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Research trends in proton exchange membrane fuel cells during 2008–2018: A bibliometric analysis

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ABSTRACT

A bibliometric analysis of proton exchange membrane fuel cells (PEMFCs) content from a total of 15.020 research publications was conducted between 2008 and 2018, the papers being detailed in the online version of SCI-Expanded, Thomson Reuters Web of Science. Data processing tools such as Hitscite, CiteSpace, ArcGIS and Ucinet 6 were used to process the information. The parameters analyzed in the analysis were: type of document; the language of publication; volume and characteristics of publication output; publication by journals; performance of countries and research institutions; research trends and visibility. The study showed that "Fuel", "Cell", "Membrane “and "Proton" were found in most of the titles of the documents, while "Performance", "Pemfc", "Pem Fuel Cell" and "Fuel Cell" were the keywords most commonly used in documents. The analysis found that PEMFC studies have tended to be growing and that leading peer-reviewed journals have produced numerous publications on the subject. The investigation revealed that the country with the most significant production in the field is USA with a contribution of 3009; 20% of the total publications. Followed by China 2480; 16.5%, South Korea 1273; 8.5% and Germany 1121; 7.5%, showing to the main world powers as the most significant contributors to the research.

1. Introduction

Proton Exchange Membrane Fuel Cells (PEMFCs) are considered to be one of the most promising systems in clean energy source systems, since their emission level is 0%, having a low operating temperature, fast start-up, and high efficiency of 60%. [1, 2, 3], Because of this, fuel cell applications are diverse, including use in aerospace and automotive vehicles, small and large-scale power generation plants, portable power generators, combined heat and power (CHP), and backup power applications [4, 5, 6].

Over the past five decades, studies of fuel cells as an energy source have intensified. [7, 8, 9, 10], Due to growing concern about air pollution from internal combustion engines (ICE) and depletion of fossil fuel reserves, proton exchange membrane fuel cells (PEMFCs), which are environmentally friendly energy conversion devices, have captured considerable attention in recent years. [11, 12], According to some reports for 2010, the total global investment in studies for clean energy generation has tripled concerning 2005 [13]. Exchange membrane fuel cells have been mentioned in several ways in the research community [14]. A continuous and rapid increase in the number of publications can be observed, mainly since 2010 when more than 2000 papers on this technology have been published, demonstrating that this technology is currently a flourishing area of research in fuel cell technology. Most of the studies in this field (PEMFC) have been carried out in different countries of the world, with the most significant number of reports coming from China and the United States [15]. Some authors have studied and analyzed articles about PEMFC, Mehta, and Cooper [16] reviewed the design and manufacture of PEMFCs, looking at membrane electrode array manufacturing alternatives, synthesis processes, and bipolar plate manufacturing options. Several authors study the subject such as Cheddie and Munroe [17] who reviewed related publications on PEMFC modeling. Cheng et al. [18] examined more than 150 articles on contamination problems in PEMFC hydrogen fuel cells, and concluded that factors such as electrode kinetics, conductivity, and mass transfer are affected by cell contamination, Tawfik et al. [19, 20] analyzed a considerable number of articles on bipolar metal plates for PEMFC.

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Bezerra et al. [21] reviewed over 120 reports on the effect of heat treatment on the catalytic activity and stability of PEMFC catalysts. Zhang et al. [22, 23, 24] studied related publications on accelerated stress testing of MEA durability and trends in scientific analysis. Kajikawa et al. [25] through the dating network, confirmed the rapid growth in demand for fuel cells, and finally, Verspagen [26] explained the path of development of fuel cell technologies through patent citation networks.

Finally, it is necessary to clarify that few scientific studies on fuel cells (PEMFCs) have been developed, which leads to the elaboration of this paper, with an analysis of bibliometric networks and using excellent tools for database processing, analyzed 15020 fuel cell documents (PEMFCs) from 2008 to 2018. The study also adopted an objective and systematic approach, to provide a clear and precise view of the position of science on a new power generation alternative such as proton exchange membrane fuel cells.

2. Materials and methods

Data were analyzed between 2008 to 2018; it was extracted from the SCI-Expanded online version of Thomson Reuters Web of Science, where the filter by title was used for the search keywords proton exchange membrane fuel cells. SCI-Expanded is highly and frequently used to broad scientific achievements in all areas of science [16, 17]. The software used to process the WoS files (Web of Science) was HistCite TM, it generates historical maps of bibliographic collections resulting from searches of subjects, authors, institutional journals or sources in the ISI Web of Science. The software generates chronological historiographies that highlight the most cited works in the recovered collection; other listings include classifications by authors, journals, institutions, countries, cited documents and keywords [27]. The analysis and classification of scientific results, subject categories, journals, authors, countries, and institutes were elaborated manually and processed in Microsoft Excel 2016 and OriginPro 8. CiteSpace [28] software was used in combination with Ucinet 6 to generate international collaboration networks. The ArcGIS software was used to process distribution of publications using cartographic representations [29, 30].

Table 1
Distribution of research for PEMFC by document types between 2008 and 2018.

Type of document	TP	%	TC	CPP
Article	12820	85.4	221829	17.3
Proceeding Paper	1116	7.4	19587	17.5
Review	556	3.7	39530	71.1
Meeting Abstract	406	2.7	143	0.4
Editorial Material	48	0.3	167	3.5
Correction	39	0.3	21	0.5
Letter	16	0.1	97	6.1

3. Results and discussions

Due to a large number of contributions made by these researchers in Proton Exchange Membrane Fuel Cells area, it is essential to analyze their behavior and trends through bibliometrics. Bibliometrics is a subdiscipline of scientometrics and provides information about researcher process results, publications, trends and visibility using quantitative methods [22, 23]. Over the years bibliometrics has become famous for its application to classify academic production (books, articles, others) and develop representative summaries considering essential results. A few decades ago, it took a long time to categorize the data because the information was collected manually [24, 25]. However, the software has allowed analyzing the data collected thanks to the substantial advances in computer science specifically software developments used to organize information and database [26]. In the literature, there are many bibliometric studies of a wide variety of aspects considered such as topics [27, 28], journals [29], universities [30] and countries [31]. The parameters analyzed included: document type; publication language; volume and published results properties; publication by magazines; countries and research institutions publication activities; and research trends and visibility. Also, there were analyzed the citations patterns and the words distribution used in title and authors keywords.

3.1. Subsection

There were reviewed 15 020 documents distributed in seven types of indexed documents in Thomson Reuters Web of Science. Article with an 85.4% occupied the most common type of document found in WoS, then proceeding articles (7,4%), reviews (3,7%), meeting abstracts (2,7%), editorial materials (0,3%), corrections (0,3%) and letters (0,1%). This information is analyzed in Table 1. The total citation (TC) in research documents related to the main topic was proportional to the total number of publication (TP). Indicates that when there is a greater amount of

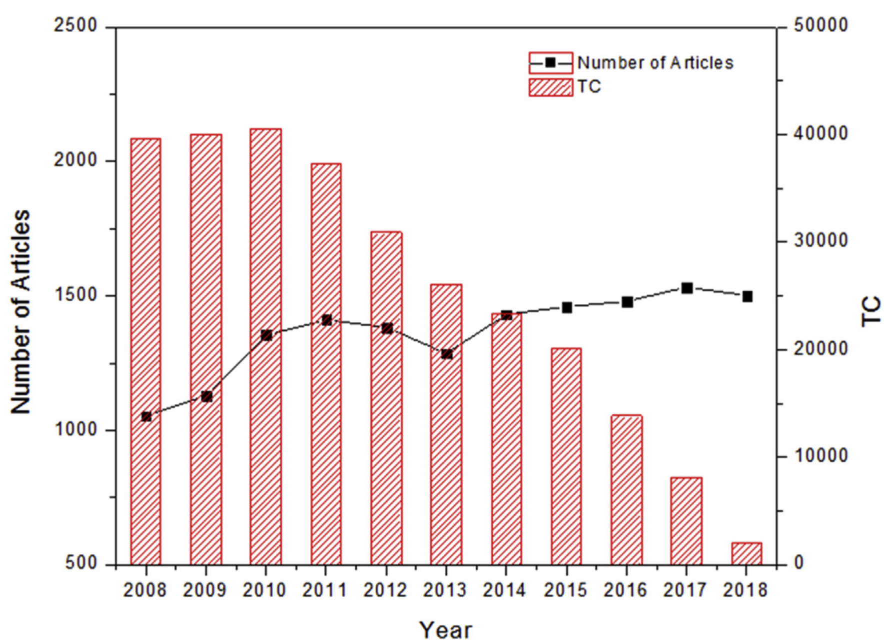

Fig. 1. Number of articles and total global citation (TC).

Table 2
Characteristics of PEMFC scientific article between 2008 and 2018.

Year	TP	NA	NA/TP	NR	NR/TP
2008	1053	4476	4.3	32006	30.4
2009	1128	5040	4.5	37924	33.6
2010	1354	6238	4.6	44515	32.9
2011	1411	6506	4.6	48895	34.7
2012	1383	6635	4.8	48558	35.1
2013	1286	6422	5	47548	37
2014	1431	6824	4.8	55508	38.8
2015	1460	6923	4.7	61082	41.8
2016	1480	7465	5	63218	42.7
2017	1532	7894	5.2	68988	45
2018	1502	7630	5.1	69299	46.1

publications for any document, there was an opportunity for growth in the visibility and probability of citation. It was not surprising that reviews had a higher citation per article (CPP) than articles [31], this is because reviews have wide coverage in the research topic and present information to readers detailed and accurate helping readers to obtain complete specifications.

3.2. Articles and languages

Research Articles (RA) trends by year were realized in Fig. 1. In 2008, there were 1053 published RA in the area of Proton Exchange Membrane Fuel Cells (PEMFC). In this year it was registered a significant increment until 2011, in which there were registered 1411 publications. This increment could be related to novel researches in the development of new advances in PEMFC, as proof of this affirmation was the achievement of the nobel price in chemistry in 2007 by Gerhard Ertl, who dedicates his studies to the operation of fuel cells [32]. For the next two years (2011–2012), there was stability in publication activities. In 2013, there was a reduction of publications reaching 1286 articles, however in 2014, there were published 1431 research articles in the area on PEMFC, this was due to the application of fuel cells in massive sales of electric vehicles, pointing that the country with the most prominent scientific contribution in this topic was the most significant buyer of cars (China) [33, 34]. In 2015 and 2016, there was a stable activity of publication with 1460 and 1480 of RA reported in WoS respectively. Finally, it is observed that in 2018, there was a little increase in RA publication getting 1502 documents at the end of the year. Respect to the number of total citation (TC), it was possible to identify a mean citation value of 25612 per year with a maximum amount of 40558 citation in 2010 and a minimum value reached in 2018 with 2002 documents cited. For another hand, the language used in records showed that a 98.2% were published in English; a deficient number of production is in another language such as Chinese, Korean, Spanish and Portuguese with 0.6%, 0.3%, 0.2% and 0.2% respectively. These results are related to a high international preponderance due to the use of English language.

3.3. Documents trends

As is shown in Table 2, the Proton Exchange Membrane Fuel Cells (PEMFC) researchers have increased, this is accompanied by a high number of authors involved in the preparation of documents related with the topic. In 2008, the number of registered authors was 4476; this number shows an acceptable interest for the scientific community. Ten Years Later (2018), there were recorded 7630 authors, which is related to the increasing trends in publications, the number of authors grew up an 41.3% respect 2008. It can be observed that in 2017 there was a high number of publications, accompanied by the significant number of authors related (7894) compared with other years reviewed. The number of

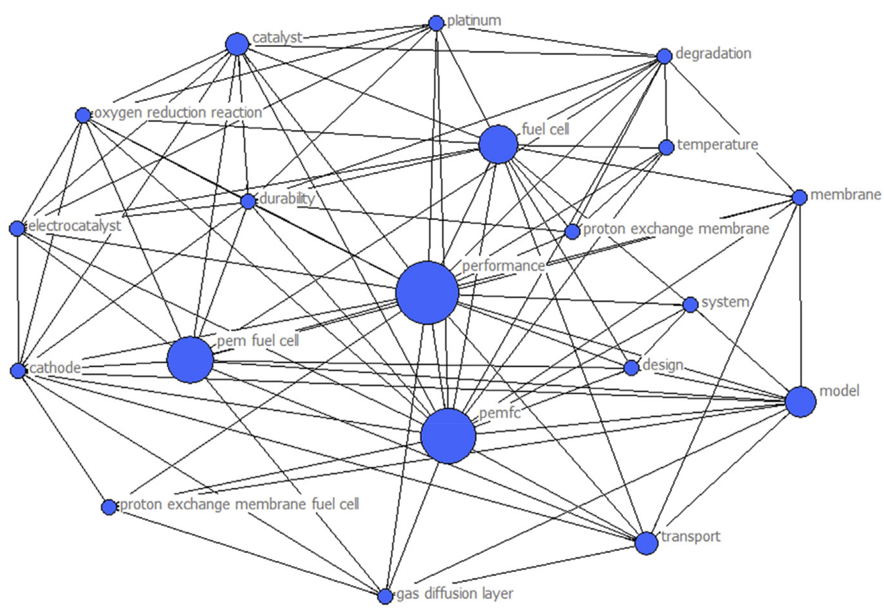

Fig. 2. Co-word network of top 20 high-frequency keywords.

Table 3
Top 10 journals in PEMFC during the period 2008–2018.

No.	Journal	TP	%
1	International Journal of Hydrogen Energy	2429	16.2
2	Journal of Power Sources	1615	10.8
3	Journal of the Electrochemical Society	577	3.8
4	Electrochimica Acta	543	3.6
5	Fuel Cells	355	2.4
6	Journal of Membrane Science	221	1.5
7	Applied Energy	213	1.4
8	Journal of Fuel Cell Science and Technology	199	1.3
9	Energy	191	1.3
10	Energy Conversion and Management	159	1.1

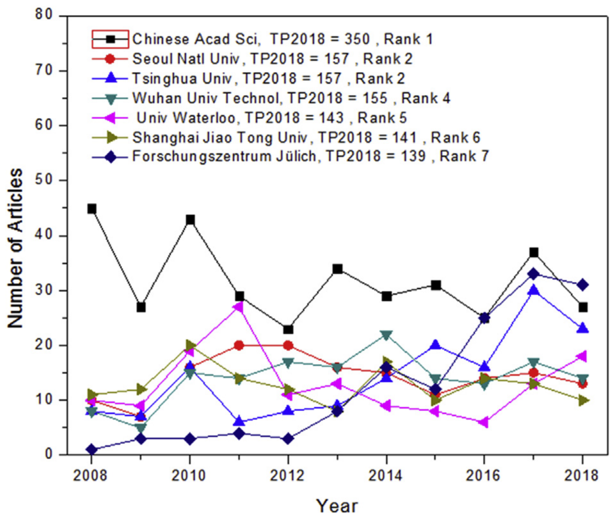

Fig. 3. Number of articles per Institutions.

authors that worked per article (NA/TP) and the number of references for article (NR/TP) on average was five and thirty-eight respectively. Otherwise, the number of cited documents describe relation respect to the behavior of total publication (TP) and some authors (NA). It is expected that in coming years these publications and author collaborations increase due to efforts realized by nations and organizations whose promote this technology.

3.4. Working trends in PEMFC

The frequency analysis of keywords in articles titles, authors and the declared in documents evidence the investigation process and indicated future trends in the research area. Title words and author keywords in different time periods can be used to determinate the investigation focus [35]. The study gave a total of 12545 words in titles such as "Fuel" (6622; 44.1%), "Cell" (4459; 29.1%), "Membrane" (3765; 25.1%) and "Proton" (2714; 18.1%) had the highest records. Other important words registered in titles were: "Cells" (2617, 17.4%), "Pem" (2595; 17.3%), "Exchange" (2476; 16.5%), "Polymer" (1595; 10.6%), "Electrolyte" (1506; 10%) and "Perfomance" (1462; 9.7%).

An author keywords analysis found 14506 words from which the most common terms were: "Performance" (3224; 21.5%), "Pemfc" (2863; 19.1%), "Pem Fuel Cell" (2528; 16.8%), "Fuel Cell"(2347; 15.6%), "Model" (1258; 8.4%), "Catalyst" (1071; 7.1%), "Transport" (1051; 7%), "Electrocatalyst" (1003; 6.68%), "Durability" (953; 6.34%) and "System" (925; 6.16%). The link between these ten words previously mentioned is shown in Fig. 2, where using lines and connectors, the main objective is to identify relationships with the 20 words more used to work with PEMFC. From Fig. 2 can be observed that keywords with more frequency utilization have a close relation and coincidence with articles pointing that words such as "Perfomance" and "Pemfc" have a significant impact and are used widely by authors.

3.5. Journal & magazines publications

As is shown in Table 3, worldwide journals with a high-impact factor contribute to the release of PEMFC works. Journals such as *International Journal of Hydrogen Energy* or *Journal of Power Sources* lead in high value the number of papers also above of the other journals and magazines of the top ten, it can be observed that on these two journals is published the 27% of reported documents. In addition, a not less relevant fact is that around 43% of the publications are distributed in the top 10 of magazines with the most number of books.

3.6. Institutions and countries contributions

The performance analysis for institutions and countries showed that 7301 research centers from 113 countries participated in PEMFC study between 2008 to 2018. Twenty of these institutions published at least 100 articles on the topic during the last ten years. Chinese Acad Sci (350 or 2.3% of the 15020 items) was the most prolific institution in general, followed by Seoul Natl University and Tsinghua University (157 or 1% of 15020 the items). According with the number of publications are followed by Wuhan University Technology (155; 1%); University Waterloo (143; 1%); Shanghai Jiao Tong University (141; 0.9%); Forschungszentrum Jülich (139; 0.9%), the chronological distribution of publications for studied period of the aforementioned institutions is shown in Fig. 3. As previously noted countries in the Asian region such as China and South Korea have a significant contribution to research on PEMFC, which is evidenced by the fact that it is supported because of the 7 universities mentioned above, four of them are from People's Republic of China (Wuhan University Technology, Chinese Acad Sci, Tongji University and Tsinghua University), and 1 institution is from South Korea (Seoul Natl University). Also, ten countries, including Canada, India, USA, Japan, Germany, England, Iran, France, Denmark and Spain, were represented with some institutions in the top 50 of institutions with the highest number of publications.

Institutions published much of the research on PEMFC during the period 2008–2018 in USA (3009; 20% of all items), followed by China (2480; 16.5%), South Korea (1273; 8.5%) and Germany (1121; 7.5%), more detailed information on the geographical distribution of the number of publications and the impact of citations by the 15 countries with the highest number of articles is shown in Fig. 4. The analysis of the study

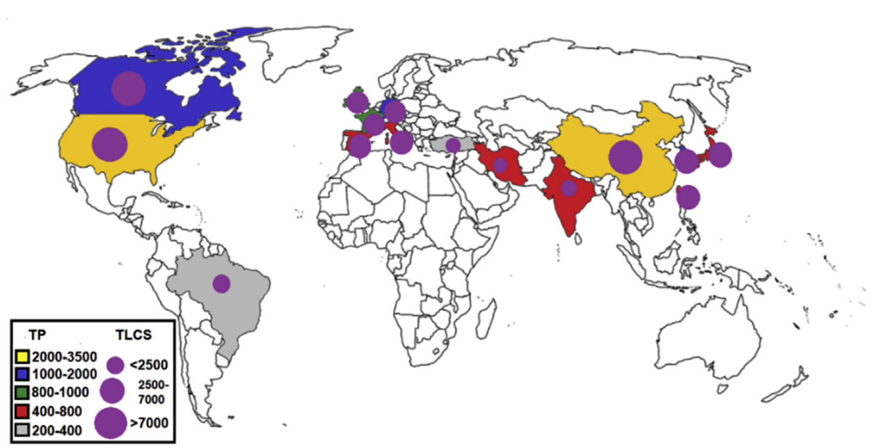

Fig. 4. Geographic distribution of the number of publications and impact of citations.

Table 4
Top 20 articles with TC2018 > 300.

Rank (TC2018)	Article title	Reference
1(802)	Polymer Electrolyte Fuel Cell Model	[36]
2(705)	Activity benchmarks and requirements for Pt, Pt-alloy, and non-Pt oxygen reduction catalysts for PEMFCs	[37]
3(673)	Scientific Aspects of Polymer Electrolyte Fuel Cell Durability and Degradation	[38]
4(510)	Fuel Cell Systems Explained	[39]
5(499)	A review of polymer electrolyte membrane fuel cells: Technology, applications, and needs on fundamental research	[40]
6(467)	State of Understanding of Nafion	[41]
7(412)	PEM Fuel Cells (Theory and Practice)	[42]
8(388)	Alternative Polymer Systems for Proton Exchange Membranes (PEMs)	[43]
9(365)	Materials for fuel-cell technologies	[44]
10(349)	A review of PEM fuel cell durability: Degradation mechanisms and mitigation strategies	[45]
11(346)	On the development of proton conducting polymer membranes for hydrogen and methanol fuel cells	[46]
12(342)	Effective diffusivity and water-saturation distribution in single- and two-layer PEMFC diffusion medium	[47]
13(336)	A review of water flooding issues in the proton exchange membrane fuel cell	[48]
14(334)	High temperature PEM fuel cells	[49]
15(326)	Approaches and Recent Development of Polymer Electrolyte Membranes for Fuel Cells Operating above 100 °C	[50]
16(322)	Review and analysis of PEM fuel cell design and manufacturing	[16]
17(314)	High temperature proton exchange membranes based on polybenzimidazoles for fuel cells	[51]
18(312)	Visualization of water buildup in the cathode of a transparent PEM fuel cell	[52]
19(308)	Understanding and approaches for the durability issues of Pt-based catalysts for PEM fuel cell	[53]
20(304)	Fundamental Models for Fuel Cell Engineering	[54]

for the contribution of nations showed that Europe contributes around 44% of the research on PEMFC, followed by the Asian continent that contributes around 42% of the research on PEMFC, followed by the American continent (32.2%) with the USA (20%) and Canada (7.1%) as the most significant contributors, followed by Africa with around 2.4% and Oceania (1.8%), which had Australia and New Zeland as the main contributors to its publications.

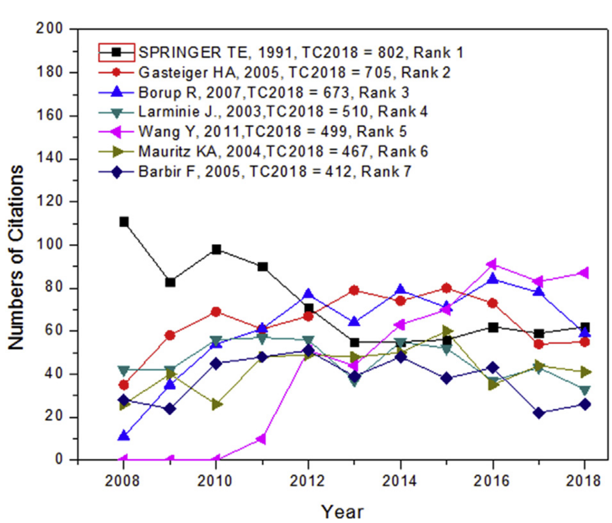

Fig. 5. Number of citations per article by year for the top seven most cited articles in PEMFC from 2008 to 2018.

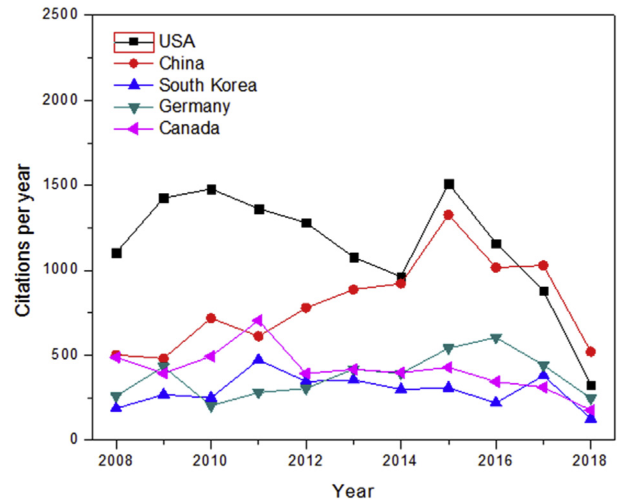

Fig. 6. Visibility of research articles by country of origin.

3.7. Article visibility and citation trends

To assess the visibility of research articles, the number of times an item was cited from publication to the end of 2018 (TC2018) was used as an indicator [27]. The scientific impact was studied by analyzing the 20 most cited publications in PEMFC research for papers published from 2008 to 2018. The list of the most cited articles (TC2018 > 300) is shown in Table 4.

Fig. 5 shows, in general, a similar behavior for the leading materials in a number of citations, suffering an apparent absence of trend that does not define a turning point for the time interval under study (2008–2018). The articles with the highest number of citations on the subject under investigation are mostly publications that are outside the range under review, which explains the initial citation behavior (2008) where except the authorship article by Wang Y (TC2008 = 0), the others have citation values above zero. Without a doubt the most critical piece on PEMFC for most of the years under study was that of Springer TE (TC2018 = 802), published more than two decades ago, the research entitled "Polymer Electrolyte Fuel Cell Model" as shown in Table 4, developed and proposed a simple, one-dimensional, isothermal model of a complete polymer electrolyte fuel cell that has provided useful information on the cell's water transport mechanisms and their effect on cell performance. In this study, membrane water/electrode water steam balance conditions were applied to the membrane/electrode interfaces and the electroosmotic and diffusion driving forces for water in the membrane and diffusion of water steam and reactive gases in the electrodes were considered to obtain material balances throughout the cell [36]. Another important document that has laid the foundation for PEMFC research is the article by Gasteiger et al. (TC2018 = 705) entitled " Activity benchmarks and requirements for Pt, Pt-alloy, and non-Pt oxygen reduction catalysts for PEMFCs ".

An analysis of trends in citation trends from PEMFC research papers for countries with the most significant number of publications is shown in Fig. 6. The visibility of the articles varies from state to state. The average profile of materials originating in USA per year was approximately 1143, a premise that confirms the claims that have been made in this study regarding the significant impact of USA on research articles on the subject. It is followed by China (~800 appointments), South Korea (~292 appointments), Germany (~275 appointments), finally, Canada (~414 appointments).

4. Conclusions

Based on the scientific analysis carried out, it was possible to obtain a clear vision of the trends and behavioral patterns in PEMFC research around the world during the years 2008–2018. In general, it can be concluded that PEMFC studies have been continuously growing and will continue to be so in the future, thanks to the intervention of world powers in the reviews and of prominent companies that are driving the development of this energy generation system. Fuel cells have aroused interest in the scientific field, and numerous studies on the subject have been included in the International Journal of Hydrogen Energy and the Journal of Power Sources. Essential institutions in the international arena have a significant presence in publications, with the Chinese Academy of Sciences standing out, which has the best numbers in papers, a situation that supports the Asian region (42% of all articles) and especially China (16.5% of all items) as a leader in research on the subject, without ignoring the USA and the European continent as the most contributors to publications. Studies such as "Polymer Electrolyte Fuel Cell Model" and "Activity benchmarks and requirements for Pt, Pt-alloy, and non-Pt oxygen reduction catalysts for PEMFCs " have set a significant precedent in PEMFC research and top the list of studies with the highest number of citations.

It can be inferred that, under the trends outlined above, long-term fuel cell power generation systems (PEMFCs) can become a means of domestic self-sufficiency in which each consumer can generate energy by storing his or her hydrogen from water and can supplement or eventually replace electrical power within their homes, while the industrial sector could also benefit greatly. Despite the high efforts made so far on the subject, the scientific community is still undergoing some critical challenges such as hydrogen storage and cost-effective energy production through this element. Also renewable application projects in remotes communities such as [55, 56, 57, 58], can involve PEMFCs applications and uses in order to promote energy storage projects and microgrids island mode operation.

Declarations

Author contribution statement

Rony Escobar Yonoff, Guillermo Valencia Ochoa: Conceived and designed the experiments.

Yulineth Cardenas-Escorcia: Performed the experiments; Wrote the paper.

Jorge Iván Silva-Ortega: Analyzed and interpreted the data; Wrote the paper.

Lourdes Meriño-Stand: Performed the experiments.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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