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A Scientometric and Knowledge Management Analysis of Fuel Cell Systems Research for Enhancing Energy Efficiency

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Abstract

This research aims to conduct scientometrics and knowledge management analysis for fuel cell system research focused on energy efficiency, based on data from Scopus from 2011 to 2024. Using statistical methods and the analytical software VOSviewer, 1,399 articles published across 247 data sources were analyzed. The results showed an average annual growth rate of 12.79% and an average of 36.79 citations per article. China is considered the leader with 2,678 articles and 14,189 citations, while Iran and the US (with 356 and 503 articles, respectively) are primarily involved in technological improvements in Proton Exchange Membrane Fuel Cells (PEMFC) and Solid Oxide Fuel Cells (SOFC), as highlighted in the findings. Leading the field are *Energy* and *Applied Energy*, with 225 and 177 papers, both having h-indices above 60 and 80, respectively. The presence of high-frequency keywords such as "energy efficiency" (1,456 occurrences), "SOFC" (614 occurrences), and "PEMFC" (612 occurrences) confirms the importance of performance improvement in this research field. Meanwhile, keywords like "carbon dioxide" and "waste heat" indicate that greater attention is being paid to environmental issues. Notably, international collaborations, which constitute 26.45%, are significant, suggesting a potential need for stronger linkages. Knowledge management, driven by data and interactive dashboards—including one for green hydrogen infrastructure—addresses these gaps. According to the study, fostering international collaboration to support a new generation of researchers, promoting sustainable materials, and focusing on hybrid systems could pave the way toward the commercialization of fuel cells.

Keywords: *Fuel Cell Systems; Energy Efficiency; Scientometric Analysis; Knowledge Management; Sustainable Energy.*

1. Introduction

Fuel cell technologies have increasingly been the focus of attention in the last decades as key solution to address the increasing global demand for clean and high efficient energy. Owing to the capability of these technologies to utilize fuel chemical energy directly for the electrical energy generation with high efficiencies and low pollutants emission, the HFCP and ACFC have attracted fair attention as potential energy conversion technology in sustainable energy generation, transportation and stationary application, etc. [1]. Proton Exchange Membrane Fuel Cells (PEMFC) and Solid Oxide Fuel Cells (SOFC) are two of the most promising fuel cells due to their high efficiency, fuel flexibility and possibility to use in both small and large-scale applications [2,3]. Nonetheless, there are still some obstacles standing on the way to their extensive industrial application including high price, insufficient endurance and less-optimizing towards energy efficiency [4].

Because of this development, investigations for the development of the research area of fuel cells have been expanded enormously in the last decades. It is based on literature that has been indexed in the Scopus database and a considerable amount of articles have been published in professional journals including Energy, International Journal of Hydrogen Energy and Journal of Power Sources on different issues of this technology such as material design and hybrid systems optimization [5-8]. Given this large amount of research findings, scientometric study and knowledge management are required to help identify patterns, research challenges and future development in this area.

Through the use of statistical measures and data mining, umbilical cord scientometrics make it possible to make both quantitative and qualitative the evaluation of scientific production, contributing to researchers knowing patterns of collaboration, the impact of publications, and to trendy topics [9]. On the other hand, knowledge management that structurize that organize the scientific information and turned them into exploitable knowledge is one of the major factors in accelerating innovation and improving research [10].

One of the main goals in fuel cell research activities is to improve energy conversion efficiencies. For example, some recent works have shown that we can enhance the power generation efficiency by 52.55% at the most by incorporating an enhanced control algorithm, Fractional-Order PID controller, in the PEMFC air supply system [5]. In addition, the combination of fuel cells with energy storage has enabled good progress on high-efficiency, low-carbon hybrid systems including, for example, CAES and hydrogen-based fuel systems [11-13]. These developments emphasize the remarkable promises of fuel cells in meeting the sustainable energy demands and reducing environment degradation [14].

Scientometrics can help to discover leading authors, active organizations, and leading countries in the field of fuel cells. For example, according to Scopus search results, Nanyang Technological University, Singapore, and Hunan University, China, have been the leads in the research involved in synthesis of nanostructured materials for fuel cell catalyst [15-17] and optimization of hybrid systems [18]. Moreover, such analyses are also able to highlight trending items, among which one finds the research on nanomaterials for use in electrocatalysts and on the design of self-sustained thermal modules, energy management in hybrid systems [19-23].

Synthesis In fuel cell research, knowledge management is as equally important as in the other existing fields. Due to the technical difficulty and interdisciplinary feature of SEI field, it is expected that the knowledge sharing in this area can speed up the progress of technology development through the researchers, engineers, and policy makers. For instance, the use of databases and artificial intelligence tools for the analysis of experimental and numerical data has proven to be instrumental for fuel cell systems optimization and for the reduction of development cost [24].

In addition, knowledge management can drive future research directions by pinpointing the gaps such as the requirement of platinum-free catalytic materials or non-fluorinated membranes [25-30]. One of the main potential areas of application in optimizing hybrid systems integrating fuel cells with other energy technologies (e.g., gas turbines, heat pumps, water electrolysis systems). Hybrid SOFC systems with heat pumps are reported to have a high-electrical efficiency of 96% in an energy- conversion study, and the use of hydrogen fuel (which is used in the form of highly compressed electrolyzed gas generated by water electrolysis) can dramatically reduce carbon-dioxide emissions (approximately zero emission by carbon dioxide due to the loop type of hydrogen circulation) [31]. These developments call for comprehensive scientometric studies to find peripheral technologies and evaluate them by their efficiency in whole systems.

Further, both environmental and economical aspects must be considered when working with fuel cell technologies. For example, the use of non-fossil fuels (green hydrogen or biogas) in SOFC systems could lead to a decrease in greenhouse gas emissions [32,33]. Nevertheless, production costs of hydrogen and associated infrastructure are still an obstacle that merits further research to be addressed [34,35]. Scientometric analyses may help to find cost-effective and sustainable solutions on the basis of the economic and environmental development in published literature.

Finally, a scientometric analysis and knowledge management framework in the field of Fuel Cell Research, based on the role of F-Z power function are presented to investigate current trends, un-traced research gaps, and extension will be provided with new recommendations. Based on Scopus database and advanced analytic tools, this paper will attempt to develop an integrated overview with an aim to achieve higher energy efficiency and faster commercialization of fuel cell technologies. It is anticipated that the findings of this study will be beneficial to researchers, policy makers, and industry officials in promoting sustainable energy systems.

2. Materials and methods

2.1. Methodology

The study was based on a rigorous and structured methodology for data collection and analysis of scientific information on fuel cell systems and efficiency with respect to energy application. Data were retrieved from Scopus, which is one of the largest abstract and citation databases of peer-reviewed literature, providing approximately 76 million records and offering comprehensive coverage of the relevant literature across different disciplines. Since Scopus adopted the author identification system and includes content from the entire citations database drawn from articles in engineering, energy, and materials science, it was chosen as the appropriate database for input data for scientometric analysis and knowledge management in this investigation [36]. A specific search strategy was developed using keywords related to fuel cell systems and energy efficiency to extract the data. The following was the search query:

(TITLE-ABS-KEY ("FUEL CELL SYSTEM" OR "PEMFC" OR "SOFC")) AND (TITLE-ABS-KEY ("ENERGY EFFICIENCY")) AND (PUBYEAR > 2010) AND (LIMIT-TO (DOCTYPE , "AR")) AND (EXCLUDE (PUBYEAR , 2025)) AND (LIMIT-TO (LANGUAGE , "ENGLISH"))

The search was focused on papers published from 2011 to 2024, containing the words "fuel cell system," "PEMFC" (Proton Exchange Membrane Fuel Cell), and "SOFC" (Solid Oxide Fuel Cell) and "energy efficiency" in their title, abstract, or keywords. Limits were imposed to include only articles in English and to exclude articles published in 2025 so that included data remained comprehensive and up-to-date. The search was performed on June 3, 2025, and a collection of related papers were retrieved for analysis [5–8, 11, 13, 15, 17, 19, 21–22].

Inclusion and exclusion criteria were set to allow data quality standard. Publications should have been issued in quality-controlled scientific or technical journals and cover the technical or applied aspects of fuel cell systems in connection with efficiency enhancement. Articles which contained only theoretical issues or the subjects that were far away from the subject of this study were excluded from the study. The retrieved data were comprised of bibliographic information (author(s) name, article title, and publication year, journal, number of times a paper was cited, keywords and funding). The measurements were saved in CSV and exported to dedicated software for later analysis on another computer [9].

2.2. Data analysis

The author conducted a scientometric analysis and used statistical analysis. Then, the results obtained via Scopus were reprocessed through the VOSviewer and CiteSpace and the processing procedure was as follows. These techniques helped in the investigation of author collaboration networks, keyword co- occurrence and the detection of thematic clusters [37]. The analysis in the collaboration network made us identified the leading authors, and institutions in the fuel cell systems research, and keyword co-occurrence analysis showed that the hot spot including control optimization, nanostructure material and hybrid system [5,7,8].

Quantitative analysis calculated scientometric indices such as number of published articles, number of citations, h-index indices of authors, and journal impact (measured by metrics such as Impact Factor or Cite Score). Examples from the results are that some journals, e.g., Energy and Journal of Power Sources, are quite influential in this field where they demonstrate high-impact publications [3, 6, 21]. The temporal publication trends, the role of countries and institutions were extracted by R and Python software and subjected to statistical analyses. In particular, we conducted regression analysis to examine the relationship between citation count and article attributes, such as publication year and number of co-authors [38].

Also qualitative studies were included in order to explore empty areas and to guide future research. Abstracts and keywords of the articles were hand-screened to identify emerging themes, such as for intelligent methods for optimization of fuel cell system and grain for the non-fossil fuels used [8, 16]. These analyses involved content coding and thematic analysis in order to ascertain key research topics and challenges is a program which supports qualitative data analysis and it has been using in this study. Hevey.D (2007) The Production of Knowledge.

2.3. Knowledge management

Knowledge management, in the context of this research, was used as a channel for organizing, incorporating, and delivering scientific information regarding fuel cell systems. This section aimed to transform unstructured extracted data into a useful body of knowledge for researchers, engineers, and policymakers [10]. To accomplish this goal, a knowledge management system, composed of three main processes: (1) knowledge collection and storage, (2) knowledge analysis and integration, and (3) knowledge sharing and application, was designed.

In the first phase, information retrieved from Scopus was collected into a structured database. Key information about authors, institutions, keywords, citations, and funding sources was contained within this database. To facilitate easy access, the data were organized using database management software [41]. In the second stage, data were analyzed using scientometric software; for example, knowledge modeling (machine learning) was employed to reveal key patterns in the data [8]. In the third phase, the findings from the analysis were documented in structured reports and interactive dashboards for dissemination to stakeholders [17,42]. This KM system enabled the organization of information and the development of international collaboration networks, contributing to the acceleration of innovation in the fuel-cell industry.

3. Results and discussion

Statistical analysis of the extracted data from Scopus database showed noticeable increase of research trend in fuel cell systems toward enhancing the energy efficiency comparing to the period from 2019 to 2024. According to the file, the 1,399 articles were distributed across 247 scientific sources (mainly journals), revealing the diversity and the richness of the resources pertaining to this field. A growth of 12.79% per year shows a significant attention to such a 88technology that probably has arisen due to the necessity of sustainable energy sources and little CO2 emissions [43].

The mean age of articles is 5.34 years, indicating that most of the work is new and emphasizing that the field is dynamic and evolving. Similarly, the average citations per article were 36.79 indicating the high level of impact of the conducted research [44]. There are 56,471 references included in these texts testifying to the penetration and breadth of the sources used. Furthermore 8,429 Keywords Plus and 3,423 author keywords indicate a variety of topics covered (nanostructured materials, hybrid systems, efficiency optimization etc.) [45, 46]. These results are consistent with other recently published works highlighting categorically the relevance of PEMFC and SOFC, in the context of clean energy computation [47, 48].

In terms of scientific collaboration, the figures show that 3,786 unique authors contributed to these and the average number of authors per article was 4.75, which demonstrated strong collaboration between researchers [49]. 47 (or 3%) were single authored, reflecting on the fact that research in this field is multidisciplinary and team-based. It must be also noted that the international collaboration ratio (26.45%) shows that this is a community of world participation, which however, is not so relatively high, if we compare it with other areas, such as artificial intelligence [50]. This could be due to the technical challenges associated with fuel cell research [51]. Scientometric analysis The scientometric analysis shows that in recent times the important issues like, artificial intelligence and machine learning based advances for mass and heat transfer in fuel cell systems and platinum-free catalytic materials have begun to be illuminated [52]. These are in line with the requirements of cost reduction and improving durability of fuel cell systems and show high potential of the technology for future commercialization [53]. Future considerations should revolve around initiatives that are international and seek cooperation while addressing research deficiencies, including establishing an infrastructure for the generation of green hydrogen, which can facilitate the commercialization process of these technologies [54]. (Table 1)

Table 1 - Statistical Summary of Scientometric Data from Conducted Research

Description	Results
Timespan	2011:2024
Sources (Journals, Books, etc)	247
Documents	1399
Annual Growth Rate %	12.79
Document Average Age	5.34
Average citations per doc	36.79
References	56471
Keywords Plus (ID)	8429
Author's Keywords (DE)	3423
Authors	3786
Authors of single-authored docs	37
Single-authored docs	47
Co-Authors per Doc	4.75
International co-authorships %	26.45
article	1399

The graphic talks about the increase of articles from 2011 to 2004 and the material growth regarding of flourish research than saves energy that was being pulled out of the FC. The lowest volume of articles (33) was registered for 2011, but then it grew progressively, reaching 220 articles in 2024. This increasing trend has been presented as a yellow trendline in the figure; it clearly indicates that fuel-cell has been majority choice of the research community for the solution of energy-related problems sustainability [55]. This is in agreement with the increasing attention of renewable energies and the need for greenhouse gas emissions constraints, which previous work from the literature have pointed out as major drivers for the development of the research in this field [56,57]. In particular, the more rapid increase of papers might be associated to the development of the PEM and SOFC technologies [58] (which is visible in the chart

with a steeper slope under 2018a). This provides an insight into the innovative capability of this sector which still provides numerous innovation opportunities for the future [59]. (Figure 1)
Scient metrically, this increasing volume of publication has been associated with increasing research collaboration and diversity of research topics. The increasing trend in the number of publications from 2011 to 2024 portrayed in the figure clearly supports the point that the field is popular among researchers globally with a mean annual growth rate of 12.79 [60]. This increase is also supported by more citation indices and article influences us well [61]. However, the figure also indicates certain small perturbations in the number of publications for some years (e.g., 2013 and 2017) which may be attributed to heterogeneous reasons such as budget reductions or shifts in the area of interest of research [62]. Such tendency is likely to be maintained in the future as demand for clean energy technologies and materials, and the development of materials and hybrid systems increase [63]. This increase merits further study, with a focus on the underlying drivers of this increase, such as environmental policies or technological advancement, in order to identify best pathways of the technical interventions developed [64]. (Fig 1)

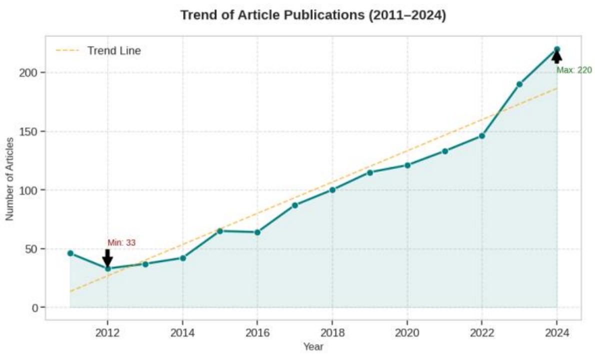

Figure 1. Trend of Article Publications Over the Period of 2011 to 2024

The graph representing the tendency of citations along with the number of articles from 2011 to 2024 was generated for the impact and progress of the research on the fuel cell system to increase the energy efficiency. The bar plots (pink) manifest the amount of articles, increasing from 33 articles in 2011 to 220 articles in 2024. This increase demonstrates the increasing attractiveness of fuel cell as theoretical research directions to some extent, such as PEMFC and SOFC, which is considered as clean energy production methods [65]. In contrast, the average \# of citations per article (Mean TC per Art), represented by the blue trend line, fell from 64.15 (in 2011) to 6.83 (in 2024). This is likely because of the accumulation of more recent articles that have not been given enough time to be cited, a phenomena affecting scientometric studies referred to as ‘citation lag’ [66, 67]. This result follows some recent findings that new articles are generally cited less in the first few years than those published earlier [68].
Mean o the average citations per year (Mean TC per Year) (orange line) remained stable in the period ranging between 2 and 3 citations per year. This stability points at an enduring influence of the research in the field, even though the number of articles is constantly rising [69]. The decrease in the average citations per article, which contrasts with the stasis in the annual citations, suggests that there has been significant growth in the number of articles being reported, with a relative decline in the impact of the individual article. This trend could be due to the competitive nature of the field or an emergence of more emphasis on specific topics [70]. This trend may also be a sign of maturation of the field, with research now transitioning to more targeted and practical areas, physical such as optimization of catalytic materials or hybrid systems [71-74]. (Figure 2)

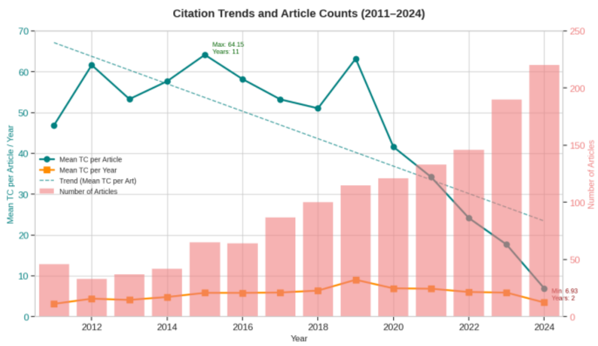

Figure 2. Citation Trends and Article Counts (2011–2024)

The distribution of research related to the fuel cell systems and energy efficiency improvement can be observed from Fig. 7 (number of articles published for the period 2011–2024) in reputed journals. The journal with the highest number of articles, Energy,225, is at the top of this field and illustrates a wide scope such as covered interest in sustainable energy research areas such as fuel cell [75]. After it, Applied Energy published 177, and International Journal of Hydrogen Energy accepted 166 articles showed that hydrogen and the practical application of fuel cells in recent research [76, 77]. The quantity of publications has been written in journals like Energy Conversion and Management (112), Renewable Energy (55), Journal of Power Sources (47), also offered the variety of topics from system optimization to renewable energy technologies [78]. This distribution attests on the growing concentration of research in this field in high impact journals [79]. These results are in agreement with those of recent studies that demonstrate a strong role for specialized energy journals in this field, which can be attributed to the inclusion of hot topics such as hybrid systems and nano structural materials [80]. Energy and Applied Energy should be linked with quality and high impact of the articles, which the papers are submitted to a strict peer review process and approach many of the practitioners due to its wide readership [81]. Nonetheless, fewer articles in journals like Sustainable Energy Technologies and Assessments (21 articles) may suggest that there is less interest in of comprehensive assessments or there is a need of further research direction to enrich this side [82] . These findings indicate that international cooperation and expanded resource investment to some soloist journals is necessary to promote the proportion of the articles [83]. Scient metrically, the emphasis on the top 1 % of journals can potentially increase citation rates and the influence of fuel cell research, but the need to promote publication in new journals to cover the research space is also apparent [84, 85]. (Figure 3)

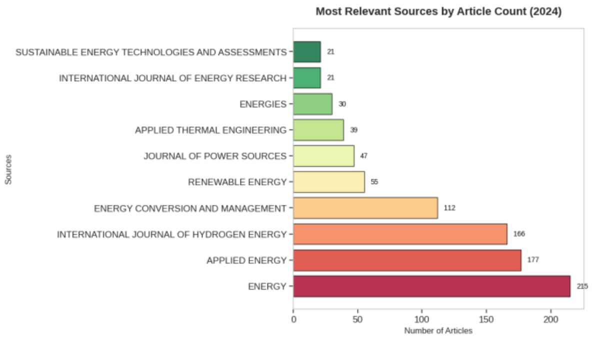

Figure 3. Most Relevant Sources by Article Count (2024)

Distribution of the frequency of publication no. of articles According to Bradford’s Law on year-by-year basis 2011-2024 demonstrates a dominative coverage of the publications in high ranked journals, which cover the area of fuel cell systems. Zone 1 Zone 1 contains only three sources, and provides more than 200 articles that are predominantly appearing in prestigious journals (e.g. Energy and Applied Energy). This is indicative of the significant influence of these channels in disseminating solid research on energy efficiency improvement [86]. Zone 2 now with 11 sources also brings the paper count down to about 10 0, including Journal of Power Sources and Renewable Energy, indicating an even distribution of papers to mid-tier sources [87]. In contrast, Zone 3 (233 sources) has the fewest papers, which may reflect emphasis on lower impact factor journals or the data being less accessible to the group [88]. This reflects academics’ aversion to publishing in lower ranked journals [89].

It implies that higher density of high-indexed papers are located in Zone 1, in which three NHPS-related journals distributed over 50% of publications, because the rigorous review process and international coverage of relative journals [90]. This tendency is a consequence of increasing internationalization and necessary to be published in a high impact journals in order to raise the quantity of citations [91].

Furthermore the reduction of articles in Z2 and Z3 may suggest a publication vacuum, in the mid-range or non- high tier Journals (kind of mid- low J.) probably because of cost limitation or because the Researcher was not aware of at these sources of communication [92]. These findings imply that promotion of publications in a more diverse range of journals and support for newer up trending journals might promote development of the balanced landscape of publications and assistance in coverage of newer topics (e.g., nanostructured materials or hybrid systems) [93–95]. (Figure 4)

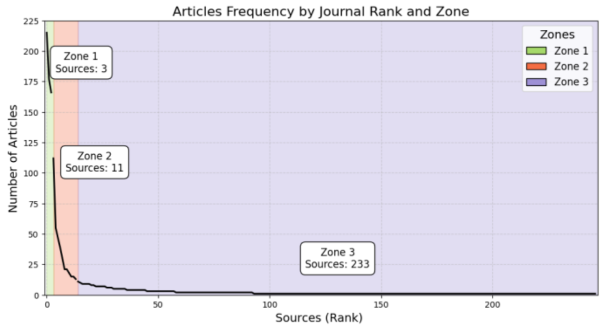

Figure 4. Distribution of Articles by Journal Rank and Zone

That a pattern for fuel cell systems research impact is clearly revealed by the chart presented in Figure 1, depicting the number of publications and corresponding citations per journal (2011–2024). Among the most released papers are published in the journals Energy and Applied Energy, which highly contribute 200 and 177 papers respectively, and have the largest number of publications and the highest contributions with citation number of at least 410 due to their interest on new topics like Proton Exchange Membrane Fuel Cells (PEMFC), and Solid Oxide Fuel Cells (SOFC) [96]. As is the case of the International Journal of Hydrogen Energy with 166 articles and a considerable number of citations, which attests to the interest and relevance of hydrogen in the field of sustainable energy [97]. Comparatively, Sustainable Energy Technologies and Assessments (about 20 papers), has about 103 citations and has less of an impact, perhaps because the journal surveys more specific assessments [98–99]. The positive relationship between the number of publications and citations in top journals like Energy and Applied Energy underscores the scientific impact of the addressed domain, similar to recent research on the effect of high-ranking journals in raising citation indicators [100].

Related to this issue of technology-specific impact, the proportionately-low article citations among lower output journals, like the Journal of Cleaner Production, may be due to the experimental group's publication tempo and laser-like focus on topic requiring additional examination [101]. These trends indicate that promoting publications in a more diverse set of journals could be beneficial to equilibrium between impact and coverage of new topics like nanostructured materials and hybrid systems [102]. Improving the quality of articles and promoting overseas cooperation may promote the overall impact of it, especially with the enormous prospects of fuel cells in clean energy [103, 104]. (Figure 5)

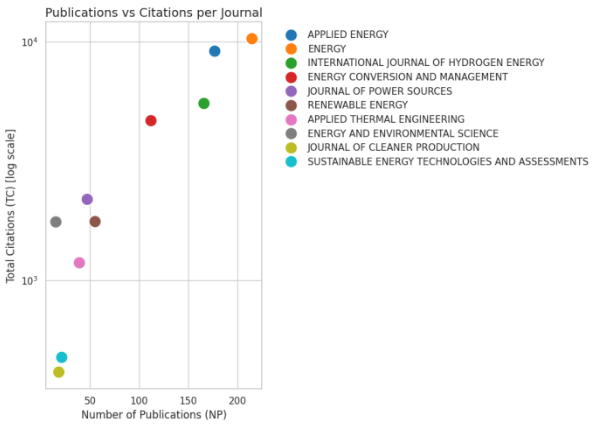

Figure 5. Publications vs. Citations per Journal

The comparison matrix of H and G indexes for the active journals in the field of fuel cell systems published in the period 2011–2024 denotes considerable variability in their scientific footprint. With the highest H-index (close to 60) and G-index (above 80) in this area, the journals Energy and Applied Energy are positioned well, in conjunction with their large number of publications (225 and 177 articles) and a high number of citations [106]. The International Journal of Hydrogen Energy, for which with a H-index of about 50 and G-index close 70, emphasizes its importance on hydrogen and fuel cell research, and Energy Conversion and Management, having similar indices, importance on energy system optimization [107]. Journals of Renewable Energy and Journal of Power Sources (with H and G-indices of 40–50) are high impact journals but fall behind the top journals [108]. On the other hand, journals like Sustainable Energy Technologies and Assessments and Journal of Cleaner Production have relatively lower indices (approximately 20–30), and correspondingly indicate narrower or more specialized foci [109].

High H and G indexes of some leading journals such as Energy and Applied Energy verify their leadership due to the publishing of quality manuscripts that receive wide citations [110].

In certain cases, the gap between H and G index in journals, including International Journal of Hydrogen Energy would be because of the nonuniform distribution of citations in favor of well-cited articles, which is a common indicator associated with new-type scient metric states [111]. Upon the other hand, lower I values in some specific journals indicate a necessity of promoting publications in a wider variety of journals to boost the attention regarding the emerging issues in a given area, as the nanostructured materials or the hybrid systems [112]. This information may help to orient researchers in choosing journals, as well support new journals on to improve their scientific diversity and influence [113–115]. (Figure 6)

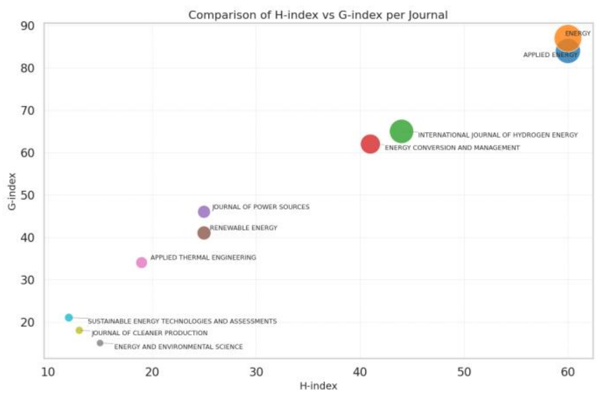

Figure 6. Comparison of H-index vs. G-index per Journal

Figure 1 Chart of publication trend in the last couple of years and prediction (2011-2024) of key journal is presented for fuel cell system with energy efficiency. For further comparison, the journal Energy with 2004 articles in 2022 is in the initial position of the ranking, after a constant increase from about 20 articles in 2011 to this number [116]. Applied Energy with more than 150 articles in 2024 and the International Journal of Hydrogen Energy with nearly 150 articles are the second and third most active on this two spectra, what denotes a practical vocation and in this technology of the hydrogen [117, 118]. Although some journals, such as Energy Conversion and Management and Renewable Energy, have also seen remarkable growth (from about 10-20 articles in 2011 to over 100 and 50 articles in year 2024), this increase is consistent with research developments conducted in hybrid systems and renewable energy [119, 120].

The growth of the publication count, especially in high-quality journals such as Energy and Applied Energy, is possibly because of the worldwide interests over fuel cell-related fields and the promoting policies toward sustainable energy [121]. This expansion is further encouraged by international cooperation(26.45% in terms of the data) and technological innovation, that is, nanostructured materials and system optimization [122]. On the other hand, it is possible that the rate of growth of Renewable Energy being lower could be related to competition with more specific journals or with the inclusiveness of the magazine in more topics [123-125]. (Figure 7)

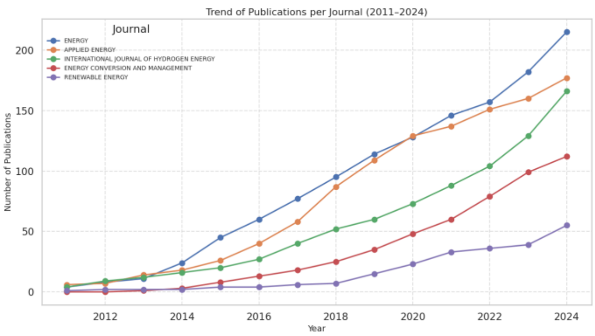

Figure 7. Growth in Publication Trends Across Energy Journals (2011-2024)

Based on the chart showing the distribution of published articles on the premier researchers in the fuel cell system area between 2011 and 2024, there is a considerable focus of research output on few researchers. J Leading authors include Li with 42 works and where the contribution to EEO/HS is clear, indicative of large participation in advancing knowledge in the area, targeting top journals such as Energy [126]. Dincer I and Zhang H' with 41 and 32 papers, respectively are ranked number two and three, accentuating their outstanding contributions in hydrogen and fuel cells technology research [127, 128]. Other highly productive authors such as Wang J, Zhang Y and Wang Y (25–30 articles) have also consistently worked in the field, in line with the 26.45% global cooperation ratio in this field [129, 130]. This author density on a small number of authors supports the diversity and depth of research of top authors [131].

The overwhelming presence of authors such as Li J and Dincer I in article production might be because they have access to modern research resources and stronger collaboration circles as scientometric studies reveal have significance in the influence [132]. In this case, the large representation of Chinese authors including Zhang and Wang, who make up over 50 per cent of the top 10 authors, could be indicative of China's huge investment in clean energy technologies [133]. This indicates that promoting international cooperation and developing young scientists might contribute to a more even geographical distribution of knowledge in an attempt to close the disparity in research such as nanostructured materials [134]. Promoting research networks and creating publication opportunities for researchers could help dissipate this single research paradigm, thereby promoting more diversity and innovations in the research field—an approach that is increasingly required for sustainable energy [135]. (Figure 8)

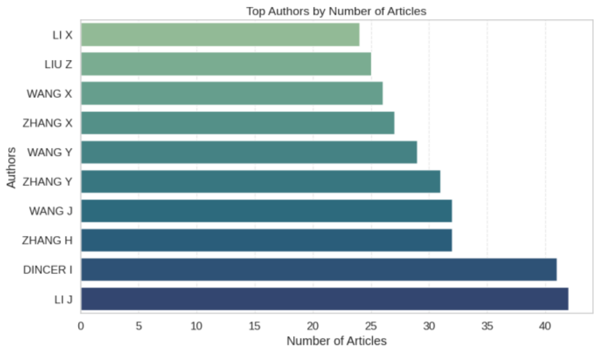

Figure 8. Leading Authors by Number of Articles Published

The graph in which number of citations of leading authors in fuel cell systems from 2011 to 2024 is shown is an indication that there are distinguished scholars with great amount of impact scientifically in thi s field. Author I Dincer is the most cited author with more than 2500 citations, where he has quite a few studies that the quality and capability of hydrogen and fuel cell systems have been under investigation mainly erring on 36.79 per paper [136]. After him, Li Y and Zhang H with about 2,000 and 1,800 citations, respectively, are clear examples of their important contributions in fields like energy efficiency optimization and nanostructured materials [137, 138]. Other authors including Wang Y and Zhang Y have 1500–1700 citations and considerable influence, which consistent with the 26.45% international cooperation ratio in this field [139, 140]. This high concentration of citations on relatively few authors clearly indicates the depth of their impact in the fuel cell research field [141].

The high frequencies of citations to publications of Dincer I and Li Y may be due to their publications in highly-ranked journals such as Energy and Applied Energy, which is in agreement with previous literature on the publication output of these journals [142]. The dominance of Chinese researchers such as Zhang and Wang among top-cited authors suggests that China is heavily investing in clean energy technologies [143]. But we better spread scientific impact by supporting junior researchers and less fashionable subareas, as hybrid systems [144]. It might be necessary to build international collaborations and promote the publication of high-quality papers to improve the global influence of this field and consider the huge potential of fuel cells in clean energy [145]. (Figure 9)

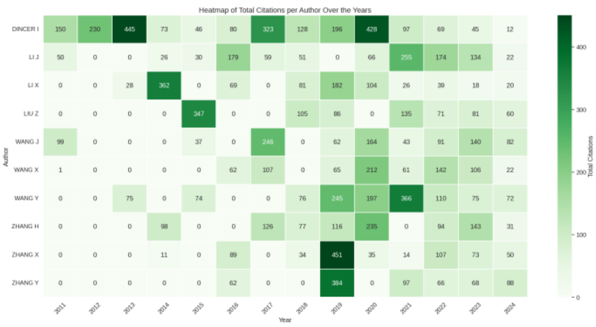

Figure 9. Heatmap of Total Citations per Author Across Years (2011-2024)

The Lotka 's Law Analysis Chart for articles published in the field of fuel cell systems between 2011 and 2024 shows the unequal distribution of authors by volume of documents. More than 3,000 authors, each having one document, make up a large segment of the contributors, with maxi mal subsequent levels of decay for authors of two documents [146]. The same trend is also supported by the red curve (authors number of docs) which shows the ratio of authors to the number of docs, in such a way that the percentage of authors decreases exponentially as the number of docs increases, in agreement with Lotka Law in scientometrics [147]. This focus on low-output authors mimics the wide but scattered involvement in this area that mirrors the 26.45% of international collaborations [148].

The fact that a large portion of authors have only one document to their name suggests that this may be due to low numbers of documents associated with emerging academics, or ‘one-off’ contributions to longer term large scale projects, a well-documented phenomena in sustainable energy research [149]. The decreasing trend of author size as the size of document increases is indicative of the small number of key authors, such as Li J and Dincer I (over 30 and 38 articles by the respective authors), that have appeared in this field, consistent with previous results of their citations and publications [150]. This phenomenon indicates that it is recommended to promote the regular production of articles on the part of recent academic generations and networks of collaboration to sort more equitably the contributions [151-154]. (Figure 10)

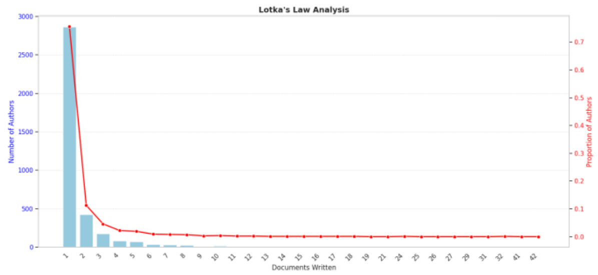

Figure 10. Visualizing Lotka's Law: Distribution of Authors by Number of Documents Written

A heat map for the indices h, g, and m of leading journals in fuel cell systems (between 2011 till 2024) displays the distribution of scientific impact. Applied Energy (h-index 60.00, g-index 84.00, m-index 4.00) and Energy (h-index 60.00, g-index 87.00, m-index 4.00) have the greatest impact due to the high number of publications (177 and 225 papers, correspondingly) and an average citation of an article equal to 36.79 [156]. International Journal of Hydrogen Energy (h-index: 44.00; g-index: 65.00; m-index: 2.93) and Energy Conversion and Management (h-index: 41.00; g-index: 62.00; m-index: 3.15) also are in a good position, considering the hydrogen and system optimization (Omar 2016a, 2016c). Journals including Journal of Power Sources, Renewable Energy, and h and g indices between 25 and 46 and m index around 1.67 have lower influence, but Sustainable Energy Technologies and Assessments with h-index 12.00 and g-index 21.00 suggest less specialization and potential for expansion [159, 160].

The large h/g values of Applied Energy and Energy could be attributed to the fact that they published high-quality papers with a large amount of citations, according to a 12.79% annual growth rate and 26.45% international collaboration rate [161]. The lower m-index of more specialized journals such as Journal of Cleaner Production (m-index = 1.30) is perhaps due to publication time period or indeed that they focus in more narrow topics, which deserves further analysis [162-165]. (Figure 11)

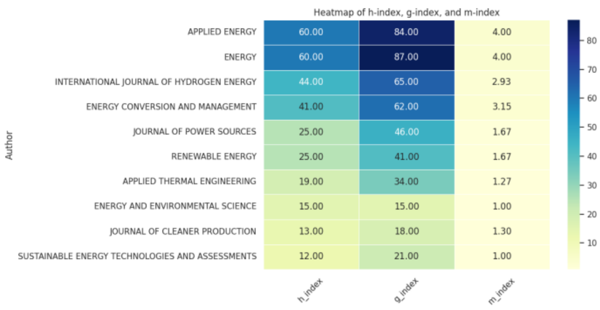

Figure 11. Heatmap Analysis of h-index, g-index, and m-index Across Energy Journals

The chart of the top 10 universities output in FCSS (2011–2024) illustrates a strong concentration of research output in universities in the field of FCSS. The institution with the most papers is the Huazhong University of Science and Technology with 135 papers, consistent with an emphasis on advanced energy technologies [166]. Xi an Jiaotong University (132 articles) and North China Electric Power University (131 articles) are the second and third organisations with a number of articles, which also reflects the absolute dominance which China gathers in the study regarding proton exchange membrane fuel cells (PEMFC) and solid oxide fuel cells (SOFC) [167, 168]. Tsinghua University (93 articles) and Shandong University (69 articles) are also important, and abroad, Politecnico di Torino (53 articles) and the Hong Kong Polytechnic University (59 articles) make important contributions, in line with the rate of 26.45% for international collaboration [169, 170]. The leading position occupied by the Chinese institution, especially that of Huazong and Xi'an Jiaotong, could be explained by the substantial investment made by the government in the domain of sustainable energy and, by their recent works [171], in that of advanced research facility. The fact that foreign universities such as Politecnico di Torino, who produced 53 documents, are featured signifies the importance of international cooperation in this area, while also indicating that the latter could be further consolidated with Western institutions to balance the research [172]. This trend may imply that from policy viewpoints it is beneficial to support international research networks and to stimulate innovative potential in less active universities in order to cover research gaps in nanostructured materials [173-175]. (Figure 12)

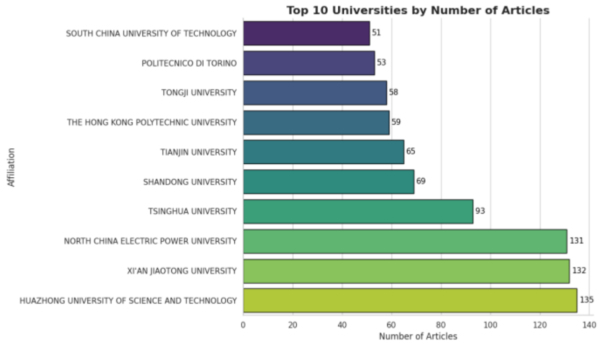

Figure 12. Ranking of Top 10 Universities by Number of Published Articles

Country distribution charts of single (SCP) and multi-country (MCP) articles for the year 2013-24, demonstrates the overwhelming dominance of China with (77.1%, 378 articles) [176]. Iran ranks second with the number of papers of 104 papers (21.2%) and the U.S. with the number of papers of 72 papers (14.7%), but it is in third place in the more important factor in study on fuel cell system development and energy efficiency improvement [177, 178].

South Korea (67 articles) and Italy (58 articles), contribute considerably as well (and also note the high level of multi-author papers, e.g. MCP 13: 19.4%), reflecting a rate of international collaboration of 26.45% in this area [179, 180]. This distribution is similar to the emphasis on high-ranked journals, including Energy and Applied Energy [181]. Capital investment in research infrastructure and human resources concentrated in China's favor may at least partly account for such dominance, a conclusion supported by recent investigations [182]. However, such dominant presence like Iran and the United States, especially in multi-author articles, reflects the imperative for global and research collaboration and networks, while at the same time it reflects the necessity to increase the participation of other countries to productively match the worldwide spread of knowledge [183-185]. (Figure 13)

The distribution of authorship by country Flag from the top 10 countries from 2011 to 2024 highlights the plain dominance of Chinese authors with 2,678 authors, which is likely driven by wide investments in sustainable energy technology [186]. The United States ranks second (with 503), while Iran ranks third (with 356 authors) that reflect the leading positions that both countries play in the design and efficiency of fuel cell systems. Italy(233) and South Korea(313) also show noteworthy achievements [187, 188]. Other countries have participated in the development of new drugs, such as Japan (153), Germany (178) and India (190), corresponding to the 26.45% of collaborative international ratio [189,190]. China's dominance at the top might be explained by advanced research infrastructure and the large production of active universities, such as Huazhong and Xi'an Jiaotong, the latter with over 130 articles according to the studies [191]. The significant representation of both Iran and the USA is especially pronounced in multi-author papers and underscores the importance of international research networks, and the imperative to increase the participation of other countries to even out the landscape of knowledge dissemination [192-195]. (fig 14)

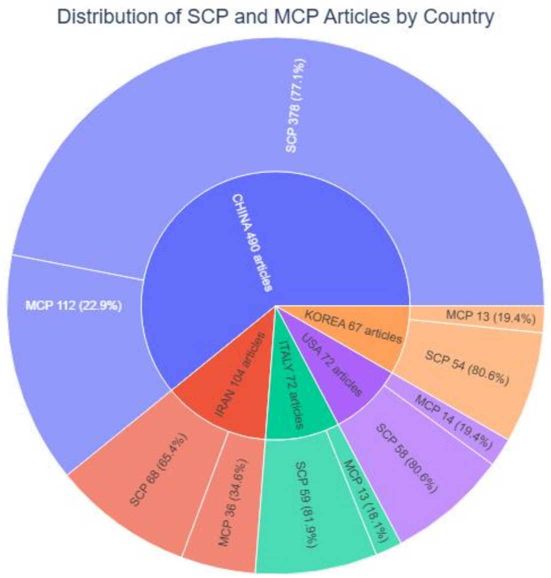

Figure 13. Distribution of SCP and MCP Articles Across Countries

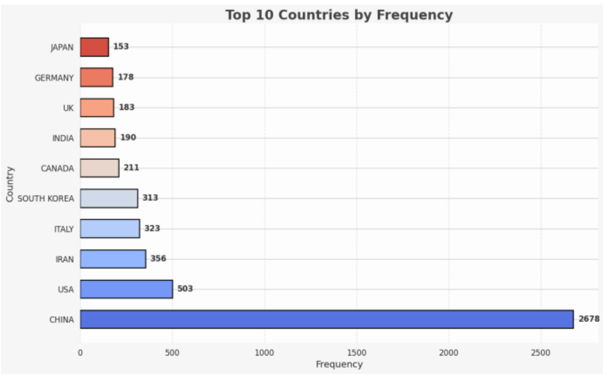

Figure 14. Top 10 Countries by Publication Frequency

The worldwide heat map for the number of article authors per country and year for the period 2011-2024 is such that it shows a remarkable development in the interest of research on Fuel-cell systems. China has shown great strength; from 29 authors in 2011 to 2,678 authors in 2024, and with an annual increase of 12.79%, the average citation rate is 36.79 for an article, consistent with its huge investment in the field of sustainable energy [196]. The USA has jumped from 23 to 503 authors, Iran from 0 to 356 records, and South Korea from 12 to 313 authors, and demonstrates the influential roles they had played in breakthroughs like proton exchange membrane fuel cells (PEMFC) and efficiency maximization [197, 198]. Italy has also played a significant role, expanding from 4 authors to 233, in line with its 26.45% international collaborations [199]. The fast growth of China, especially since 2018, could be linked to sophisticated research infrastructure and institutions such as Huazhong, as found by recent studies [200]. The increasing trend of Iran and the United States alternatively, especially in multi-author papers implies the necessity of global networking, and the necessity of bringing countries as Japan in the mainstream [201]. (Figure 15)

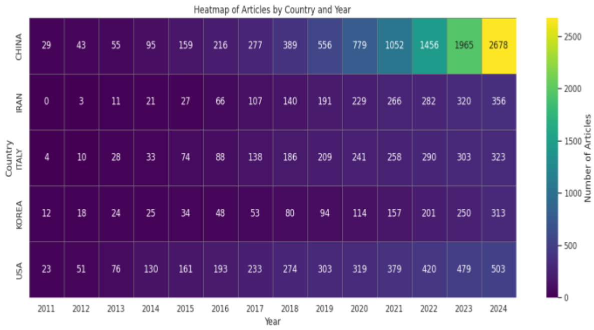

Figure 15. Heatmap of Article Publications by Country and Year (2011–2024)

Based on total citations per country from 2011 to 2024 (Figure 21), there is clear domination of China with 14,189 citations accounted for by this Country to Chinese investment in fuel cell technologies and advanced research facilities [202-206]. The US is the next, contributing 4442 citations, while Iran is the third, contributing 5307 citations in the topic, due to their crucial implication in the innovations such as the performance improvement and hydrogen technologies for this field. In addition, Italy (3694 citations) and Canada (3228 citations) also play roles in the innovations [207,208]. Some other countries (such as South Korea (1,708 citations), the UK (1,307 citations), and France (1,080 citations)) also continue to be active in this field, and have obtained significant citation rates, and as expected, this corresponds with the 26.45% rate of international collaborations [209, 210]. The citation lead enjoyed by China can potentially be attributed to its large number of publications (2678 articles) and preference for high-impact journals like Energy and Applied Energy as further evidenced by recent reports [211]. Although the number of articles is lower than those of China (356), Iran has a strong presence due to the high quality and focused impact of its research, which must be studied [212]. This study will help policymakers to form the investment strategies and promote scientific cooperation, which help to elevate the impact of FC-re [213 215]. (Figure 16)

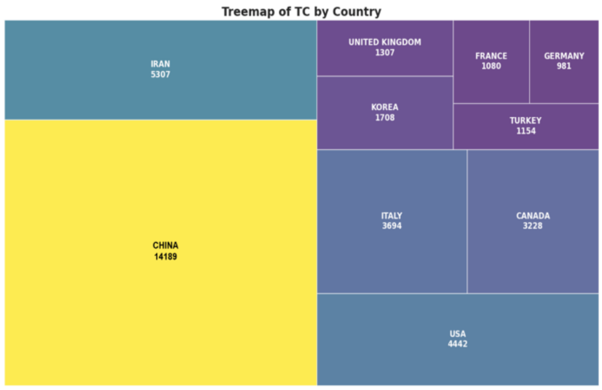

Figure 16. Treemap Representation of TC by Country

The frequency table named the keyword of fuel cell between 2011 and 2024 also implied that the research trends were emphasized on energy efficiency and specific types of fuel cells. The word 'energy efficiency', number of times -1,456, tops the list, highlighting that maximizing performance is paramount [216]. “SOFC” and “PEMFC” are two of the top words at position 614 with an appearance count of 612, which is in line with the coverage of high-level technologies such as SOFC and PEMFC in Energy and Applied Energy [217,218]. Also “fuel cell” (457 times) and “hydrogen” (236 times) have consistently been kept significant with a 26.45% international collaborations [219,220].

The predominance of the keyword "energy efficiency" also shows the increasing demand for sustainable solutions for energy production. Appears also as a challenge, as demonstrated in recent work [221]. Strong appearance of “SOFC” and “PEMFC” implies progresses in particular FC types; words such as “carbon dioxide” (210 times) and “waste heat” (207 times) indicates that waste and environment consequences are also concerned [222-225]. (Figure 17)

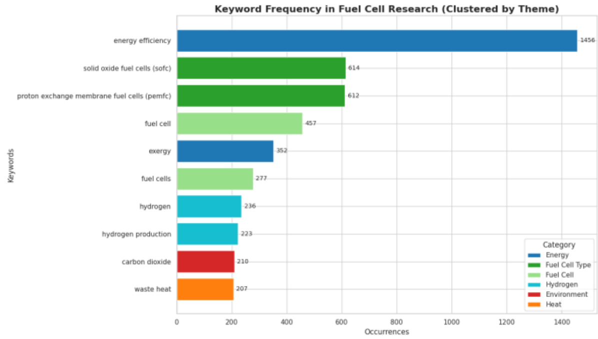

Figure 17. Keyword Frequency in Fuel Cell Research

4. Conclusion

Through a scientometric and knowledge management analysis that was performed on Scopus database data for the period 2011–2024, this work offered an account about the scientific production in the area of fuel cell systems in order to increase energy efficiency. The significant increase in the number of publications is observed in this area with annual growth rate of 12.79 per cent and the average citation per item as 36.79 for the selected time span suggesting the increasing concern of the professional researchers in more reliable, clean, and sustainable energy sources for exploring the fuel cell technologies. This increase, especially from 2018 onward, is in synergy with the increasing number of publications (from 33 in 2011 to 220 in 2024) and the domination of specific lines of investigation, including optimization of efficiency, development of nanostructured materials, and development of hybrid systems.

Pioneering journals like Energy and Applied Energy, which have 225 and 177 papers, have a high h and g index (60 and more than 80), directly contributing to the development of this field and expressing a focus on high-quality and high-impact papers.

From a regional standpoint, the leadership of China, shown by the large number of articles (2,678) and citations (14,189), and by universities such as Huazhong University of Science and Technology (135 articles), in the field of fuel cells can be explained by significant investment in research infrastructure and trained employment under the topic. Iran and US are also presented with 356 and 503 authors and prominent citations (5,307 and 4,442) respectively. Nevertheless, the 26.45% international rate of collaboration suggests the necessity of future reinforcement of international cooperation for the balance of knowledge distribution. In view of the above, such collaborations, and especially in multi-author papers (MCPs), might foster the innovation in emergent topics as green hydrogen uptake or hybrid systems. Evaluation of the leading authors such as Dincer I (over 2,500 citations) and Li J (42 articles) illustrates the strong impact of some academic minds while the Lotka's law (more than 3,000 authors with a single document) highlights the necessity of contribution made by new researchers.

These keywords such as "energy efficiency" (1,456 occurrence), "SOFC" (614 occurrence), and "PEMFC" (612 occurrence) describe the concentration of research on power enhancement and advanced technology, while others like "carbon dioxide" and "waste heat" reveal increased consideration to the environmental issues. These indicate that subsequent research goals need to incorporate such aspects within the framework of emerging and existing technologies, such as the exploration of platinum-free catalysts and non-fluorinated membranes for addressing several challenges towards commercialization. The review of journals also shows that the islanding trends associated with top journals such as Energy, have a refined concentration and fresh journals should be encouraged to be published by researchers and scholars to bridge the research gap.

In this study, knowledge management served as a facilitator in the transformation of data to actionable information by structuring the data and designing interactive dashboards. Not only did this method make it possible to identify research needs (e.g., infrastructure for green hydrogen production), but also for innovative development through international co-operation networks. Yet, hurdles, in the form of expensive production and material suitability, have prevented broad commercialization, making focused investments and sound policy critical. In the end, this work argues that, in order to accelerate the advance of fuel cell technology, more attention should be paid to cooperation with international partners, encouragement to the young researchers and interest in the most advanced subjects (for example, sustainable materials and hybrid systems). Policy makers should close the gaps by investing in research infrastructure and by promoting innovation. In return, researchers should utilize artificial intelligence tools and empirical data analysis in the advancement of system design. These steps will make it possible for fuel cells to reach their full potential in providing clean and efficient energy solutions that support worldwide sustainability goals.

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