highest impact factor on this list is Renewable and Sustainable Energy Reviews, which also has the highest h-index but comparatively fewer articles in solar cooling research. The journals with higher impact factors such as Applied Energy and Energy Conversion and Management have low h-index than Applied Thermal Engineering and Solar Energy. On the other hand, the International Journal of Refrigeration, which is a prominent journal in solar cooling research, has been placed towards the end of the list along with the Journal of Solar Energy Engineering.

Table 4: Top 10 publication sources (journals) related to solar cooling research.

Source	NP	TC	h-index	PY_start	IF
Applied Thermal Engineering	273	6440	44	1996	4.026
Energy Conversion and Management	252	5640	41	1981	7.181
Solar Energy	249	7072	46	1975	4.674
Energy	177	3836	37	1991	5.537
Renewable Energy	176	4354	39	1994	5.439
Energy and Buildings	161	4280	37	1981	4.495
Applied Energy	158	5147	42	1983	8.426
Renewable & Sustainable Energy Reviews	146	10648	51	2000	10.556
International Journal of Refrigeration-Revue Internationale Du Froid	135	3537	32	1991	3.177
Journal of Solar Energy Engineering-Transactions of the ASME	73	809	16	1980	1.19

Note: NP = Number of publications, TC = Total citations, PY_start = Publication year starting, IF = Impact factor

The cumulative evolution of these journals in fig. 7 demonstrates that during the past two decades, the number of articles from Applied thermal Engineering, Solar Energy, and Energy Conversion and Management has improved significantly. Meanwhile, journals like Energy and Buildings, Renewable Energy, Applied Energy, Energy, Renewable and Sustainable Energy Reviews, and International Journal of Refrigeration have advanced moderately over time. The Journal of Solar Engineering-Transactions of the ASME has shown a prolonged growth, although it is one of the earliest published sources in solar cooling research.

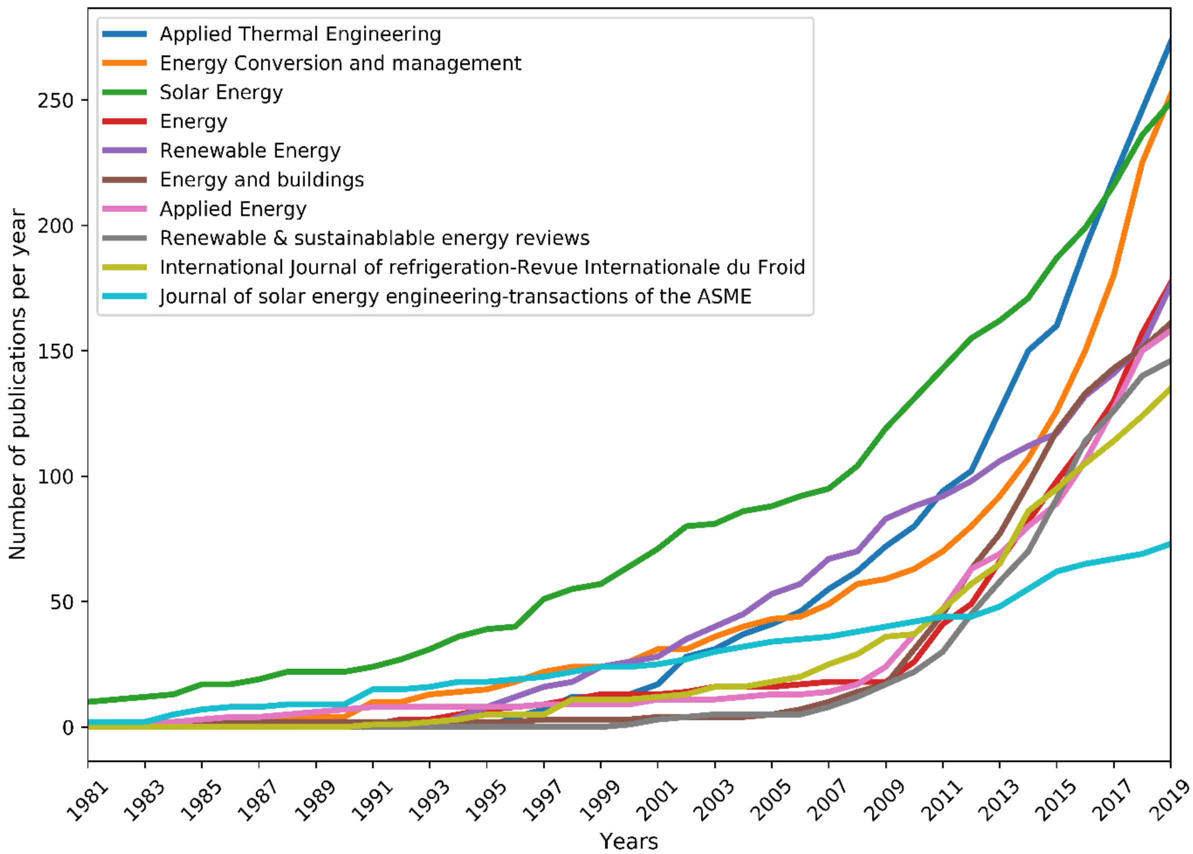

Fig. 7: Temporal evolution of the top 10 publication sources.

3.5 Institutions'/Universities' performances

Analyzing the affiliations involved in solar cooling, a total of 1810 institutions were found to publish 3639 documents, out of which 999 has contributed only one document. Table 5 shows the top 20 most productive institutions based on publication count. The list includes four China-based institutions and two from the USA. This again highlights the fact that Chinese researchers are actively engaged in the solar cooling field. The other institutions are from countries such as India, Saudi Arabia, France, Mexico, Canada, UK, Greece, Japan, Spain, Iran, Hong Kong, and Singapore. Each of these countries is affiliated to at least one institution in this list.

Table 5: Most productive research institutions in the solar cooling field.

Affiliations	Country	Articles
Shanghai Jiao Tong University	China	199
Kyushu University	Japan	61
King Fahd University of Petroleum and Minerals	Saudi Arabia	52
University of Tehran	Iran	51
Southeast University	China	48
Universidad Nacional Autónoma de México	Mexico	48
University of Nottingham	UK	44
National Technical University of Athens	Greece	40
University of Naples Federico II	Italy	40
City University of Hong Kong	Hong Kong	38
Universiti Kebangsaan Malaysia	Malaysia	34
Hong Kong Polytechnic University	Hong kong	32
Universitat Rovira i Virgili	Spain	32
National University of Singapore	Singapore	30
Universidad Carlos III de Madrid	Spain	29
Xi'an Jiaotong University	China	29
Tianjin University	China	27
Ege University	Turkey	25
University of Ontario Institute of Technology	Canada	25
Zhejiang University	China	25

The collaboration network between the leading solar cooling research institutions has been obtained from VOSviewer software (Fig. 8). The minimum number of records published by each institution is considered to be eight. Under these eligibility criteria, 148 institutions have been identified, of which 123 have a co-authorship relationship between them. The remaining 25 institutions without co-authorship have been omitted from the analysis. The largest nodes with the maximum number of co-authored links are Shanghai Jiao Tong University (China), Kyushu

University (Japan), and King Fahd University of Petroleum and Minerals (Saudi Arabia), which also have the highest number of publications.

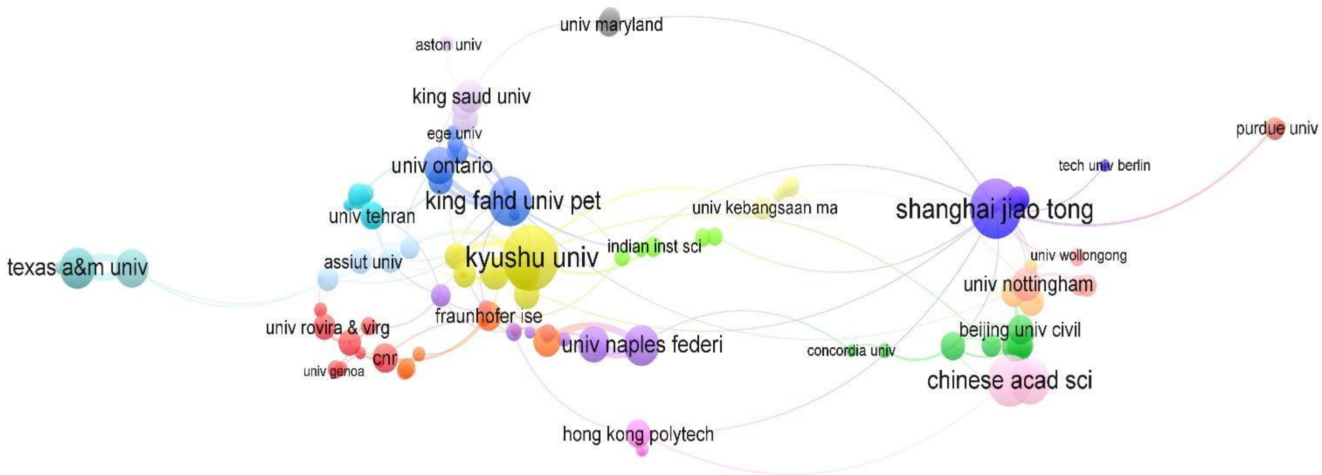

Fig. 8: Collaboration network among institutions (based on co-authorship) by applying a threshold of 8 or more papers.

3.6 Evaluation of keywords and research hot points

Since keywords can represent the main idea and methodology of scientific research, table 6 lists the most frequently used 100 keywords with their number of occurrences taking into account the minimum occurrence of a keyword as 15. Solar cooling, followed by absorption and heat pump is the most common keyword in solar cooling research. This again highlights the main focus of this bibliometric analysis, the use of solar energy for cooling purposes. Trivial keywords like solar energy, renewable energy, technology, etc. are not included in the list. Many of the keywords are similar with slight variations, such as “absorption systems”, “absorption system”, or “absorption cooling system”. Most of the keywords emphasize the core technologies for achieving solar cooling, such as absorption, adsorption, ejector cooling, desiccant cooling, trigeneration, etc. Some keywords of interest to researchers can be related to parameters and methods of performance analysis like exergy analysis, simulation, optimization, TRNSYS, energy-saving, energy efficiency, and economic analysis.

Table 6: Keywords and number of occurrences (obtained by VOSviewer data mining).

Keywords	Keywords	Keywords
Solar cooling (353)	Efficiency (56)	Cogeneration (29)
Absorption (209)	Energy (56)	Concentrating solar power (29)
Heat pump (209)	Solar thermal (56)	Numerical simulation (27)
Air-conditioning (208)	Economic analysis (55)	Biomass (26)
Adsorption (199)	Parabolic trough collector (55)	HVAC (26)
Exergy analysis (197)	Phase change materials (55)	Sustainable development (26)
Refrigeration (185)	Hybrid System (54)	Solar heating and cooling (25)
Absorption chiller (157)	Building (52)	Solar heating (24)
COP (148)	Heating (51)	Solar radiation (24)
Cooling (138)	Adsorption chiller (49)	Combined heat and power (23)
Ejector cooling (121)	Energy efficiency (48)	Exergy efficiency (23)
Solar collector (120)	Evaporative cooling (48)	Heat and mass transfer (23)
Simulation (115)	Organic rankine cycle (48)	Multigeneration (23)
Photovoltaics (113)	Silica-gel (47)	Heat pipes (22)
Desiccant cooling (99)	Solar refrigeration (47)	Polygeneration (22)
Performance analysis (98)	Energy storage (46)	Energy analysis (21)
TRNSYS (89)	Thermodynamic analysis (42)	Absorption heat pump (20)
Optimization (87)	Regeneration (41)	District heating and cooling (19)
Thermal energy storage (86)	Activated carbon (40)	Chiller (18)
Ammonia-water (83)	Dynamic simulation (39)	Multi-objective optimization (18)
Experimental study (81)	Adsorption cooling (37)	Parametric analysis (18)
Ground source heat pump (78)	Desalination (37)	Sorption (18)
Absorption refrigeration (76)	Geothermal energy (34)	Ammonia-lithium nitrate (17)
Dehumidification (66)	Combined cooling heating and power (33)	Energy consumption (17)
Modelling (66)	Heat transfer (33)	Solar fraction (17)
Absorption cooling (65)	Waste heat recovery (33)	Water (17)
Liquid desiccant (65)	Photovoltaic/thermal (32)	Zeolite (17)
Solar air-conditioning (61)	Evacuated tube collector (31)	Desiccant dehumidification (15)
Energy saving (60)	Heat recovery (31)	Ejector refrigeration (15)
Trigeneration (60)	Water heating (31)	Exergoeconomic (15)
LiBr-water (59)	Desiccant Wheel (30)	Life cycle assessment (15)
Adsorption refrigeration (58)	Solar assisted heat pump (30)	Primary energy savings (15)
	Solar thermal energy (30)	Solar absorption cooling (15)

The evolution of highly occurred keywords might help researchers to understand the research trend and potential research gaps. Fig. 9 represents the overlay visualization of author keywords (nodes) constructed using VOSviewer. The color of the nodes (from blue to yellow) is the variation in the average year in which they appeared, and the size of the nodes is the degree of occurrence (Zhang and Yuan, 2019; Guo et al., 2019). The link between two keywords represents the strength of the co-occurrence, as described in the VOSviewer manual. The average year of publication can indicate whether a particular keyword or research hotspot is newly introduced or old and mature (Palmblad and van Eck, 2018). For example, solar cooling, which is one of the most commonly reported keywords, averaged between 2010 and 2015. Keywords such as absorption, absorption chiller, refrigeration, ammonia-water, solar collector, etc. which appear in blue colors, indicate that these research areas were more concentrated around the year 2000. The yellow circles (photovoltaics, optimization, TRNSYS, dynamic simulation, organic rankine cycle, multigeneration, etc.) are keywords that have occurred around 2015 and can be considered relatively new or hot areas of research.

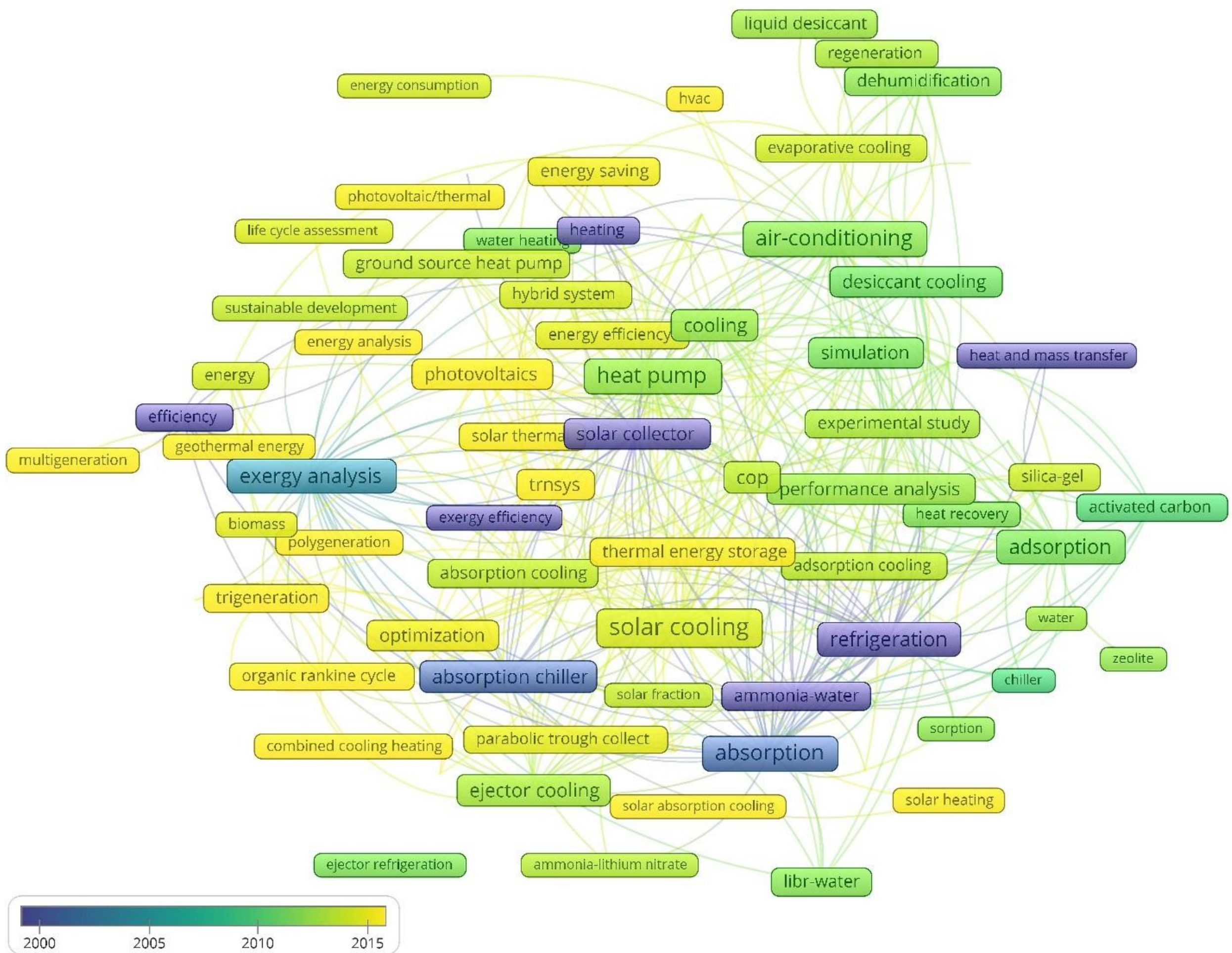

Fig. 9: Density visualization of author keywords with more than 20 occurrences.

A manual classification of keywords (see Appendix A, Table A. 1, A. 2, A. 3, A. 4, and A. 5) is performed based on the various technologies of solar cooling due to the vagueness of the clusters of keywords obtained from VOSviewer. In VOSviewer, many of the keywords are not correctly matched with the research themes of the clusters. This can be due to the reason that the keywords used by the authors in this field are inter-related, which leads to overlapping clusters. However, it is important to note that while manual clustering may not be accurate and leaves room for confusion, it is sufficient enough to see the temporal evolution of these clusters in our solar cooling database. For classification purpose, keywords that have appeared more than four times are mapped to the most commonly researched solar cooling technologies which are namely absorption cooling, adsorption cooling, desiccant cooling (solid and liquid), photovoltaic compression cooling, and solar combined power and cooling (Hwang et al., 2008).

It can be seen from fig. 10 that using solar thermal energy is the most common solar cooling technique. Absorption cooling technology shows remarkable growth compared to adsorption and desiccant solar cooling. Moreover, a steady increase in research can be observed with combined solar cooling technology in the last couple of years. Overall, research in solar thermal cooling technology has seen a rapid growth starting around 2004, which is still continuing, although there are a few drops over the years. This rate of growth can be explained by various technological and economic developments such as the development of improved solar collectors, invention of adsorption chillers, and increased market for solar thermal technology (Lazzarin and Noro, 2018). By the end of 2014, there were 1200 solar cooling installations, including all technology types and system capacity, mostly in Europe (Jakob, 2016). According to recent IEA statistics, this number has increased up to almost 2000 worldwide as of 2018, which indicates that solar cooling remains to be a niche market due to low demand (IEA, 2019). With respect to solar thermal cooling, the lack of economic viability and insufficient knowledge about solar thermal systems are the main obstacles to the broader use of this technology (Ayadi and Al-Dahidi, 2019). The Mediterranean countries remain to be the main market where Italy emerged as the most impressive one in 2018 due to the high investment subsidies. The Middle East and Australia have also seen a growth in the solar cooling market (REN21, 2019). Surprisingly, there has been no rapid growth in terms of publications in solar photovoltaic cooling, although photovoltaic panel prices have declined dramatically over the last 10-15 years, challenging solar thermal cooling. There are only a few examples of solar photovoltaic cooling so far that have been reported scientifically (Lazzarin and Noro, 2018). This may be due to the fact that PV is primarily considered for the production of electricity in general. This electricity can indeed be used for cooling, but also for other applications as well. Thus, less research focuses specifically on PV cooling, and consequently, these are not included in our research.

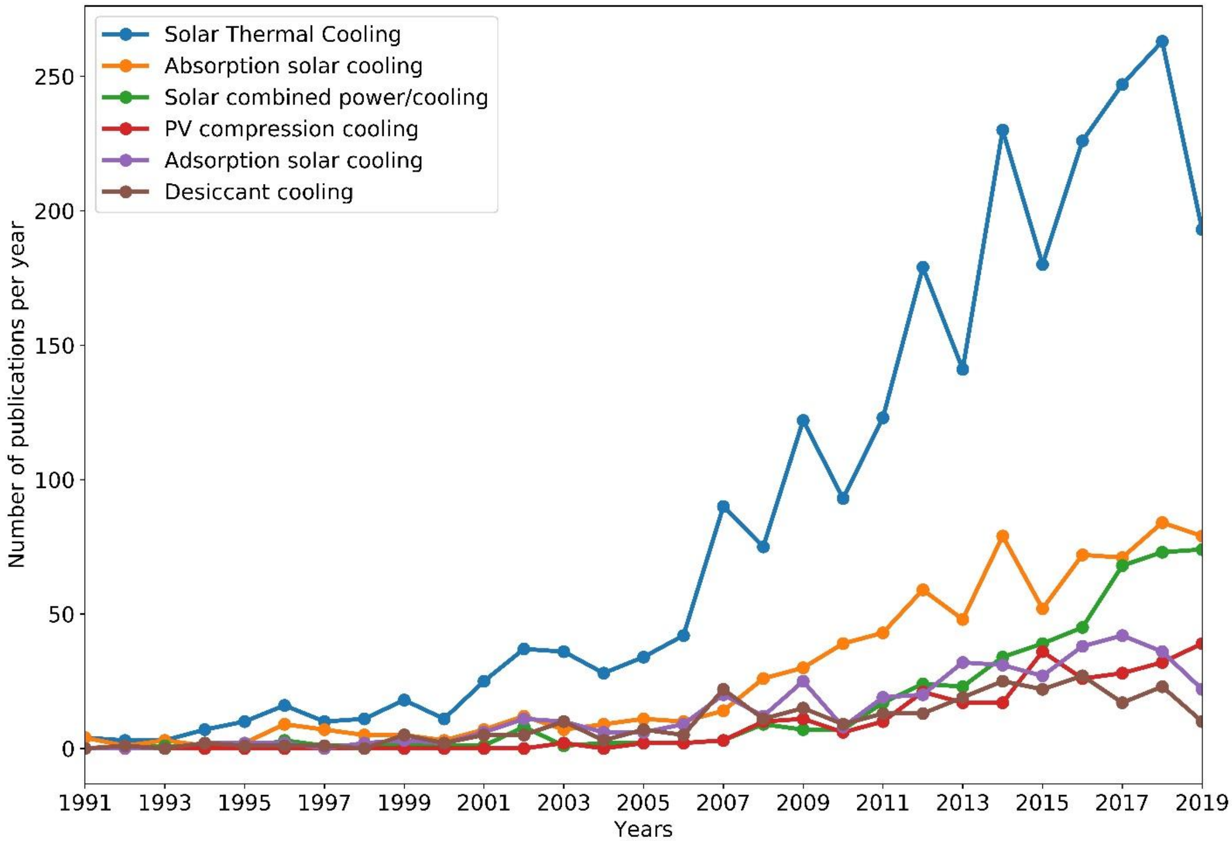

Fig. 10: Time evolution of different solar cooling technologies.

4. Concluding remarks

In this study, the scientific literature related to solar cooling is reviewed with the help of advanced data analysis and visualization. It was found that research in the solar cooling field has entered a stage of rapid development around 2005, and the numbers are still growing. The main contribution to this research domain is centered in China. Many other European and middle eastern countries are catching up as well. We presented the distribution of most productive countries, journals, authors, and institutions, and research communities involved in solar cooling research were identified and visualized. Analysis of author-defined keywords revealed that various solar cooling technologies had been developed and analyzed over the last 50 years, and the latest research hotspots are related to the optimization of solar cooling systems from energy, environmental, and economic point of view. Furthermore, time evolution in solar cooling research showed that solar thermal cooling is still predominant. Although there is an increased activity for utilizing solar photovoltaic cooling, it is yet to come in force. Therefore, solar photovoltaic cooling is one of the research domains which can be explored further in the future.

The results of a bibliometric study are strongly dependent on the quality of the data collected. Sincere efforts have been made in this paper to include all relevant papers in solar cooling research. However, due to the constraint of logical operators and possible alternatives of various keywords, it is difficult to claim the absolute inclusion of all possible records in this field. Nevertheless, we anticipate the minimal margin of error in the database will influence our findings profoundly, particularly the trends in solar cooling research. To monitor the progress of this research field qualitatively and explore the most interesting research questions, an extensive literature review is highly recommended.

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Appendix A. Keyword clusters

Table A.1 List of author-keywords under solar thermal cooling technology

Solar thermal Cooling				
Absorption compression	Composite adsorbent	Evacuated tube	Lithium chloride	Solar heat
Absorption cooling	Composite sorbent	Evacuated tube collector	Maisotsenko cycle	Solar pond
Absorption cooling system	Compound adsorbent	Evacuated tube solar collector	Membrane	Solar thermal
Absorption cycle	Compound parabolic concentrator	Evacuated tube solar collectors	Membrane distillation	Solar thermal collector
Absorption heat pump	Concentrated solar power	Evacuated tubes	Methanol	Solar thermal energy
Absorption heat pumps	Concentrating solar power	Evaporative	Multi-generation	Solar thermal refrigeration
Absorption machine	Cooling tower	Evaporative cooler	NH_3 H_2O	Solar thermal system
Absorption machines	Crystallization	Evaporative cooling	NH_3 $LiNO_3$	Solar thermal systems
Absorption power cycle	CSP	Falling film	NH_3 NaSCN	Solar water heating
Absorption refrigeration	DEC	Falling film absorber	NH_3-$LiNO_3$	Solid adsorption
Absorption refrigeration system	Dehumidification	Flat plate collector	Nitrate	Solid desiccant
Absorption refrigerator	Dehumidifier	Fresnel	Parabolic trough	Solid desiccant cooling
Absorption system	Desiccant	GAX	Parabolic trough collector	Solid gas sorption
Absorption systems	Desiccant coated heat exchanger	Generation	Parabolic trough collectors	Sorption
Activated carbon	Desiccant cooling	Generator	Parabolic trough solar collector	Sorption storage
Activated carbon ammonia	Desiccant cooling system	H_2O LiBr	Regeneration	Sorption system
Activated carbon methanol	Desiccant dehumidification	Heat storage	Regenerator	Sorption systems

Activated carbon-methanol	Desiccant dehumidifier	Heat transformer	Rotary desiccant wheel	Spray absorber
Adsorbate	Desiccant evaporative cooling	Humidification	Seasonal storage	Steam ejector
Adsorbent	Desiccant material	Humidification-dehumidification	Silica gel	Steam jet ejector chiller
Adsorption	Desiccant regeneration	Hydrogen	Silica gel water	Storage
Adsorption chiller	Desiccant system	Indirect evaporative cooling	Silica gel-water	Stratification
Adsorption cooling	Desiccant wheel	Ionic liquid	Silicagel	Thermal
Adsorption cooling system	Desiccant wheel DW	Ionic liquids	Silica-gel	Thermal cooling
Adsorption cycle	Desiccants	Kalina cycle	Single effect	Thermal energy storage
Adsorption heat pump	Desiccation	Latent heat storage	Single effect absorption chiller	Thermal storage
Adsorption kinetics	Desorption	LiBr	Single-effect	Thermochemical
Adsorption rate	Diffusion absorption	LiBr H_2O	Single-effect absorption chiller	Triple effect
Adsorption refrigeration	Diffusion absorption refrigeration	LiBr H_2O absorption chiller	Single stage	Triple effect absorption chiller
Adsorption refrigerator	Distillation	LiBr solution	Solar absorption	Two stage
Adsorption system	Double effect	LiBr water	Solar absorption chiller	Two-stage
Ammonia	Double effect absorption	LiBr- H_2O	Solar absorption cooling	Variable geometry ejector
Ammonia lithium nitrate	Double effect absorption chiller	LiCl H_2O	Solar absorption cooling and heating system	Vapor absorption
Ammonia water	Double-effect	Liquid	Solar absorption cooling system	Water ammonia

Ammonia water mixture	Double-effect absorption chiller	Liquid desiccant	Solar absorption refrigeration system	Water LiBr
Ammonia/lithium nitrate	Drying	Liquid desiccant air conditioning	Solar adsorption	Water lithium bromide
Ammonia-lithium nitrate	Ejector	Liquid desiccant cooling	Solar adsorption chiller	Water-lithium bromide
Ammonia-water	Ejector cooling	Liquid desiccant cooling system	Solar adsorption cooling	Working fluid
Ammonia-water mixture	Ejector cooling system	Liquid desiccant dehumidification	Solar adsorption refrigeration	Working fluids
Aqua ammonia	Ejector cycle	Liquid desiccant system	Solar adsorption refrigerator	Zeolite
Aqua-ammonia	Ejector refrigeration	Lithium	Solar assisted heat pump	Zeolite water
Bubble pump	Ejector refrigeration system	Lithium bromide	Solar desiccant cooling	Zeolites

Table A.2: List of author-keywords under solar photovoltaic cooling technology

PV compression cooling		
Carbon dioxide	Photovoltaics	Solar cell
CO_2	PV	Solar cells
Compression	PV system	Solar photovoltaic
Electrical efficiency	PV/T	Subcooled compression
Electricity	PVT	Vapor compression
ETC	R123	Vapor compression cycle
Photovoltaic	R134a	
Photovoltaic system	R22	
Photovoltaic thermal	R290	
Photovoltaic/thermal	R600a	
Photovoltaic/thermal collector	R744	

Table A.3: List of author-keywords under solar combined power/cooling technology

Solar combined power/cooling		
Biomass energy	District heating and cooling	Power
Biomass gasification	Fuel cell	Power and cooling
Brayton cycle	Heating and cooling	Power generation
CCHP	Heating and cooling systems	Rankine cycle
CCHP system	Heating and power	Scroll expander
CHP	Hybrid	Solar absorption cooling and heating system
Cogeneration	Hybrid system	Solar cooling and heating
Combined cooling	Hybrid systems	Solar desalination
Combined cooling and power	Multi generation	Solar heating and cooling
Combined cooling heating and power	Multigeneration	Solar heating and cooling systems
Combined cooling heating and power CCHP	Multi-generation system	Steam rankine cycle
Combined cooling heating and power CCHP system	NH_3 NaSCN	Supercritical CO_2
Combined cycle	ORC	Tri generation
Combined heat and power	Organic rankine	Trigeneration
Combined power and cooling	Organic rankine cycle	Tri-generation
Combined power and refrigeration cycle	Organic rankine cycle orc	trigeneration system
CPC	Polygeneration	

Table A.4: List of author-keywords under solar absorption technology

Absorption solar cooling		
Absorption cooling system	Double effect	Nitrate
Absorption cycle	Double effect absorption	Single effect
Absorption heat pump	Double effect absorption chiller	Single effect absorption chiller
Absorption heat pumps	Double-effect	Single-effect
Absorption machine	Double-effect absorption chiller	Single-effect absorption chiller
Absorption machines	Falling film	Solar absorption
Absorption power cycle	GAX	Solar absorption chiller
Absorption refrigeration	Generation	Solar absorption cooling
Absorption refrigeration system	Generator	Solar absorption cooling and heating system
Absorption refrigerator	H_2O LiBr	Solar absorption cooling system
Absorption system	Heat transformer	Solar absorption refrigeration system
Absorption systems	Hydrogen	Triple effect
	Ionic liquid	Triple effect absorption chiller
Ammonia/lithium nitrate	Kalina cycle	Two stage
Ammonia-lithium nitrate	LiBr	Two-stage
Ammonia-water	LiBr H_2O	Vapor absorption
Ammonia-water mixture	LiBr H_2O absorption chiller	Water ammonia
Aqua-ammonia	LiBr solution	Water LiBr
Bubble pump	LiBr water	Water lithium bromide
Calcium chloride	LiBr-H_2O	Water-lithium bromide
Collector/regenerator	Lithium	Working fluid
Diffusion absorption	Lithium bromide	Working fluids
Diffusion absorption refrigeration	Lithium bromide solution	Spray absorber
Distillation	NH_3-$LiNO_3$	Ionic liquids
		Falling film absorber

Table A.5: List of author-keywords under solar adsorption and desiccant technology

Adsorption solar cooling	**Desiccant solar cooling**
Adsorbate	Activated carbon
Adsorption	Activated carbon ammonia
Adsorption chiller	Activated carbon methanol
Adsorption cooling	Activated carbon-methanol
Adsorption cooling system	Adsorbent
Adsorption cycle	Carbon
Adsorption heat pump	Desiccant coated heat exchanger
Adsorption kinetics	Desiccant dehumidifier
Adsorption rate	Desiccant material
Adsorption refrigeration	Desiccant regeneration
Adsorption refrigerator	Desiccant wheel
Chemisorption	Desiccant wheel DW
Composite adsorbent	Desiccation
Composite sorbent	LiCl H_2O
Compound adsorbent	Liquid
Ethanol	Liquid desiccant
Silica gel water	Liquid desiccant air conditioning
Silica gel-water	Liquid desiccant cooling
Silicagel	Liquid desiccant cooling system
Silica-gel	Liquid desiccant dehumidification
Solar adsorption	Liquid desiccant system
Solar adsorption chiller	Lithium chloride
Solar adsorption cooling	Membrane
Solar adsorption refrigeration	Membrane distillation
Solar adsorption refrigerator	Methanol
	Regenerator
	Rotary desiccant wheel
	Silica gel
	Solid adsorption
	Solid desiccant
	Solid desiccant cooling
	Zeolite
	Zeolite water
	Zeolites