APPLICATION OF NANOFLUIDS IN SOLAR ENERGY RESEARCH: A BIBLIOMETRIC ANALYSIS OF TRENDS FROM 2007 TO 2021 AND FUTURE IMPLICATIONS

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Abstract; The advent of nanotechnology has spurred the development and utilization of nanomaterials and nanofluids in solar energy research. This paper presents for the first time a bibliometric analysis of scientific publications on nanofluid application to solar energy research. Data sourced from the Scopus® database covering 15 years were employed in this study. Network analyses of the participating organizations and countries, citations of documents and sources, and co-occurrence of author keywords were performed using VOS viewer® software. The result showed that 1630 articles consisting majorly of journals (76.4%) were published with the year 2021 recording 23.48% of the total publications. Engineering (922 articles) emerged as the subject of study with the most published articles. The results revealed that China and the University of Malaya with the highest number of publications were the most productive country and organization, respectively. The work of Ghasemi H. published in 2014 was the leading paper with 1049 citations while "Solar Energy" was the leading journal with 5456 citations. The most used keyword was "Nanofluid". Research hotspots focused on the optical and thermal properties of different nanofluids and their application in solar energy devices. Development of green and novel nanoparticles and base fluids, deployment of thermal enhancement techniques, and increased studies on hybrid nanofluids and solar still are future research undertakings. The compendium of findings herein is expected to benefit the solar energy research community and serve as the catalyst for future studies in this regard.

Keywords: bibliometric analysis, nanofluid, nanoparticles, solar collector, solar energy

1. INTRODUCTION

The aftermath of prolonged dependence on fossil fuels (non-renewable) for electricity generation is climate change and global warming [1], [2]. Amongst the solutions to this challenge are the use of solar, wind, tidal, geothermal, and nuclear energy as renewable sources of electricity generation [1], [3]. The abundance of sunshine, the huge potential of harvesting solar energy from the sun, the need for clean energy, and the ever-increasing demand for energy have ignited unprecedented research in this regard [1], [3]–[5]. Solar energy is harvested as electricity and heat using photo-thermal, photo-chemical, and photo-voltaic conversion, of which photo-thermal conversion is the most used because of its simplicity and directedness. Solar energy harvesting has found tremendous applications in flat plate collectors, solar still, parabolic collectors, thermal storage, concentrated solar plants, vacuum tube collectors, direct absorption solar collectors, and hybrid PV/Thermal collectors [3], [6], [7].

Owing to the application, different working fluids such as ethylene glycol, water, thermal oil, water-ethylene glycol mixture, etc., have been deployed in solar energy research [3], [8]. However, low thermal efficiencies have been reported as a result of their low solar radiation absorption abilities due to their poor thermal, optical, and other fluid properties [8]. The advent of nanotechnology via the pioneering works of Masuda et al. [9] engineered the formulation of nanofluids (mono and hybrid) as advanced working fluids with improved optical, thermal, and fluid properties in comparison with the conventional fluids [10], [11]. Mono and hybrid nanofluids have been formulated as superior photothermal materials employed in different solar energy applications such as flat plate [11]–[13], direct absorption [3], [8], [14], [15], vacuum tube [7], [16], [17], U-tube [18], [19], parabolic solar [20]–[22], and hybrid PV/thermal collectors [23], [24], and concentrated solar plant [6], [25]. Results showed that the deployment of mono and hybrid nanofluids enhanced the thermal efficiency of these solar energy devices compared with conventional thermal fluids.

Bibliometrics as a branch of information science uses statistical and quantitative techniques to evaluate scientific publications to study research evolution. This applies to any specific field of study. Bibliometrics can also be used to unfold the initiation and growth of new technology [26].

It is suitable to monitor information and management of knowledge. Several authors have employed bibliometrics in diverse areas of study including nanotechnology and nanomaterials applications in food packaging [27], wastewater treatment [28], and China's emergence in nanotechnology [26], agriculture [29], indoor air quality [30], neuroscience [31], energy-saving [32], biodiesel research [33], carbon mitigation technology [34], atmospheric pollution sources [35], nanofluid applications [36], big and streaming data on carbon emission and management [37], and musculoskeletal science [38], to monitor research hotspots and trend.

A limited number of bibliometric studies have been found in the open literature concerning nanotechnology and nanomaterials application and solar energy research [26]–[28], [36], [39]–[41]. Guan and Ma [26] used bibliometric analysis to study the emergence of China in the community of nations concerning nanoscience and nanotechnology research. The data were from 1985 to 2004. They showed that China is an emerging force behind the United States in terms of nanoscience and nanotechnology development. In the bibliometric studies conducted by Aleixandre-Tudo et al. [27] (1997 – 2018) and Giwa et al. [36] (1998 – 2020), China and Iran were reported to be the leading countries in the employment of nanomaterials and nanotechnology in food packaging and nanofluid research, respectively. De Paulo and Porto [40] performed a bibliometric study on solar energy open innovation and technologies using data from the web of Science covering a period of 14 years (2000 – 2013). China and United States were the leading countries in terms of publication and collaboration. In a bibliometric study of solar energy-related research conducted by Dong et al. [39] from 1991 to 2010, they reported that the United States followed by China topped the list of countries with the most publications. Recently, David et al. [41] performed a bibliometric analysis of solar energy management research tendencies and revealed that the United States, India, and China had the most scientific publication outputs.

The above literature survey showed that bibliometric analyses were carried out on nanomaterials and solar energy research, separately. Thus, implying that a bibliometric study on the utilization of nanofluids in solar energy research is lacking. This study presents the deployment of mono and hybrid nanofluids as advanced fluids in different solar collectors and the evolution of nanofluid-based solar energy research (NBSER). The availability of scientific publications in the public domain for over 10 years of research on the applications of diverse nanofluids (mono and hybrid) in different solar energy devices such as solar collectors, calls for the need to perform a bibliometric study to evaluate and understand research trends in terms of the hotspot topics, research evolution, and future research. The publication pattern and growth, the field of study involved, collaboration of participating organizations and countries, and top-cited research papers and journals were performance metrics reported in this work.

2. METHODOLOGY

2.1. Data source

The data used in this work were sourced from the Scopus® database being the largest in the world [32]. In addition, this database is known to possess more than 20% of the number of articles in the Web of Science database [37]. The search query (nanofluid* AND "solar collector*" OR "solar energy collector*" OR "solar energy" OR "solar energy harvesting") was typed into the title, abstract, and keywords space on the Scopus® website. Limits were set for the year (beginning to 2021), document type (articles, review, conference paper, book chapter, and conference review), source type (journal, book series, and conference proceedings), and language (English only). The query used in this work was selected in line with the topic, focus, and spelling. The retrieval of data related to individual solar collectors, nanoparticles, base fluids, etc., was carried out by including the appropriate words in the initial query. The final filtered data contained the citation, author name, year page, affiliation, keywords, title, etc. The retrieval date was May 30th, 2022.

2.2. Data analysis

The final obtained data were input into the VOS Viewer® software to generate and analyze networks for the bibliometric analysis. The software helps in the visualization of the dynamics and structures of scientific outputs [42]. In this study, the networks of co-authorships of organization and country, citation of source and document, and co-occurrence of author keywords were analyzed using the software according to previous studies in the literature [34], [37]. The impact factor, Quartile, h-index, and Cite Score of the journals were used as indicators to evaluate their performances. The values associated with these indicators were sourced from the Scimago®, Journal Citation Reports of 2021, Scopus®, and the home page of journals. The network created using the VOS Viewer® contains items (bubbles and labels) and links. Items are bubbles and labels whereas the links as lines connecting the bubbles in the network. Big bubble size indicates the high weight of the item and a thick link signifies high link strength. The closeness of the bubbles indicates the relatedness of the items [41].

3. RESULTS AND DISCUSSION

3.1. Research publication growth

The publication year, number, percent, and growth of scientific outputs for the NBSER are given in Table 1. A total of 1630 articles were published concerning NBSER from 2007 to 2021. This translates to 109 papers per annum. The share of journals, reviews, conference papers, book chapters, and conference reviews published was 76.38%, 9.14%, 13.25%, 0.74%, and 0.49% of the total number of papers, respectively. The publication trend was characterized by an increase in units (1 – 8 papers) from 2007 to 2009, an increase in tens (12 – 80 papers) from 2010 to 2015, and an increase in hundreds (104 – 386 papers) from 2016 – 2021. The period from 2007 to 2009 marked a slow start in the NBSER which indicated the early stage of the knowledge and research on nanofluids coupled with their application to solar energy. From 2010 on, awareness, and knowledge grew continually leading to more publications as the research community was abreast of the development of nanofluids and their applications in improving the efficiency and performance of solar collectors. A total of 19 fields of study participated in the NBSER. Engineering was the most productive field having published 29.27% of the total number of scientific articles.

Table 1. Publication trend of nanofluid-based solar energy research

Year	Publications	% publication	Growth
2021	386	23.68	42.44
2020	271	16.63	15.81
2019	234	14.36	15.84
2018	202	12.39	31.17
2017	154	9.45	48.08
2016	104	6.38	30.00
2015	80	4.91	6.67
2014	75	4.60	59.57
2013	47	2.88	56.67
2012	30	1.84	25.00
2011	24	1.47	100.00
2010	12	0.74	50.00
2009	8	0.49	300.00
2008	2	0.12	100.00
2007	1	0.06	

3.2. Country participation

The analysis of the co-authorship of country was performed and the top 20 countries that participated in the NBSER are given in Table 2. The analysis showed that 133 countries participated in the NBSER by way of scientific publications, and 51 countries were found to publish at least four articles with at least four citations. The top five countries with the highest number of publications were China (325 papers; 14.7%), India (317 papers; 14.4%), Iran (282 papers; 12.8%), Malaysia (168 papers; 7.6%), and Saudi Arabia (139 papers; 6.3%). These countries contributed over 60% of the total publication of 2209 of the top 20 countries with China emerging as the most productive country. The top five countries with the most citations were Iran (12746 citations), China (11113 citations), the United States (8091 citations), India (7252 citations), and Malaysia (6991 citations) while the United States has the highest average citations of 66.32 (from 122 articles and 8091 citations). This implies that the United States was the most cited country in terms of citations per article. It is observed that 11 Asian countries (55%) make up the top 20 countries that participated in previous studies that reported China as the most productive country regarding research on the nanomaterial utilization for wastewater treatment and food packaging, and solar energy development and open innovation [27], [39]–[41], [43].

Table 2. Country participation in nanofluid based solar energy research

Country	Total link strength	Documents	Citations	Average citations
China	241	325	11113	34.19
India	190	317	7252	22.88
Iran	247	282	12746	45.20
Malaysia	238	168	6991	41.61
Saudi Arabia	283	139	5051	36.34
United States	109	122	8091	66.32
Pakistan	192	108	3809	35.27
United Kingdom	160	95	3069	32.31
Turkey	77	72	3110	43.19
Egypt	94	70	2009	28.70
Spain	44	68	1452	21.35
United Arab Emirates	109	68	3300	48.53
Australia	101	67	3241	48.37
Iraq	91	66	1823	27.62
Italy	53	60	1957	32.62
South Korea	21	47	1181	25.13
Bangladesh	42	42	731	17.40
Vietnam	83	38	1348	35.47
Greece	15	30	1921	64.03
Canada	46	25	858	34.32

The network of the co-authorship of country for the NBSER is presented in fig. 1. The network analysis classified the countries into 11 clusters as depicted by the bubble colors based on the co-authorship connection. With

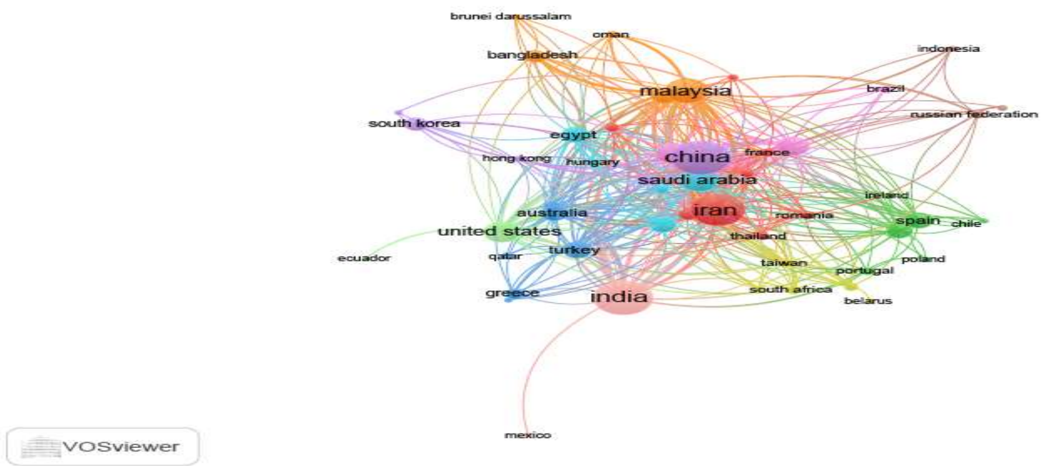

Fig. 1. Country participation network for nanofluid based solar energy research

the bubble and label size indicating the country's number of publications, it can be observed that China (purple bubble), followed by India (peach bubble), Iran (red bubble), Malaysia (orange bubble), and Saudi Arabia (turquoise blue) were the five most prolific countries. The closeness of China to Iran, France, and Saudi Arabia showed strong relatedness between them. This indicates a strong research collaboration between the researchers based in these countries. Similarly, a strong research collaboration was noticed between the United States and Australia, Qatar, and Turkey as illustrated by the nearness of the countries in fig. 1. However, relatively weak collaborative works can be noticed between China and South Korea, Russian Federation, Indonesia, South Africa, Greece, and Spain. With the line thickness between the countries signifying the link strength, the total link strength of the network showed the degree of research collaboration among the countries. Total link strengths of 241, 190, 247, 239, 192, and 283 were recorded for China, India, Iran, Malaysia, Pakistan, and Saudi Arabia, respectively, showing that these countries have the highest frequency of collaborations of all the countries that participated in the NBSER. This implies that Saudi Arabia has the most research collaboration of all the countries that participated in NBSER.

3.3. Institution participation

The results of the co-authorship of organization analysis showed that 3103 organizations participated in the NBSER with 117 organizations having more than four articles and citations. Table 3 gives the top 18 participating organizations. It can be observed that the University of Malaya (Malaysia) has the most publication (30 articles). This was followed by the Harbin Institute of Technology (China), Babol Noshirvani University of Technology (Iran), Ton Duc Thang University (Vietnam), King Fahd University of Petroleum and Minerals, Saudi Arabia, and Ferdowsi University of Mashhad (Iran) with 29, 25, 23, 22, and 16 articles, respectively. The three top-cited organizations were the Ferdowsi University of Mashhad (Iran), University of Malaya (Malaysia), and Harbin Institute of Technology (China) with 1760, 1758, and 1615 citations, respectively while the University of Engineering and Technology (Pakistan) has the most citation per article (137.8). It shows that the top six organizations that participated in NBSER are from Asia with 16 of the top 18 organizations emanating from the same continent. This makes Malaysia and Asia frontiers in the applications of nanofluid and nanomaterial in solar energy research. These results are supported by the works of Jiang et al. [28] and Aleixandre-Tudo et al. [27] on nanomaterials and those of Dong et al. [39], David et al. [41], and de Paulo and Porto [40] on solar energy research.

The network of co-authorship of organization for the NBSER is presented in fig. 2. The network is classified into 9 clusters as identified by 9 different colors. The biggest bubble and label size identified as the University of Malaya (Malaysia) showed that this organization has the highest number of scientific outputs based on the co-authorship network connection. In fig. 2, the displayed organizations showed weak relatedness as poor network connections were found among them. Also, only organizations within the same cluster have relatively strong relatedness (network connection), thus, research collaboration was strong within organizations within each cluster. For example, strong collaborative works were noticed between the University of Leeds and the Harbin Institute of Technology, which were within the red cluster. The organizations with the most collaboration works can be linked to the highest total link strengths of 29, 26, and 21 recorded for Babol Noshirvani University of Technology, Ton Duc Thang University, and University of Malaya, respectively.

3.4. Citations of participatory publications

The analysis of the citation of document performed concerning the application of nanofluids in solar energy research showed that a total of 1680 articles were published with 1134 papers recorded to have a minimum of 10 documents. A list of the 20 most cited papers on NBSER is given in Table 4. The five most cited papers were the works of Ghasemi et al. (2014), Mahian et al. (2013), Otanicar et al. (2010), Yousefi et al. (2012a), and Tyagi et al. (2009) with citations of 2323, 1540, 1080, 851, and 782, respectively. Thus, the work of Ghasemi et al. (2014) was the leading paper and focused on the utilization of volumetric trough solar collectors for steam generation using nanofluid as a thermal fluid. Fifteen of the top 20 cited papers were original research papers while five were review articles and they reported the deployment of different types of nanofluids in solar stills and solar collectors. The normalized citations of the top-cited papers as shown in Table 4 gave an estimation of the influence of year of publication, journal type, and subject area on the citation counts of the papers. Based on the normalized citation, the five top-cited papers in the

Table 3. Institution participation in nanofluid based solar energy research

Institution	Total link strength	Documents	Citations	Average citations
University of Malaya, Malaysia	21	30	1758	58.60
Harbin Institute of Technology, China	18	29	1615	55.69
Babol Noshirvani University of Technology, Iran	26	25	1288	51.52
Ton Duc Thang University, Vietnam	29	23	618	26.87
King Fahd University of Petroleum and Minerals, Saudi Arabia	14	22	1609	73.14
Ferdowsi University of Mashhad, Iran	10	16	1760	110.00
University of Leeds, United Kingdom	17	15	815	54.33
Bangladesh University of Engineering and Technology, Bangladesh	2	14	214	15.29
Duy Tan University, Vietnam	14	11	357	32.45
Comsats University Islamabad, Pakistan	10	11	176	16.00
Beihang University, China	9	9	465	51.67
Lancaster University, United Kingdom	11	9	253	28.11
Quaid-I-Azam University, Pakistan	5	8	677	84.63
Shahrood University of Technology, Iran	7	8	530	66.25
University of Tehran, Iran	4	7	461	65.86
University of Engineering and Technology, Pakistan	4	6	827	137.83
Beihang University, China	8	6	297	49.50
College of Technological Studies, Kuwait	2	6	20	3.33

Fig. 2. Institution participation network for nanofluid based solar energy research

NBSER were Ghasemi et al. (2014), Mahian et al. (2013), Mahian et al. (2019), Yousefi et al. (2012a), and Tyagi et al. (2009) with values of 13.42, 12.06, 11.96, 8.96, and 6.23, respectively. The citation counts and year of publication are observed to affect the value of the normalized citations of papers. For instance, the work of Ghasemi et al. (2014) has a citation value of slightly three-fold higher than that of Mahian et al. (2019) but the formal was published five years earlier than the latter, which resulted in normalized citations of 13.42 and 11.96, respectively. This shows the effect of an article's year of publication and citation count on the normalized citation.

Fig. 3 shows the network of the analysis of citation of document. The network was classified into 16 clusters as indicated by the colors of the bubbles. The red bubble labeled Ghasemi et al. (2014) was observed to be the largest bubble and thus, revealing that the work of Ghasemi et al. (2014) was the most cited paper. Other leading papers were those of Mahian et al. (2013) – sky blue bubble, Shin D. (2011a) – purple bubble, and Taylor R.A. (2011a) – perch bubble. Strong relatedness was observed between Ghasemi et al. (2014) and Taylor R.A. (2011a) while very weak relatedness was noticed between Mahian et al. (2013) and Shin D. (2011a).

3.5. Citations of participatory sources

Based on the analysis of the citation of source, the number of journals that participated in the NBSER was 443. With a minimum of four documents and four citations, 79 journals were involved in the NBSER. The 20 leading journals were listed in Table 5. The five leading journals that participated in NBSER were *Solar Energy* (citations = 5456), *Renewable Energy* (citations = 5013), *Energy Conversion and Management* (citations = 4641), *Renewable and Sustainable Energy Review* (citations = 4289), and *International Journal of Heat and Mass Transfer* (citations = 3830). Therefore, *Solar Energy* is the most-cited journal in NBSER and also published the highest number of scientific papers (106). This implies that most authors in the NESER community published their research output in *Solar Energy* and also cite papers published in *Solar Energy*. These scenarios which contributed to the quality and impact of *Solar Energy* attracted performance metrics of impact factor of 5.742, h-index of 181, Cite Score of 8.9, and rank Q1 (quartile). Of the 20 top-cited journals, only one is dedicated to review articles. The scope of four of the top five cited journals centered primarily on energy (renewable and solar energy inclusive) while one mainly focused on heat transfer as a form of energy.

From Table 5, it can be observed that the *Solar Energy* journal published the highest number of papers (106), followed by *Renewable Energy* (87), *Energy Conversion and Management* (72), *Solar Energy Materials and Solar Cells* (58), and *Journal of Thermal Analysis and Calorimetry* (54). Also, the *Nanoscale Research Letters* has the highest citation per paper (142.25) followed by *Experimental Thermal and Fluid Science* (117) and the *International Journal of Heat and Mass Transfer* (95.75). In addition, the impact factor range of 2.384 – 17.881 and h-index of 37 – 295 were recorded. The relatively high values of these metrics coupled with a high Cite Score (for applicable journals) and 85% of the top 20 journals ranked Q1, showed that these top-rated journals were impactful in the scientific journal community. This further proved the high quality of works published through these outlets on nanofluid engagement in solar energy studies. Fig. 4 illustrates the network of the citation of source analysis for the application of nanofluids to solar energy research. The network classified the sources into 10 clusters. It can be observed that the biggest bubble was the purple bubble labeled “Solar Energy”. This also implies that *Solar Energy* followed by *Renewable Energy* were the two most cited and leading journals in NBSER.

3.6. Co-occurrence of keywords

Analysis of keywords is a viable tool used to evaluate scientific research trends, evolution, and hotspots in bibliometric studies [33]. The network analysis of the co-occurrence of author keywords of NBSER showed that 2698 keywords were involved in this research. With the minimum occurrence of 10 keywords, 89 keywords were found to be used in the NBSER. A list of the top 22 keywords is provided in Table 6. The top seven leading

Table 4. Citations of participated papers in nanofluid based solar energy research

Paper	Citations	Normalised citations	Publication type
Ghasemi H. (2014)	1049	13.42	Original
Mahian O. (2013)	937	12.06	Review
Otanicar T.P. (2010)	638	8.96	Original
Yousefi T. (2012a)	509	6.23	Original
Tyagi H. (2009)	486	4.63	Original
Taylor R.A. (2011b)	410	4.48	Original
Shin D. (2011a)	358	3.91	Original
Mahian O. (2019)	338	11.96	Review
Lenert A. (2012)	328	4.01	Original
Taylor R.A. (2011a)	300	3.28	Original
Mehrali M. (2014b)	287	3.67	Original
Gupta M. (2017)	275	6.07	Review
Kasaeian A. (2015)	273	4.62	Review
Ni G. (2015)	265	4.49	Original
Mahian O. (2017)	262	5.78	Original
Bellos E. (2016)	241	4.14	Original
Saidur R. (2012)	223	2.73	Original
Verma S.K. (2015b)	221	3.74	Review
Yousefi T. (2012b)	220	2.69	Original
Taylor R.A. (2012a)	214	2.62	Original

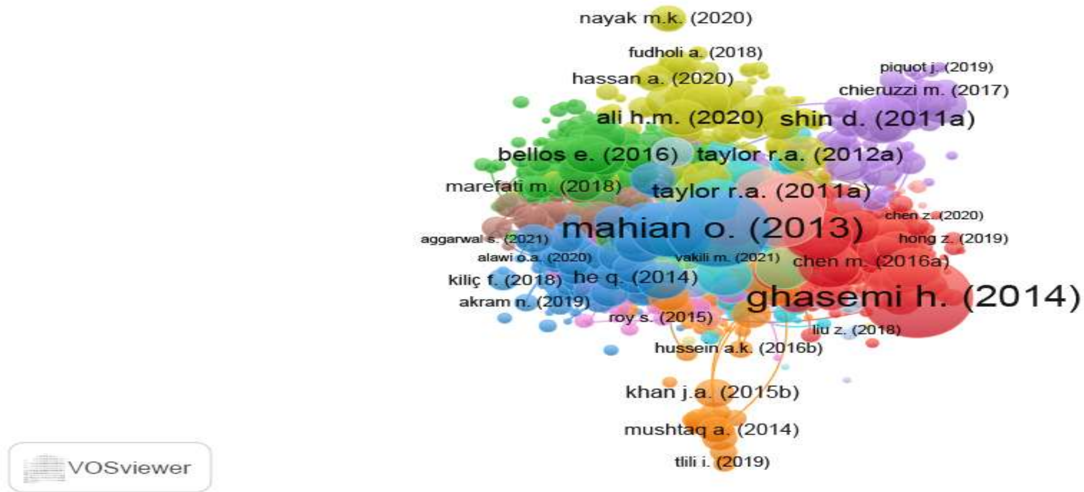

Fig. 3. Document citation network for nanofluid based solar energy research

Table 5. Citations of participated sources in nanofluid based solar energy research

Journal	Total link strength	Documents	Citations	Average citations	HI	IF	CS	Q
Solar Energy	2247	106	5456	51.47	181	5.742	8.9	Q1
Renewable Energy	2034	87	5013	57.62	191	8.001	10.8	Q1
Energy Conversion and Management	1607	72	4641	64.46	192	9.709	15.9	Q1
Renewable and Sustainable Energy Reviews	1240	45	4289	95.31	295	14.98	30.5	Q1
International Journal of Heat and Mass Transfer	1061	40	3830	95.75	208	5.584	9.6	Q1
Solar Energy Materials and Solar Cells	1176	58	2577	44.43	186	7.267	13.1	Q1
Applied Thermal Engineering	968	50	2231	44.62	158	5.295	10.1	Q1
Applied Energy	719	27	1798	66.59	212	9.746	17.6	Q1
Journal of Cleaner Production	604	24	1302	54.25	200	9.297	13.1	Q1
Journal of Thermal Analysis and Calorimetry	601	54	1244	23.04	92	4.626	NA	Q2
Energy	485	30	1232	41.07	193	7.147	11.5	Q1
International Communications in Heat and Mass Transfer	370	28	1193	42.61	110	5.683	6.1	Q1
Nanoscale Research Letters	154	8	1138	142.25	107	4.703	NA	Q1
Journal of Molecular Liquids	379	25	952	38.08	111	6.165	8.42	Q1
Journal of Solar Energy Engineering, Transactions of the ASME	108	15	928	61.87	83	2.384	NA	Q2
Nano Energy	128	9	738	82.00	171	17.88	25.6	Q1
Sustainable Energy Technologies and Assessments	510	34	596	17.53	39	5.353	5.9	Q2
International Journal of Energy Research	393	29	506	17.45	95	5.164	NA	Q1
Case Studies in Thermal Engineering	176	22	470	21.36	37	4.724	5.9	Q1
Experimental Thermal and Fluid Science	250	4	468	117.00	111	3.444	7.4	Q1

NA = not available

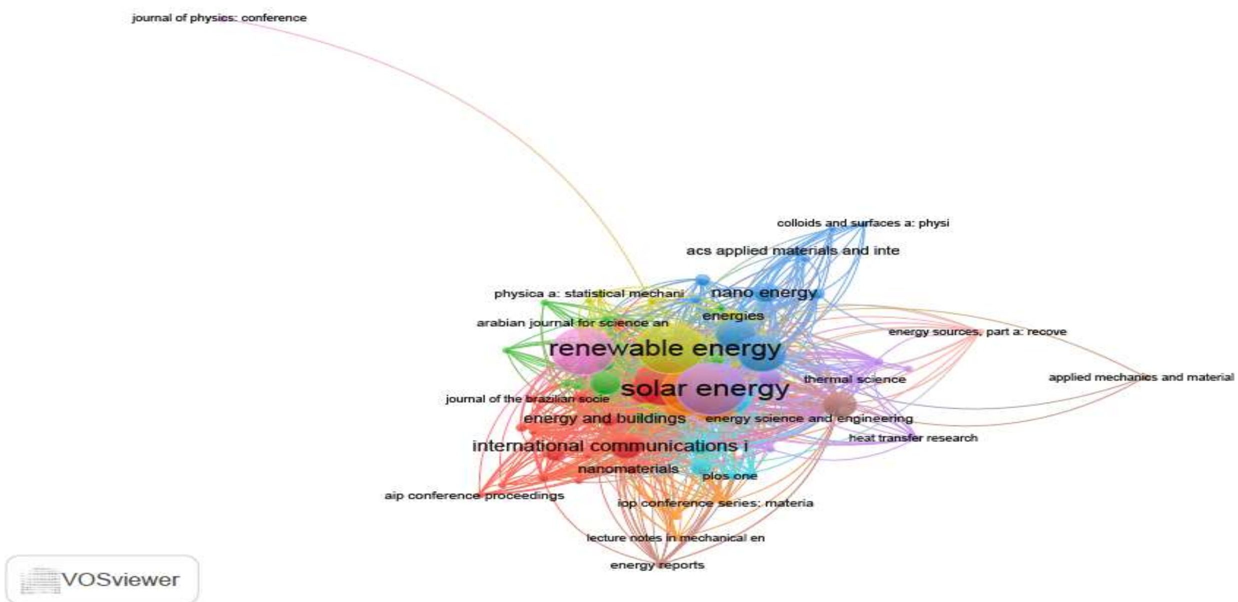

Fig. 4. Source citation network for nanofluid based solar energy research

keywords in the order of increasing occurrence were "Nanofluid" (833 occurrences), "Solar Energy" (292 occurrences), "Thermal Efficiency" (171 occurrences), "Solar Collector" (160 occurrences), "Direct Absorption Solar Collector" (111 occurrences), "Nanoparticles" (105 occurrences), and "Heat Transfer" (104 occurrences). It can be noticed that "Nanofluid" was the keyword with the highest occurrence followed by "Solar Energy". This was because they were important search words relevant to the retrieval of data related to NBSER. In addition, "Nanofluid" and "Nanoparticles" are advanced thermal fluids and materials, respectively, utilized in NBSER, thus, emphasizing their importance via the high values of their occurrence. The leading keywords given in Table 6 revealed the hotspots in the solar energy applications of diverse nanoparticles and nanofluids. The employment of "Nanoparticles" – mono and hybrid – for the formulation of nanofluids was found to be increasingly crucial to solar energy research. The use of different solar collectors with decreasing order of importance as depicted by the occurrences of the keyword are direct absorption, flat plate, parabolic trough, photovoltaic/thermal, concentrated solar power, etc., which are used along with nanofluids to improve the thermal, exergy, and energy efficiency, thermal performance, and exergy, and reduce entropy generation via enhanced heat transfer, thermophysical properties (mainly thermal conductivity), and optical properties were observed to be the leading and trending areas of application of nanoparticles and nanofluids in solar energy research.

Table 6. Keywords in nanofluid based solar energy research

Keyword	Total link strength	Occurrences	Average citations
Nanofluid	1502	833	40.17
Solar Energy	568	292	41.53
Thermal Efficiency	325	171	39.21
Solar Collector	319	160	44.69
Direct Absorption Solar Collector	194	111	36.29
Nanoparticles	239	105	50.71
Heat Transfer	245	104	38.25
Flat Plate Solar Collector	198	102	45.95
Parabolic Trough Collector	159	88	28.90
Thermal Conductivity	173	85	53.82
Hybrid Nanofluid	127	65	24.14
Exergy	133	51	37.57
Entropy Generation	96	45	41.38
Optical Properties	101	43	49.72
Stability	64	36	34.78
Thermal Energy Storage	90	35	42.91
Heat Transfer Enhancement	74	30	43.80
Thermal Performance	61	30	34.33
Energy	73	28	31.57
Energy Efficiency	76	28	25.50
Photo-Thermal Conversion	44	27	32.19
Photothermal Conversion	46	27	27.63

In addition, the leading studied parameter was "Thermal Efficiency" whereas "Direct Absorption Solar Collector" was the leading solar collector type. The trending technique and base fluid used in the NBSER was the computational fluid dynamics and molten salts, respectively, with the stability of nanofluids receiving increasing research attention. Thus, it can be inferred from the top 22 leading keywords that the use of advanced and superior materials/thermal fluids was significant to the future of solar energy research. Fig. 5 presents the network of the analysis of the co-occurrence of author keywords. The keywords were classified into 7 clusters according to the network connection of the analysis. The fig. 5 showed that the keyword "Nanofluid" has the largest bubble size (red) and it can be said to have the highest number of occurrences. This was followed by "Solar Energy" with the green bubble. The total link strengths of 1502, 568, 325, 319, and 245 were recorded for "Nanofluid", "Solar Energy", "Thermal Efficiency", "Solar Collector", and "Heat Transfer" as the leading five keywords. These values indicate the keyword network connections represented by the lines between the keywords and thus suggest the interaction between the keywords.

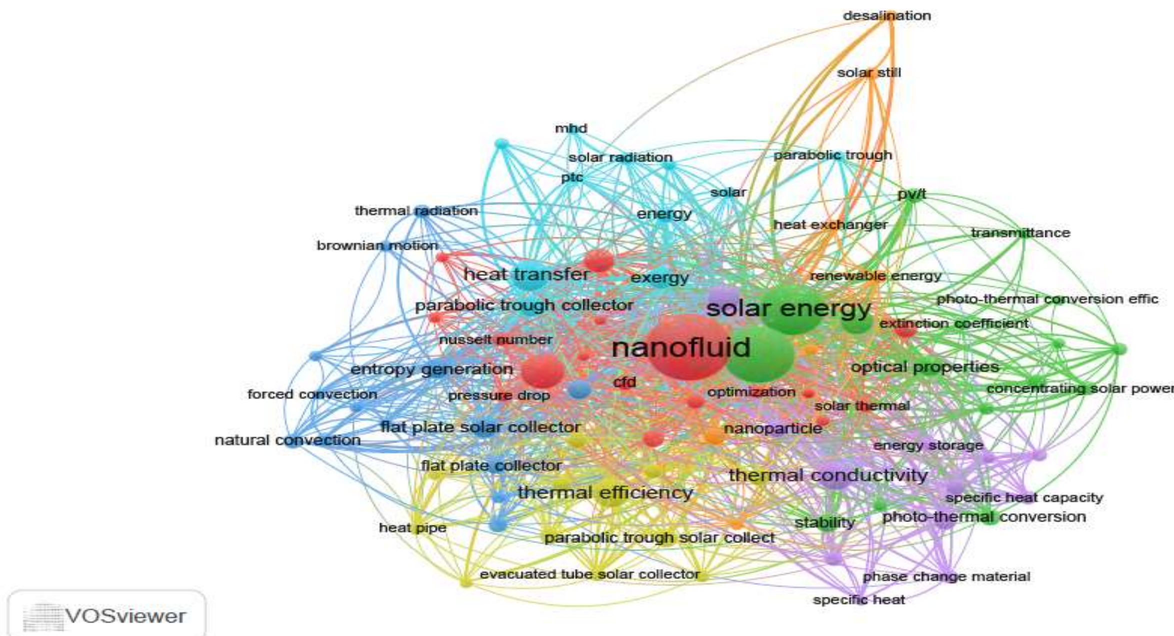

Fig. 5. Keyword network for nanofluid based solar energy research

4. EVOLUTION OF RESEARCH AND FUTURE DEVELOPMENT

4.1. Evolution of studied solar energy devices

The NBSER involves the utilization of nanofluids as advanced thermal fluids in different solar collectors (flat plate, parabolic, vacuum tube, direct absorption, heat pipe, and photovoltaic /thermal), solar stills, and concentrated solar power. Fig. 6 illustrates the temporal trend of publications regarding the use of nanofluids in various solar energy devices. The trend showed that the thermal performance of direct absorption solar collectors was first studied (2007) using Al_2O_3/water nanofluid [44], followed by the flat plate collector and the solar steam generation devices in 2009. For the period under consideration, a total of 343, 285, 281, 95, 94, 86, 69, and 44 articles have been published concerning the use of various nanofluids in trough collectors, flat plate collectors, direct absorption solar collectors, photovoltaic/thermal collectors, concentrated solar power, vacuum collectors, heat pipe collectors, and solar stills, respectively. The deployment of nanofluids in trough solar collectors was the most studied solar device in this regard which came after those of direct absorption and flat plate collectors. Publications on trough solar collectors attracted over 25% of the total number of publications while those on flat plate and direct absorption solar collectors were 21.15% and 20.95%, respectively. The NBSER community showed an increasing interest in the use of nanofluids in the studies involving trough, flat plate, and direct absorption solar collectors as revealed by the publication of 80, 69, and 45 scientific articles, respectively, in 2021 (see fig. 6). In addition, steady growth in interest amongst researchers is observed with the application of nanofluids in solar still studies as reflected in fig. 6.

4.2. Evolution of nanofluid application in solar energy devices

The temporal evolution of NBSER (since inception to 2021) as analyzed using the co-occurrence of author keywords is provided in fig. 7. The items are embedded in four clusters as identified by the purple, green, lemon, and yellow bubbles. Each cluster with its unique color represents a specific trend in the NBSER. The purple, green, lemon, and yellow bubbles represent the temporal evolution for the period of 2007 – 2017, 2018, 2019, and

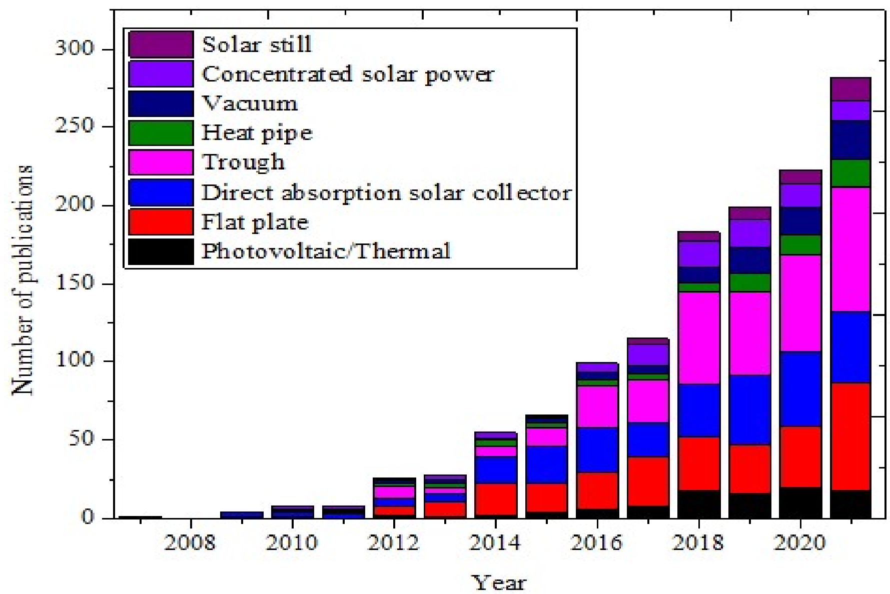

Fig. 6. Evolution of nanofluid-based solar energy devices

2020 – 2021, respectively. For the research period represented by the purple cluster, the items were thermal conductivity, viscosity, specific heat, optical properties, transmittance, flat plate collector, heat transfer coefficient, finite element method, extinction coefficient, forced convection, magnetic field, heat pipe, thermal energy storage, molten salt, nanoparticle, etc. This implies that articles published during this period focused on the utilization of different nanoparticles for the formulation of nanofluids used in flat plate and heat pipe collectors in addition to the thermal (thermal conductivity, viscosity, specific heat), optical (transmittance and extinction coefficient), and fluid (heat transfer coefficient) properties of these nanofluids. The deployment of the magnetic field to enhance the performance of collectors, the use of the finite element method to analyze heat and flow conditions (majorly forced convection) in the NBSER, and the engagement of molten salt as a thermal storage medium and base fluid are notable during this time frame.

The green cluster representing studies conducted in 2018 contains items such as nanofluids, solar energy, solar collector, flat plate solar collector, direct absorption solar collector, efficiency, entropy generation, heat transfer, energy, optimization, stability, photovoltaic/thermal, solar radiation, parabolic trough, nanoparticles, Al_2O_3, heat transfer enhancement, friction factor, heat pipe, collector efficiency, exergy analysis, mixed convection, etc. Published articles in this period reflected the continual use of different nanoparticles (mainly Al_2O_3 nanoparticles) to formulate nanofluids deployed in various solar correctors namely flat plate, direct absorption, photovoltaic/thermal, and heat pipe solar collectors. Most studies focused on the mixed convection mode of heat transfer with efficiency, entropy generation, heat transfer enhancement, friction factor, and exergy analysis as predominantly studied performance metrics. Optimizing the performance of solar devices using nanofluids as thermal fluids and investigating the stability of nanofluids (significant on their properties and overall performance) are important features of the studies in this period.

The cluster containing the lemon bubbles signifies the research outputs of 2019 with items such as thermal efficiency, computational fluid dynamics, thermal performance, energy storage, solar thermal energy, photothermal conversion, phase change materials, evacuated tube solar collector, graphene, porous media, Nusselt number, parabolic trough collector, renewable energy, heat exchanger, desalination, natural convection, etc. This period involved studies that markedly deployed porous media, phase change/energy storage materials, evacuated tube and parabolic trough collectors, heat exchangers, natural convection, desalination process, and computational fluid dynamics to NBSER. Graphene was a notable nanoparticle used as a nanofluid to investigate the performance of solar energy devices with Nusselt number, thermal efficiency, and thermal performance as their key performance indicators.

The cluster with yellow bubbles (in fig. 7) depicts the research trend from 2020 to 2021 and also reveals the emerging research focus of nanofluid-based solar energy. The cluster has hybrid nanofluids, energy efficiency, thermophysical properties, graphene oxide, solar still, magnetohydrodynamics, porous media, exergy efficiency, thermal performance, and solar thermal energy. The research trend for this time frame showed the prominence of the acceptance, adoption, and investigation of solar still with nanofluids as thermal fluids. This agrees with the

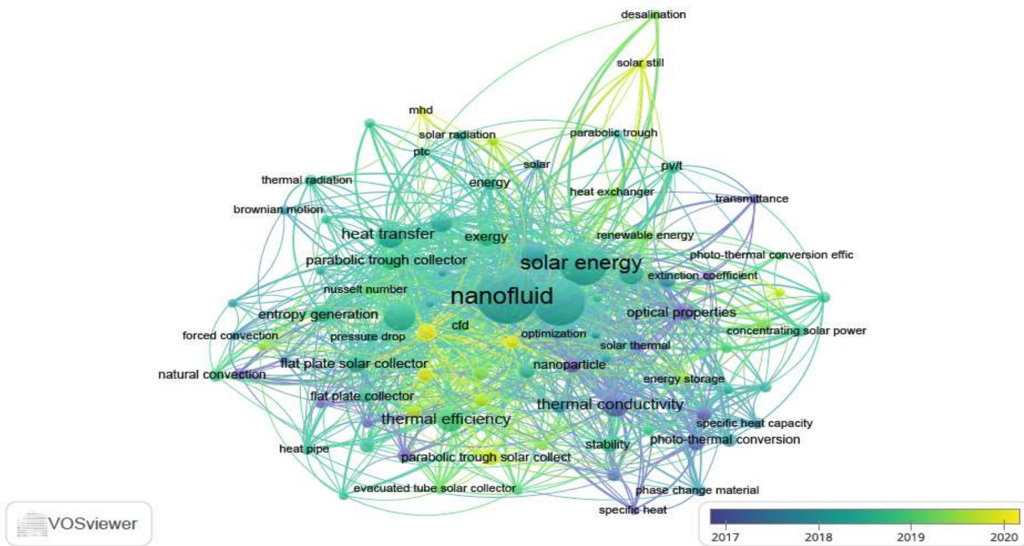

Fig. 7. Evolution of nanofluid based solar energy research

earlier results in this present study that nanofluid-based solar still is currently receiving attention from the NBSER community (see fig. 6). The utilization of porous media in NBSER as a passive technique to improve thermal characteristics continued to be relevant from 2019 to 2021 along with the active deployment of magnetohydrodynamics to further enhance the performance of the studied solar energy devices. Principal performance indicators studied were the energy and exergy efficiency and thermal performance while the hybrid nanofluids (coupled with their thermal properties) and the graphene oxide were notable and emerging nanofluids and nanoparticles, respectively, studied in the NBSER.

4.3. Future development

The studies involving the use of nanofluid in various solar energy devices have increased steadily over the years from its inception. Most of these studies have been carried out using mono nanofluids. However, hybrid nanofluids have been reported to be better thermal fluids than mono nanofluids in improving the performance of solar energy devices [45], [46]. Also, a huge gap in the publication is observed between the use of mono and hybrid nanofluids, despite the recent introduction and adoption of the latter. This informs the urgent need to intensify the deployment of hybrid nanofluids in solar energy research. For the deployment of mono nanofluids in the NBSER, a slightly higher number of experimental studies over numerical work was observed which is equally the same for the hybrid nanofluids except in the year 2021. Thus, a good balance of experimental and numerical studies is of utmost importance in the NBSER in the future for a better understanding of the physics, underlying mechanisms, and performance of solar energy devices.

In addition, innovation in terms of the synthesis of green and novel nanoparticles is of the essence for the future of NBSER [47], [48]. Most synthesis processes and studied nanoparticles are not environmentally friendly and impact negatively on the environment and public health [47]. With Okonkwo et al. [49] reporting the use of barley husk- and olive leaf extract-based nanofluids as thermal fluids in parabolic trough collectors, similar studies are highly expected in the future to further develop NBSER. Also, the development of green and innovative base fluids that can improve thermal transport in the NBSER outside the use of water and EG should be researched in the future. The deployment of active and passive techniques such as metal foam, electric field, porous media, and magnetic field to further improve the performance of solar devices with nanofluids as thermal fluids should be considered by the research community as a future research direction. Furthermore, the use of nanofluids, especially hybrid nanofluids in solar still need to be intensified and the same goes for heat pipe, parabolic trough, photovoltaic/thermal collectors, and concentrated solar power. In conclusion, the stability of nanofluids (mono or hybrid) is critical to their optimal performance as thermal fluids in solar devices [50]. Thus, it is important to achieve stable nanofluids via good preparation and the measurement of stability using established scientific methods.

5. CONCLUSION AND RECOMMENDATIONS

A bibliometric analysis was performed on the extracted scientific articles from the Scopus® database for NBSER covering 15 years. The result showed that a total of 1630 articles were published with 23.68% of the total publications recorded in the year 2019. Engineering produced the highest number of publications. The results of the co-authorship of country and organization showed that China and the University of Malaya were the most productive, respectively, in the NBSER. The work of Ghasemi H. published in 2014 was the leading paper (1049 citations) while *Solar Energy* was the leading journal (5456 citations). The keyword with the highest occurrence was "Nanofluid". Generally, the research hotspots focused on the optical and thermal properties of different nanofluids (Cu, Ag, Al_2O_3, MWCNT, and CuO) and the application of the same in solar energy devices (parabolic trough, direct absorption, and flat plate collectors). Future research direction involved the development of green and novel nanoparticles and base fluids, deployment of thermal enhancement techniques/materials, and increased studies on hybrid nanofluids as thermal media and solar still. The information provided through this study is expected to immensely benefit the NBSER community and future studies.

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