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Scientometric Review of Advancements in The Development of High-Performance Cathode for Low and Intermediate Temperature Solid Oxide Fuel Cells: Three Decades in Retrospect

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Abstract

Solid oxide fuel cells (SOFCs) have the potential to replace conventional thermal power plants due to their high efficiency and low emission. As the activation loss of the cathode usually limits the SOFC performance, the development of high-performance and durable cathode materials has received extensive attention in the past few decades. It is therefore essential to keep track of the research progress to identify significant research gaps and future directions. In this study, we retrieved the bibliometric data of 1101 cutting-edge research articles focused on cathode development for SOFCs and conducted a scientometric review. Even though significant research in cathode development for intermediate to low temperature SOFCs started in the 1990s, significant growth in the research output appeared in the year 2000 and remarkably continued till 2010 before exhibiting a sinusoidal pattern. Overall, there is a record of average decadal progress in this research area. We found that only a small percentage of countries in the world (i.e., about 29%) are involved in the research for the development of intermediate to low temperature SOFC cathodes. A highlight of core assessment criteria for cathode developments is presented with a summary of the most recent articles (i.e., including those in 2021). This paper can help early-stage

researchers, journal outlets, governments, funding authorities, and investors understand the current progress in this area and how close researchers are to a breakthrough that could lead to the commercialization of this emerging technology.

Keywords: Solid oxide fuel cells, Cathode, Low temperature, Intermediate temperature, Scientometric review.

1. Introduction

To address the global warming and pollution issues, it is of paramount importance to utilize renewable resources as well as to maximize energy conversion efficiency. Although renewable solar and wind energy as well as renewable biomass will play increasingly more important roles in the global energy supply, conventional fossil fuels such as natural gas will continue to be important energy sources in the near and medium-term. Natural gas and biomass are usually used in conventional thermal power plants for energy conversion, which is based on thermodynamic cycle. As the efficiency of conventional thermal power plants is limited by the Carnot efficiency and it is very difficult to further improve, the search for alternative technologies with higher efficiency and low emission for energy conversion is of paramount importance. Among different available technologies, solid oxide fuel cells (SOFCs) are very promising for replacing conventional thermal power plant due to their high efficiency, fuel flexibility, low emission, scalability, and quiet operation. The energy conversion processes of a conventional thermal power plant and SOFC are compared in Figure 1.

In 1937, the first fuel cell with solid ceramic electrolyte was developed and operated by Baur and Preis [1] which then paved way for further research in the development of solid oxide fuel cells

(SOFCs). The earlier developed SOFCs operate at high temperatures ($800 - 1000$ ℃) so that the ceramic electrolyte can gain sufficient ionic conductivity needed for the proper operation of the entire energy conversion system. The residual heat generated during its operation can be efficiently harnessed and integrated with a gas turbine or even used as thermal energy in the form of cogeneration [2]. Interestingly, SOFCs have the advantage of having relatively low maintenance cost, good compatibility with multiple fuels, and excellent modularity property [3–5].

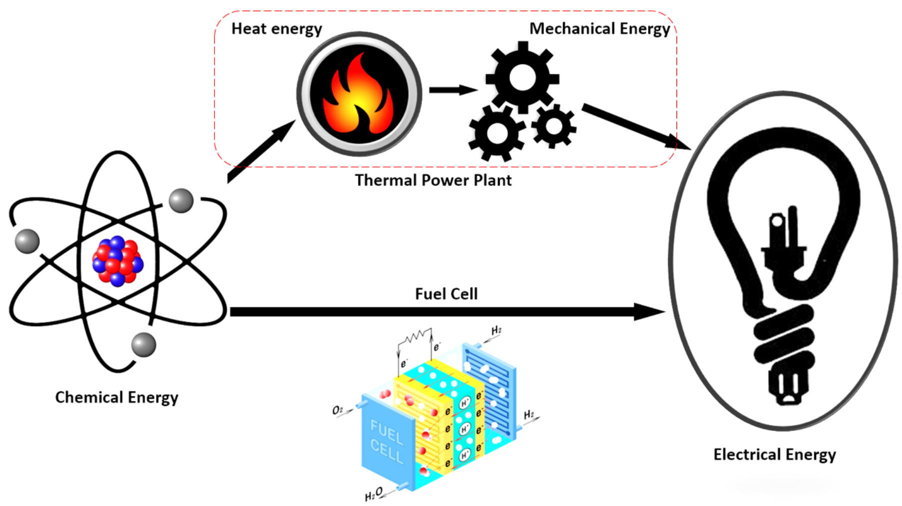

Figure 1: Energy conversion procedure in a fuel cell compared to that of a thermal power plant.

Compared with other types of fuel cells, one distinct feature of SOFC is fuel flexibility. The use of coal as a fuel has been reported in [6], gaseous and liquid hydrocarbons in [7–9], carbon monoxide in [10,11], ammonia in [12], and ethanol in [13,14]. All these buttresses some of the advantages of SOFCs over other fuel cells; Polymer Electrolyte Membrane Fuel Cells (PEMFC) [15], Direct Methanol Fuel Cells (DMFC) [16], Alkaline Fuel Cells (AFC) [17], Phosphoric Acid Fuel Cells (PAFC) [18], and Molten Carbonate Fuel Cells (MCFC) [19].

In operation, the electrons from the anode react with oxygen at the cathode to form oxygen ions, which are transported to the anode side through the dense ion-conducting electrolyte as illustrated in Figure 2. At the anode side, the oxygen ions react with the fuel (such as H_2) to produce steam and electrons. The generated steam is taken out from the fuel cell while the electrons will flow to the cathode through an external circuit to produce useful electricity. Although a high working temperature is beneficial for oxygen ion transport through the electrolyte, it requires complicated thermal management and poor cell durability. In particular, the mismatch in thermal expansion coefficient (TEC) between the cell components may cause thermal stress, which in turn may damage the cell structure in the long run. Therefore, in the recent two decades, efforts have been made to develop SOFCs working at an intermediate or low temperature, from 300^o to 600^oC. However, lowering the temperature of SOFC causes high overpotential losses due to a lower ionic conductivity of the electrolyte and lower electrocatalytic activity of electrodes. Thus, it is critical to developing novel electrolyte and electrode materials that can work effectively at an intermediate or low temperature. The ohmic loss of the electrolyte can be reduced by developing alternative electrolyte materials with high ionic conductivity or by reducing the thickness of the electrolyte since the ohmic loss is inversely proportional to the electrolyte thickness. Therefore, the activation loss at the cathode is usually the limiting factor for SOFC performance. For instance, SOFCs with yttria-stabilized zirconia electrolyte that is thick and LSM cathode have been reported to show low power density at intermediate temperatures due to the increase in the polarization resistance (Rp) of the electrodes and ohmic resistance (Ro) of the electrolyte [5,20]. Using a thin film electrolyte for YSZ and doped ceria-based electrolytes have been reported to reduce the ohmic resistance to an acceptable level down to the temperatures ranges of 700 to 550 degrees Celsius [21–23].

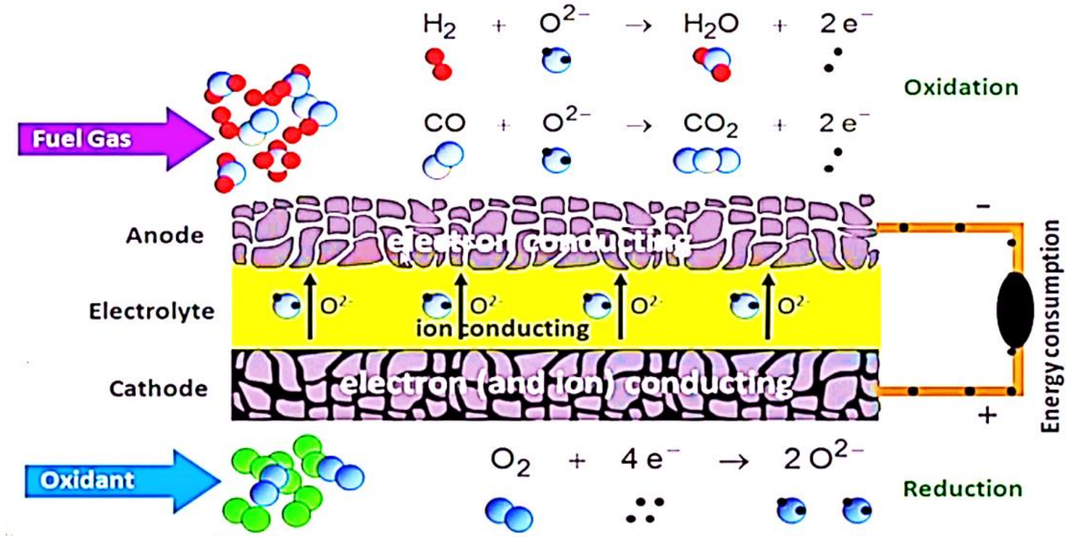

Figure 2: Operation of a solid oxide fuel cell [24]

Hence, the development of cathode materials is paramount to realizing intermediate to low temperature operating SOFCs. The last 30 years have witnessed remarkable progress in developing high-performance cathodes for intermediate to low-temperature SOFCs. In the 1990s, the research output in this area was quite low but getting to the 2000s, research interest skyrocketed, and various research was carried out by different researchers from different geographical regions to develop cathodes for intermediate to low-temperature SOFCs. To recognize the waves of research in this area, prominent researchers have carried out various systematic reviews. Kim and Manthiram [25] reviewed the use of $LnBaCo_2O_{5+\delta}$ (Ln = Nd, Sm, Gd, and Y) oxides as cathodes for intermediate temperature solid oxide fuel cells, Lee et al. [26] reviewed the earlier use of $LnBO_2(001)$ (B = Mn, Fe, Co, and Ni) as cathodes for solid oxide fuel cells, Zhou et al. [27] reviewed the use of $Ba_{0.5}Sr_{0.5}Co_{0.5}Fe_{0.5}O_{3-\delta}$ perovskite oxide materials as cathodes for SOFCs, Tarancon et al. [28] reviewed the use of layered perovskites as promising cathode materials for SOFCs, and Jiang et al.[29] reviewed the use of LSM as cathodes for SOFCs. Recently, Yang et al.[5] reviewed the 15 years of their research group contributions to the development of cathodes for intermediate to low-temperature SOFCs. The above-mentioned literature reviews provided insights into the material properties and mechanisms of the cathode reaction processes. However, a scientometric review of the research in the development of cathodes for intermediate to low temperature SOFCs has not been conducted. A scientometric analysis is an unbiased approach for critically reviewing research trends and contributions in any area of interest.

To further contribute to the understanding of advancements in the cathode for intermediate to low temperature operating SOFCs, we have conducted a scientometric review of the progress in the development of cathodes for SOFCs. We retrieved all related quality research articles in the past 30 years from one of the most trusted bibliometric database websites (Scopus) and generated a network of researchers' collaborations, keyword co-occurrences, article co-citations, and geographical distribution of the most contributing countries in this area of interest. The essence of this is to critically examine them and identify the most productive researchers, highest impact journals, and highest impact research co-occurrence networks and keywords and finally deduce cogent key focus areas from the research themes. This research will make evident to researchers and industries the states-of-the-art advancements in cathode development for intermediate to low-temperature SOFCs. This study combines scientometric analysis with insightful discussions to give a holistic perspective of research developments to SOFC stakeholders. Most importantly, new researchers in this field and research grant committees will find this work helpful in providing an overview of the level of progress in this research area from different angles.

2. Research methods

The research approach and tools used in carrying out the scientometric analysis are outlined in this section. The subsequent sections give a compendious outlook of the research methodology employed. The flowchart illustrated in Figure 3 presents the overview of the research methodology. The succeeding sections expatiate each of the concepts illustrated in the flowchart.

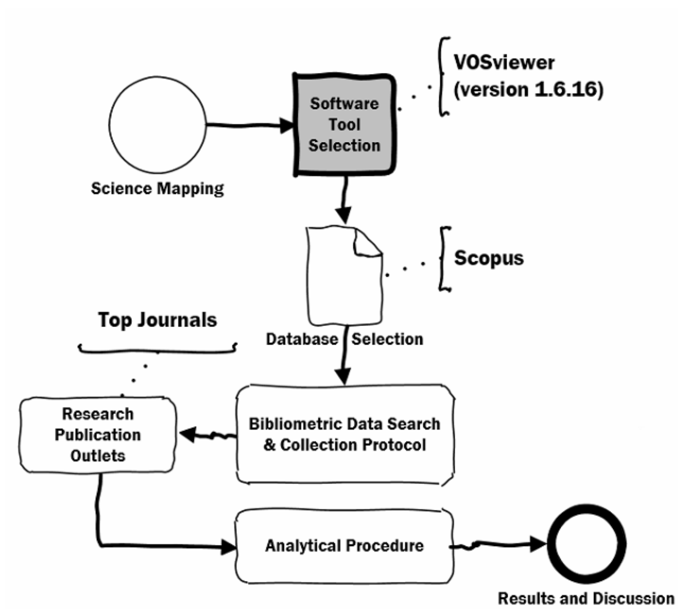

Figure 3: Flow chart for research methodology

2.1 Science mapping and scientometric analysis

A quantitative science mapping approach is employed in this study to quantitatively map out networks and patterns from a database of bibliometric data as described by Cobo et al. [30]. Science mapping, alternatively known as bibliometric network visualization, has become a veritable tool employed by researchers to identify and describe large collections of bibliometric data for various purposes [31,32]. Particularly, this technique helps to resolve challenges associated with tedious manual review processes attributed with unraveling connections between studies based on researchers, countries, regions, funding, research outlets, keywords, etc., within a research domain of interest[33]. In this study, attention will be focused on scientometric analysis which is one of the core subcategories of science mapping[30]. Scientometric analysis encapsulates the entirety of the process of measurement and analysis of networks of research fields, researchers, universities, and countries within the scope of interest [34].

2.2 Software tools selection

Many software tools of wider coverage have been designed for scientific mapping of literature [30]. Some of these tools are designed for specific applications while others are designed for general science mapping purposes. Each of these tools has its specific capabilities and limitations which make it unique. Proper care must then be exercised in selecting an appropriate science mapping tool to meet the desired objectives of the study. In that case, knowledge of the specifics of each tool such as features, strengths, and limitations is very essential [35]. Some of the existing science mapping tools are CitNetExplorer [36], IN-SPIRE [37], BibExcel [38], VOSviewer [39], Gephi [40], CiteSpace [41], CoPalRed, Network Workbench Tool and VantagePoint. In this study, VOSviewer (version 1.6.16) was selected to map literature of advances in the development of high-performance cathodes for SOFC. This software was selected because it is open-source with features sufficient for the visualization of bibliometric networks and the capability for accurately executing scientific mapping of literature[30,39]. It has been widely used by prominent researchers for scientometric reviews [42]. For instance, it has been used to map knowledge in constructed wetland microbial fuel cells [43], and in hydrogen storage which is one of the major fuels used in SOFCs [44].

2.3 Database selection

The databases that index the most prominent and credible research works in the field of energy-related research are Scopus and Web of Science. Even though these databases are very comprehensive in scope for the extraction of relevant bibliometric data, the number of indexed publications in these two databases under the same research area differs. Scopus was selected as the main database for bibliometric data extraction in this study because it has a wider coverage of research articles and includes more recent publications compared to Web of Science and Google Scholar [45]. Furthermore, VOSviewer science mapping software supports direct importation of bibliometric data from Scopus as well as other databases such as Dimensions, Web of Science, PubMed, Crossref JSON, Crossref API, and RIS. Therefore, the adoption of Scopus suits the purpose perfectly since it is compatible with the file formats of VOSviewer.

2.4 Bibliometric data extraction and journals selection

The commonly used keywords that pertain to studies related to the development of intermediate-low-temperature high-performance cathode for SOFC were used to fetch all relevant and encompassing bibliometric datasets. For this study, the precedent researches in the field, particularly by the group of Wei Zhou [5] and Zongping Shao [46], were considered for the selection of the most appropriate keywords in the current study. Based on the focus of this study, the search keywords considered for the retrieval of bibliometric data are “SOFC” OR "solid oxide fuel cell" AND “cathode” OR "cathode development" OR "cathode material" OR "high-performance cathode" OR "oxygen reduction" OR "oxygen reduction reaction" AND "low temperature" OR "intermediate temperature" OR “ITSOFC” OR “ILT SOFC” using the “article title/abstract/keyword” search functionality. Searching these keywords on the Scopus database without defining any exclusion or limitation generated 1,335 articles (as of April 15, 2021).

Therefore, streamlining the dataset through a highly fine-tuned approach using the search combination functions is necessary. To achieve this, only the “article title” search functionality was deployed in the first two levels of the search, and the “article title/abstract/keyword” search functionality was used in the last level since some of those keywords may not necessarily be in the article title alone but within the article title/abstract /keyword scope due to their relevance. To further retrieve the most relevant dataset, the document type was set to be limited to only articles and reviews. The conference papers were excluded in the searches because they complicate the analytical process yet add almost no value to the results[47]. The journals from which bibliometric data were extracted with at least 10 articles (based on our search criteria) in the order of those with the most to the least published articles include *Journal of Power Sources; International Journal of Hydrogen energy; Ceramics International; Journal of the Electrochemical Society; Solid State Ionics; Electrochimica Acta; Journal of Alloys and Compounds; Journal of Materials Chemistry A; Materials Research Bulletin; Electrochemistry Communications; ACS Applied Materials and Interfaces; Journal of the European Ceramic Society; Journal of Solid State Electrochemistry; ACS Applied Energy Materials; Chemistry of Materials; and Fuel Cells.*

The language of the articles considered was restricted to English. With the above criteria in place, the total number of articles that met all stated conditions was 1101 (as of April 15, 2021). The bibliometric data was retrieved in the Comma Separated Values (CSV) file format which was then imported into the VOSviewer for scientometric analysis of research literature about the development of high-performance cathode for low-intermediate-temperature solid oxide fuel cells.

2.5 Analytical procedure

The analysis of the imported bibliometric data was carried out in different stages after proper scrutiny of the imported bibliometric data to avoid discrepancies and analysis of error-infested data.

At first, VOSviewer functionality "Create a map based on bibliometric data" was employed to generate maps of article co-authorship, keyword co-occurrence, co-citation, bibliographic coupling, journal citations, country citations, and document citation. Thereafter, the total article citations, average citations, average normalized citations, link strengths of articles, authors, and countries were documented.

Secondly, the feature in VOSviewer "Create a map based on text data" was employed to create a co-occurrence map based on the text data. This procedure was used to generate a map of terminologies mostly reported by researchers in cathode development for intermediate to low-temperature SOFCs. The keywords were carefully studied and elaborated. The co-occurrence map is illustrated in Figure 13. The interpretations were carefully reported and discussed in the results and discussion section of this article.

3. Science mapping results and discussions

3.1 Annual publication trend

Although the first ceramic fuel cell also known as solid oxide fuel cell was first developed in 1937, it appears that interest in developing high-performance cathode for SOFCs started in the last 3 decades with a handful of publications addressing this concern in the 90s. This study fetched a total of 1101 articles published in the last 30 years (i.e., from 1990 to 2021). The bibliometric data retrieval was not time-constrained but the earliest publications in the development of cathode for intermediate to low-temperature SOFCs appeared to first appear in 1990 on the Scopus database as illustrated in Figure 4.

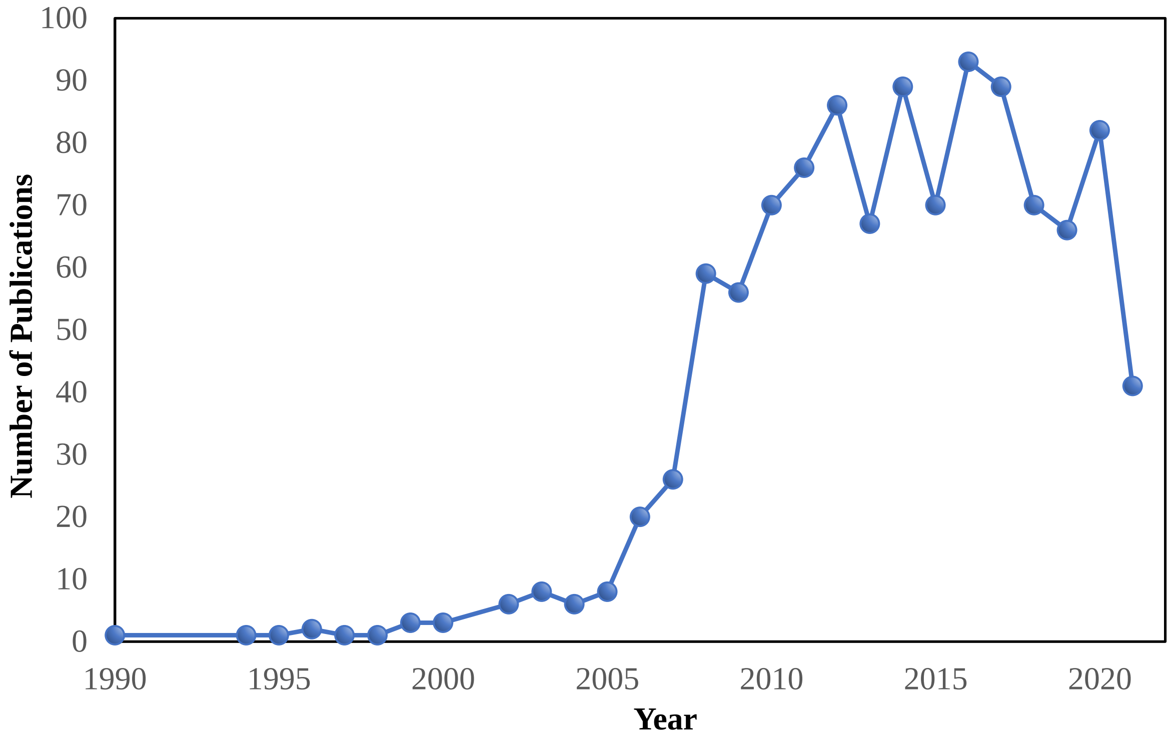

Figure 4: Annual publication trend for articles in the development of high-performance cathode for intermediate to low-temperature SOFC from 1990 to 2021

The annual publication trend was crawling in the 1990s until it picked up in the 2000s. This is understandable as the first research publication in this area was first established in 1990 and partly because research in this area requires sophisticated experimental procedures to measure certain material properties of interest. Although it appeared that there were dips in 2013, 2015, 2018, and 2019 but generally whenever there is any decrease in the number of publications in one year, the publication frequency in the following year often supersedes the previous year which could be because of the arduous nature of experimental research that needs to be conducted before putting forward any new findings to the research and scientific community. It can also be observed that the number of publications in this research area skyrocketed between 2005 and 2010. The average continuous increase in research could be driven by the increasing concern about the adverse environmental effects of GHGs emission, increasing energy demands, and the motivation for a decentralized power source.

3.2 Science mapping research outlets

Research outlets represent one of the major avenues through which quality research findings and discoveries are being shared with the scientific community and other interested bodies. These outlets are specialized bodies that compartmentalize research articles based on scope, targeted audience, and other useful metrics. The identification of key journals in the desired research area is cogent in systematically mapping research trends in that field. Figure 5 shows the citation network of 23 top journals that publish articles on the development of high-performance cathode for intermediate to low temperature operating solid oxide fuel cells. These research outlets have at least 5 research articles with a minimum of 100 citations. These parameters were specified while generating the network on VOSviewer.

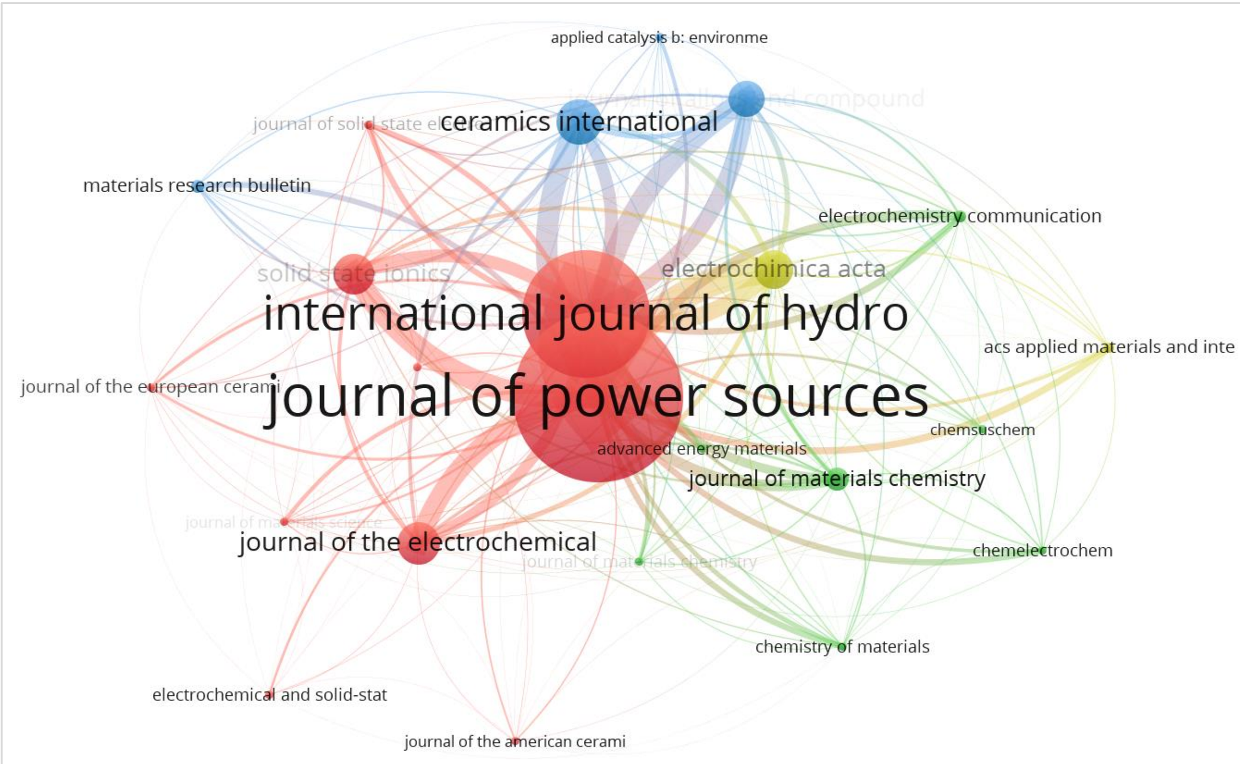

Figure 5: Network of top research outlets in the development of high-performance cathode for intermediate to low-temperature SOFCs.

The minimum values in generating the network were not based on any standard since one does not exist, but basically on the authors' discretion and understanding. Table 1 presents a detailed summary of the network of the top 23 prominent research outlets in the development of high-performance cathode for intermediate to low-temperature SOFCs.

Table 1: Popular research outlets in cathode development for intermediate to low-temperature SOFCs

Research Outlet	No of articles	Total citations	Av. Citations	Total link strength
Journal of Power Sources	229	8770	38	1982
International Journal of Hydrogen Energy	172	3775	22	1488
Journal of The Electrochemical Society	58	2566	44	434
Solid State Ionics	55	2419	44	464
Electrochimica Acta	53	1487	28	607
Journal of Materials Chemistry	8	1048	131	114
Journal of Solid-State Electrochemistry	11	930	85	166
Journal of Materials Chemistry A	32	892	28	341
Electrochemistry Communications	17	778	46	229
Journal of Alloys and Compounds	49	716	15	517
Ceramics International	62	604	10	500
Chemistry of Materials	10	573	57	171
Journal of Materials Science	5	511	102	100
Advanced Energy Materials	7	467	67	101
Journal of The European Ceramic Society	12	436	36	90
Applied Catalysis B: Environmental	5	362	72	82
ACS Applied Materials and Interfaces	14	332	24	139
Materials Research Bulletin	18	308	17	122
Electrochemical and Solid-State Letters	8	276	35	37
Journal of The American Ceramic Society	5	245	49	42
Chemsuschem	5	178	36	79
Fuel Cells	10	131	13	55
Chemelectrochem	7	108	15	146

The source citation network function of VOSviewer was used to generate the network illustrated in Figure 5. The size of each node on the network represents the number of citations (i.e., impact) from that research outlet (i.e., journal). For example, the nodes in *Journal of Power Sources*; *International Journal of Hydrogen Energy*; *Journal of the Electrochemical Society,* and *Solid State Ionics* are relatively larger than the other research outlets. This highlights the relative impacts of each research outlet from the others. The research outlets closely packed together indicate that they belong to the same cluster and the thickness of the lines of connection shows the strength of the connections based on cross citation between the research outlets. For instance, the *Journal of Power Sources* shows a strong citation connection with *Journal of the Electrochemical Society*, *Solid State Ionics, Ceramics International, Journal of Alloys and Compound,* and *International Journal of Hydrogen Energy* within the scope of research in the development of cathode for intermediate to low temperature operating SOFCs. These journals are usually cross-cited in this research area.

As seen from Table 1, all of these research outlets have connections with other journals in terms of citations as observed from the column of total link strength from Table 1. Research outlets that belong to the same cluster are usually represented with the same color. This cluster could be based on research focus area or frequency of inter-journal citations. For instance, in the red cluster, some of the journals in this category are *Journal of Power Sources; Journal of the European Ceramic*; *Journal of Electrochemical*; *Electrochemical Solid State*; *Journal of the American Ceramic*; and *Journal of Materials Science*. Within the blue cluster, we have *Materials Research Bulletin; Ceramics International; Journal of Alloys and Compounds and Applied Catalysis B: Environmental,* and in the green cluster, we have *Electrochemistry Communication; Chemistry of Materials; Chemsuchem; Chemelectrochem;* and *Advanced Energy Materials.*

In terms of the frequency of research articles in the various outlets, the top five (5) outlets that contribute the most to research outputs in cathode development for SOFCs are *Journal of Power Sources (229); International Journal of Hydrogen Energy (172); Ceramics International (62); Journal of the Electrochemical Society (58); and Solid State Ionics (55).*

The research outlet that contributes the least number of publications is *Chemsuschem (5).* However, there are certain changes in the order when the journals are ranked based on the total number of citations. The top five most cited (5) journals are *Journal of Power Sources (8870),* *International Journal of Hydrogen Energy (3775); Journal of the Electrochemical Society (2566); Solid State Ionics (2419), and Electrochimica Acta (1487).* Whereas the research outlet with the least number of citations is *Chemelectrochem (108).* For instance, some of the top-cited articles in the *International Journal of Hydrogen Energy* that pertains to cathode development for intermediate to low-temperature operating SOFCs are illustrated in Table 2.

Table 2: Top-cited articles published in International Journal of Hydrogen Energy that concerns cathode development for intermediate and low-temperature operating SOFCs

Authors (Year)	Article Title	Citations	Ref.
Leng et al. (2008)	Development of LSCF-GDC composite cathodes for low-temperature solid oxide fuel cells with thin film GDC electrolyte	264	[48]
Jiang et al. (2014)	Chromium deposition and poisoning of cathodes of solid oxide fuel cells - A review.	225	[49]
Zhao et al. (2011)	Synthesis, characterization, and evaluation of $PrBaCo_{2-x}Fe_xO_{5+\delta}$ as cathodes for intermediate-temperature solid oxide fuel cells	81	[50]
Mat et al. (2007)	Development of cathodes for methanol and ethanol fuelled low temperature (300-600 °C) solid oxide fuel cells.	77	[51]
Ling et al. (2010)	Investigation of cobalt-free cathode material $Sm_{0.5}Sr_{0.5}Fe_{0.8}Cu_{0.2}O_{3-\delta}$ for intermediate temperature solid oxide fuel cell	70	[52]
Zhou et al. (2012)	$La_{0.6}Sr_{0.4}Fe_{0.8}Cu_{0.2}O_{3-\delta}$ perovskite oxide as cathode for IT-SOFC	70	[53]
Gu et al. (2009)	Oxygen reduction mechanism of $NdBaCo_2O_{5+\delta}$ cathode for intermediate-temperature solid oxide fuel cells under cathodic polarization	62	[54]
Kim et al. (2012)	Characterization of layered perovskite oxides $NdBa_{1-x}Sr_xCo_2O_{5+\delta}$ (x = 0 and 0.5) as cathode materials for IT-SOFC	62	[55]
Pang et al. (2010)	Structural, electrical and electrochemical characterizations of $SrNb_{0.1}Co_{0.9}O_{3-\delta}$ as a cathode of solid oxide fuel cells operating below 600 °C	60	[56]
Jun et al. (2012)	Characterization of cation-ordered perovskite oxide $LaBaCo_2O_{5+\delta}$ as cathode of intermediate-temperature solid oxide fuel cells	58	[57]

3.3 Co-occurrence network of keywords

Keywords are important indexation terms that give a quick overview of research contents and help in the organization of articles. Therefore, the mapping of keywords within a given research context can help to quickly retrieve relevant information that could help achieve various research objectives. Figure 6 presents the analysis of the co-occurrence network of author keywords in the 1101 research articles in the development of high-performance cathode for SOFCs. This was based on recommendations by Chen et al.[42] and Wuni et al [58]. On the VOSviewer software, the analysis type selected was "co-occurrence" with the "counting method" set to "fractional counting" and the "unit of analysis" selected was "Author keywords". The default number of occurrences of the keyword (i.e., five) was selected. Out of 1452 keywords detected from the 1101 articles, only 114 met the threshold which led to the generation of Figure 6. The analysis of the co-occurrence of the keywords, as well as the connection strengths between these keywords, are presented in Table 3.

Table 3: Top commonly used keywords in the research of developing cathodes for intermediate to low temperature SOFCs

Keyword	Occurrences	Total link strength
Cathode	297	285
Solid oxide fuel cell	228	210
Solid oxide fuel cells	228	215
Electrochemical performance	148	144
Oxygen reduction reaction	90	88
Composite cathode	89	89
Perovskite	71	70
SOFC	70	63
Thermal expansion	59	58
Electrical conductivity	55	55
Cathode material	41	41
Cathodes	41	41
Impedance spectroscopy	39	38
Layered perovskite	37	37
Electrochemical impedance spectroscopy	36	35
Polarization resistance	36	33
ITSOFC	31	29
Electrochemical properties	30	30
Stability	24	23
Cathode materials	23	22

The top 20 commonly used author keywords in articles focusing on the development of cathode for intermediate to low-temperature SOFCs are presented in Table 3 detailing their various occurrences and total link strengths. More so, keywords closely associated with one another are grouped in clusters as clearly illustrated in Figure 6.

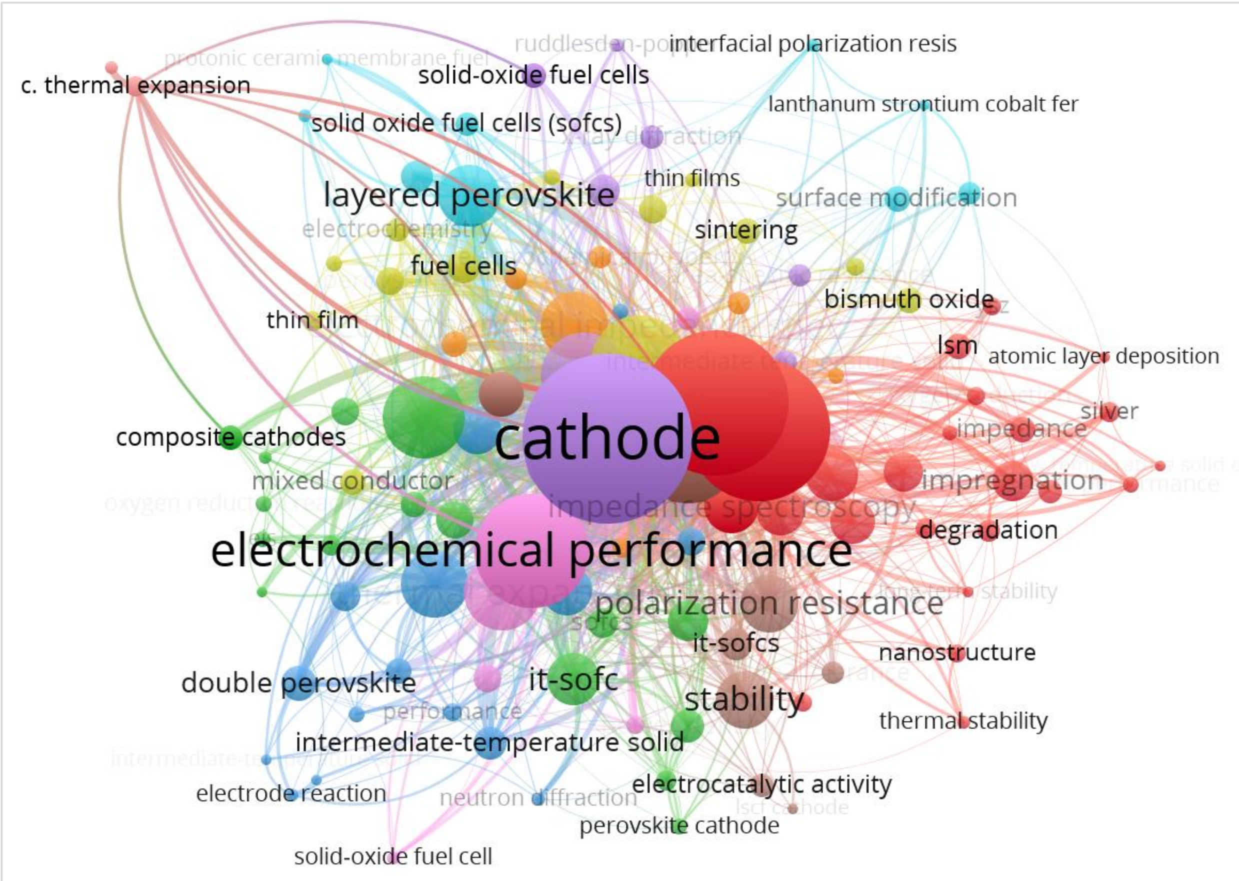

Figure 6: Co-occurrence network of author keywords for research articles in the development of cathode for intermediate to low-temperature SOFCs.

For instance, in the red cluster, the keywords: *solid oxide fuel cells, oxygen reduction, impregnation, impedance, impedance spectroscopy, atomic layer deposition, degradation, thermal stability, and nanostructure* frequently co-occurred. Furthermore, the size of each node denotes its frequency of occurrence. It is evident from Figure 6 that *cathode, electrochemical performance,* and *solid oxide fuel cell* are the keywords that co-occurred the most in all the 1101 articles analyzed. Out of the 1452 author keywords detected, the keywords presented in Table 3 indicate the top 20 high impact keywords that occurred at least 23 times and co-occurred with other related keywords at least 22 times. The knowledge of this can guide researchers who intend to venture into the development of cathode for SOFCs to narrowly tailor their choice of keywords to help in the proper indexing and easy retrieval of their research contributions in the field. This section only covers the aspect of author keywords, the analysis of all the keywords in the complete articles will be x-trayed in section 3.1 to highlight the key assessment areas researchers are interested in.

3.4 Co-authorship network analysis

The partnership between different researchers and academic institutions facilitates the diffusion of useful ideas and often leads to remarkable progress in solving pressing scientific problems. This section discusses the analysis of the network of articles with multiple authors to detect the important collaborations in studies on the development of cathodes for intermediate to low-temperature SOFCs. The metrics defined for the identification of co-authorship networks between researchers are (a) a minimum of 10 research documents, and (b) a minimum of 100 citations. Interestingly, only 110 authors out of the 2136 authors met this threshold. Figure 7 shows the co-authorship network between the most impactful authors in the research area under consideration. The link strengths and total citations of the respective authors are presented in Table 4.

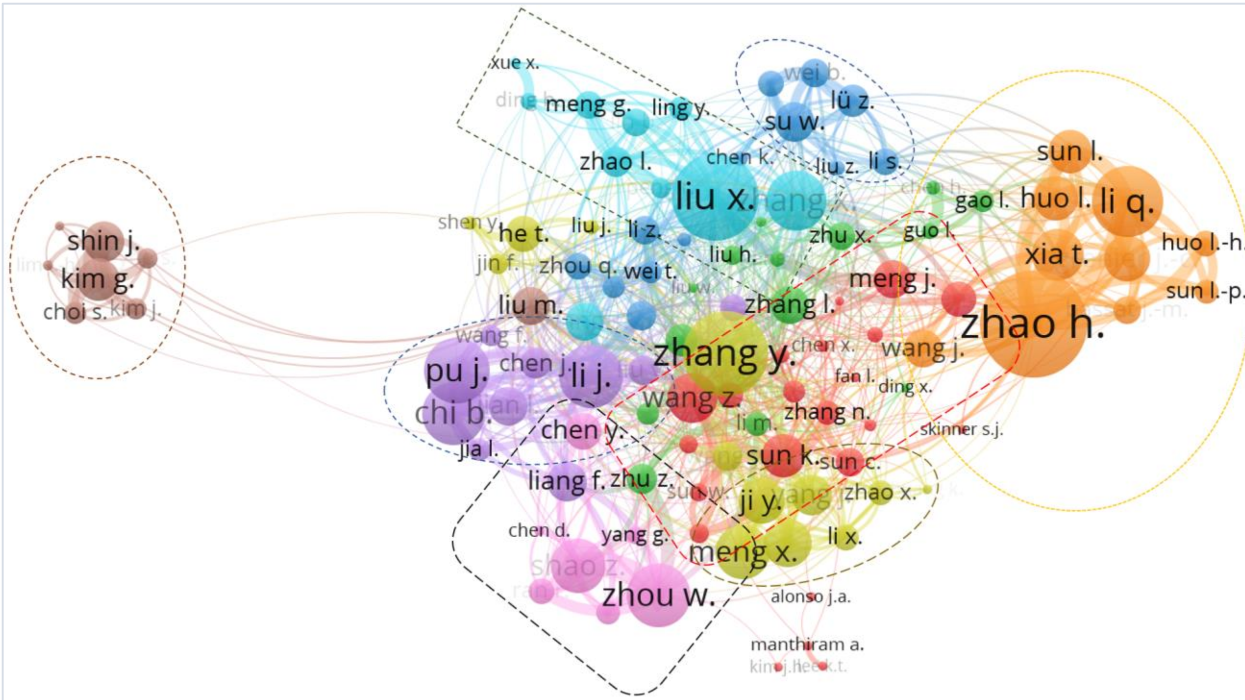

Figure 7: A network analysis of co-authorship between top researchers focused on the development of cathode for intermediate to low-temperature solid oxide fuel cells.

There are multiple clusters of collaborative researchers in the development of cathodes for intermediate to low-temperature SOFCs as illustrated in Figure 7 with each cluster represented with a different color. There appear to be multiple overlaps of different research group members with other research groups. It is almost impossible for any research group member not to have collaborated with all the groups or with another group that has a connection with every other group in this research area. The yellow cluster group appears to be the central group that has a direct collaborative link with every other group. Based on total link strength, which constitutes the total number of documents, citations, links, and normal citations, the Zhao H. group appears to be the most prominent group judging from the node size followed by the yellow cluster group headed by Zhang Y. and then other groups with a node of almost equal sizes. Table 4 further buttresses the idea nurtured in Figure 7 by providing a list of the top collaborative researchers in the field of cathode development for intermediate to low-temperature SOFCs.

Table 4: Analysis of top collaborative researchers in the development of cathodes for intermediate to low-temperature solid oxide fuel cells

Author	Documents	Citations	Av. Citations	Total link strength
Zhao h.	50	1014	20	179
Liu x.	47	1118	24	144
Zhang y.	41	805	20	142
Li q.	30	564	19	118
Pu j.	29	768	26	110
Li j.	41	671	16	107
Zhou w.	40	2184	55	106
Chi b.	28	697	25	105
Zhang x.	30	594	20	100
Shao z.	37	4756	129	91
Meng x.	25	381	15	91
Xia t.	19	347	18	87
Wang z.	33	672	20	83
Lü s.	19	291	15	81
Grenier j.-c.	17	551	32	78
Ji y.	23	620	27	77
Huo l.	16	228	14	74
Sun k.	29	581	20	72
Sun l.	16	264	17	72
Kim g.	29	1172	40	71

A quantitative summary of the co-authorship network analysis is presented in Table 4. There is variation in the chronological order of researchers when consideration is given to either the total number of articles or citations only. For instance, the top three (3) authors with the highest number of published articles in the development of cathode for intermediate to low-temperature SOFCs are Zhao h. (50), Liu X. (47), and Zhang Y. and Li J. (41) while the top three (3) authors with the most citations are Shao Z. (4756), Zhou W. (2184) and Jiang S. P. (1995). The top three (3) authors with the most collaborative link strengths are Zhao H. (179), Liu X. (144), and Zhang Y. (142).

3.5 Network analysis of article citations

One of the metrics used in assessing the quality of research articles is the number of citations. Therefore, research articles with high citations are often considered to be highly impactful even though that might not always be the case. To analyze articles in the development of cathode for intermediate to low-temperature SOFCs based on the number of citations, the least number of citations set for an article to be considered for analysis was 100 but only 61 documents out of the total 1101 articles analyzed met this criterion. Figure 8 shows the density map of the articles that met the criterion set above. This assessment is purely based on the total number of citations of each article and the links that exist between the articles.

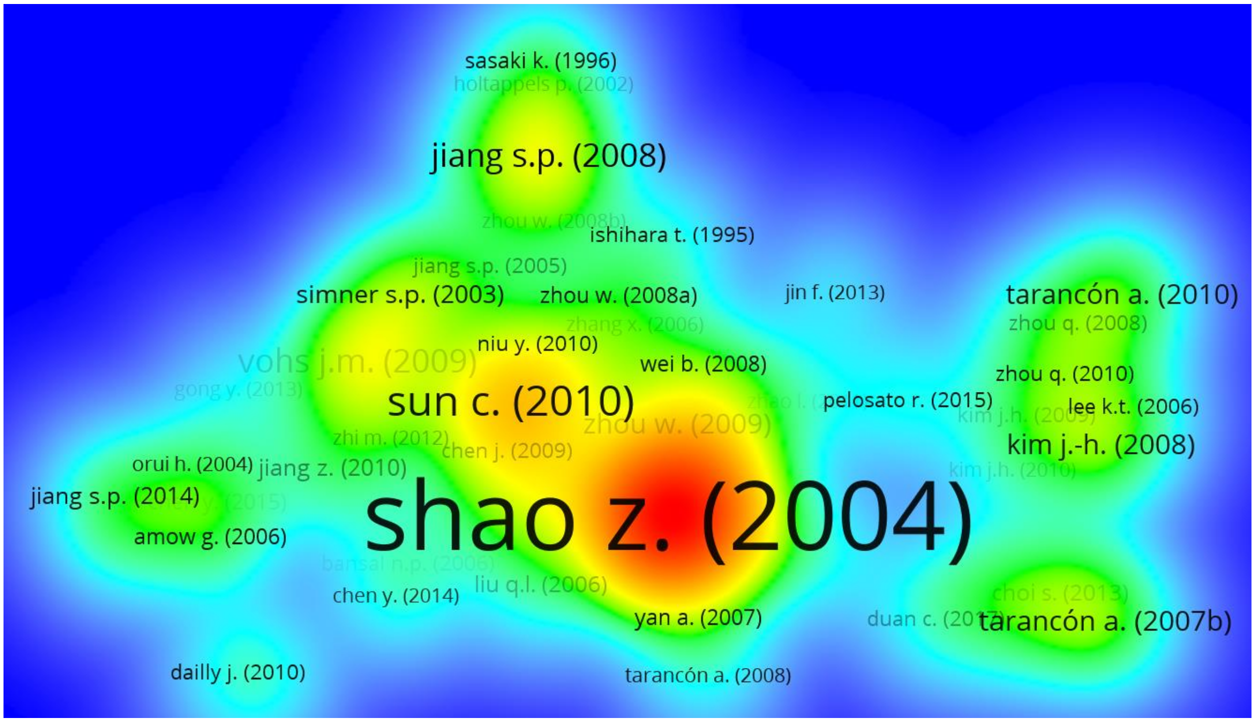

Figure 8: Density map of most-cited authors of articles in the development of cathodes for intermediate to low-temperature solid oxide fuel cells.

Table 5 presents the most impactful research articles in the development of superior cathodes for intermediate to low-temperature solid oxide fuel cells based on the number of citations. The timeline of the articles considered was from 30 years ago in the 1990s when the research in this area commenced till the early months of 2021 (i.e., March 2021) when the bibliometric data was retrieved. The top five most cited articles are Shao and Haile [46], Sun et al. [75], Dusastre [76], Vohs et al. [77], and Jiang et al. [49]. In the early years of research in the development of cathode materials for improved solid oxide fuel cells (SOFCs), Ishihara et al. [59] studied the characteristics of the perovskite-based oxide, $Ln_{0.6}Sr_{0.4}MnO_3$ (where Ln is Pr, Nd, Gd, Y, La, Sm, La and Yb) as cathode materials with respect to their operating temperatures in order to develop a higher-performance cathode with low overpotential at a significantly reduced temperature. The current interruption method was used to ascertain the overpotential and current density of the electrode. They found out that the cathodic overpotential depended on the rare-earth cation used for the Ln site in $Ln_{0.6}Sr_{0.4}MnO_3$ and these overpotentials decreased in the order Y > Yb > La > Gd > Nd > Sm > Pr. The overpotential at the cathode was asserted to be influenced by either the geometrical morphology of the powders used for the electrode or the surface area of the electrode. They also observed that the cathodic overpotential when Pr was used for the Ln site remained low even at low temperature range (about 973 K) [60]. Furthermore, they confirmed the compatibility of this oxide with the thermal expansion coefficient of YSZ. This then led to their conclusion that $Pr_{0.6}Sr_{0.4}MnO_3$ will be a promising oxide as cathode for low-temperature SOFCs. Years later, Jiang et al. [61] conducted a classic review of the development of lanthanum strontium manganese (LSM) as cathode materials for solid oxide fuel cells. The top cited article highlighted in Table 5 was authored by Shao [46]. It unveiled the popular $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$ (BSCF) cathode material which was reported to have a high cathodic performance with an excellent power density of 1.01 W cm^{-2} at 600 °C when humidified hydrogen and air are used as the fuel and cathode gas, respectively. The peak power densities at different operating temperatures as well as the area specific resistances of the electrode are illustrated in Figure 9.

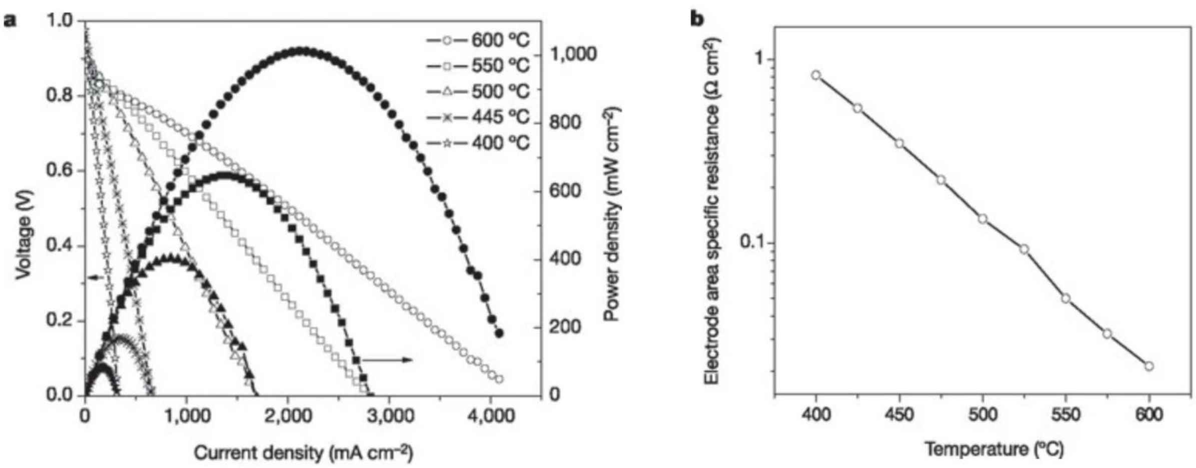

Figure 9: The performance of $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$ (∼20 μm) | $Sm_{0.15}Ce_{0.85}O_{2-\delta}$ (∼20 μm) | Ni + $Sm_{0.15}Ce_{0.85}O_{2-\delta}$ (~700 μm) fuel cell with (a) Power density and cell voltage as a function of current density (b) The area-specific resistance of the material at different temperatures [46].

Dusastre [76] investigated the performance of $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}/Ce_{0.9}Gd_{0.1}O_{2-\delta}$ composite cathodes for intermediate temperature operating SOFC. Even though LSCF has mixed ionic and electronic conductivity, the activation enthalpy for oxygen to undergo self-diffusion is 186±5 kJ mol^{-1} which is considered high. This implies that the ionic conductivity will drop rapidly with temperature. To enhance the ionic conductivity, LSCF/CGO was proposed, and the evaluation of the electrochemical performances at low temperatures showed improved performance compared to when only LSCF is used as the cathode material [76]. Some of the other top-cited articles highlighted in Table 5 are review articles such as the ones authored by Jiang et al. [61], Tarancón et al. [28], Zhou et al. [62], and Lee et al. [26]. These are interesting systematic review articles of earlier published articles in the development of cathode materials for intermediate to low temperature operating SOFCs. One of the top research articles in the development of cathode which garnered lots of citations was that authored by Kim et al [63]. In this article, cation-ordered perovskite-based oxides with the structure $LnBaCo_2O_{5+\delta}$ (where Ln =La, Nd, Sm, Gd, and Y) were investigated as potential cathode materials for intermediate temperature operating SOFCs. They observed that as the size of Ln cation decreased from La > Nd > Sm > Gd > Y, thermal expansion coefficient (TEC), oxygen content, and electrical conductivity of the perovskite oxides decreases. The decrease in the TEC across the range of constituent cation in the perovskites studied was due to reducing bond strength between Ln-O bonds, while that of electrical conductivity was because of the bending of the O-Co-O bonds from the ideal 180 degrees and increasing oxygen ion vacancy concentration from La to Gd. The study provides a holistic analysis of the effects of various parameters on the TEC, electrical conductivity, and oxygen ion concentration in the perovskite oxide structure. Another interesting research was conducted by Wang et al. [64] in which composite cathodes were used in intermediate temperature SOFC. They had better results compared to the popular LSM cathodes for high temperature operating SOFCs.

Table 5: Most cited research articles in cathode development for SOFCs.

Article	Article title	Citations	Links
Shao [46]	A high-performance cathode for the next generation of solid oxide fuel cells	2435	24
Sun et al. **[75]**	Cathode materials for solid oxide fuel cells: review	778	9
Dusastre [76]	Optimization of composite cathodes for intermediate temperature SOFC applications	680	11
Vohs et al. **[77]**	High-performance sofc cathodes prepared by infiltration	511	9
Jiang et al. [49]	Development of lanthanum strontium manganite perovskite cathode materials of solid oxide fuel cells: A review	493	9
Tarancón et al. [28]	Layered perovskites as promising cathodes for intermediate temperature solid oxide fuel cells	347	1
Zhou et al. [50]	Progress in understanding and development of Ba0.5Sr0.5Co0.8Fe0.2O3-δ-based cathodes for intermediate-temperature solid-oxide fuel cells: A review	341	16
Lee et al. [26]	Ab initio energetics of LaBO3 (001) (B=Mn, Fe, Co, and Ni) for solid oxide fuel cell cathodes	332	0
Kim et al. [52]	LnBaCo2O5+δ oxides as cathodes for intermediate-temperature solid oxide fuel cells	329	6
Tarancón et al. [78]	Advances in layered oxide cathodes for intermediate temperature solid oxide fuel cells	322	1
Simner et al. **[79]**	Optimized lanthanum ferrite-based cathodes for anode-supported SOFCs	280	5
Leng et al. [80]	Development of LSCF–GDC composite cathodes for low-temperature solid oxide fuel cells with thin-film GDC electrolyte	263	7
Wang et al. [80]	High performance lanthanum-ferrite based cathode for SOFC	260	6
Xia and Liu [81]	Novel cathodes for solid oxide fuel cells	236	6
Jiang et al. [82]	Nano-structured composite cathodes for intermediate-temperature solid oxide fuel cells via an infiltration/impregnation technique	212	13
Hibino et al. [83]	A Solid Oxide Fuel Cell Using Y-Doped BaCeO3 with Pd-Loaded FeO Anode and Ba0.5Pr0.5CoO3 Cathode at Low Temperatures	220	1
Choi et al [84]	Highly efficient and robust cathode materials for low-temperature solid oxide fuel cells: PrBa0.5Sr0.5Co2−xFexO5+δ	198	7
Fu et al. [58]	Electrochemical characteristics of LSCF-SDC composite cathode for intermediate temperature SOFC	184	1
Jiang et al. [85]	Development of (La , Sr) MnO3-Based Cathodes for Intermediate Temperature Solid Oxide Fuel Cells	179	2
Liu et al. [86]	High-performance low-temperature solid oxide fuel cell with novel BSCF cathode	178	7
Zhou et al. [87]	Barium-and strontium-enriched $(Ba_{0.5}Sr_{0.5})_{1+x}Co_{0.8}Fe_{0.2}O_{3-\delta}$ oxides as high-performance cathodes for intermediate-temperature solid-oxide fuel cells	170	7
Amow et al. [88]	A comparative study of the Ruddlesden-Popper series, $La_{n+1}NinO_{3n+1}$ (n = 1, 2 and 3), for solid-oxide fuel-cell cathode applications	170	2
Yan et al. [89]	Investigation of a Ba0.5Sr0.5Co0.8Fe0.2O3−δ based cathode IT-SOFC: I. The effect of CO2 on the cell performance	169	5
Sasaki et al. [90]	Microstructure ‐ Property Relations of Solid Oxide Fuel Cell Cathodes and Current Collectors: Cathodic Polarization and Ohmic Resistance	169	2

By carefully examining the links between the authors with most citations, it was observed that Shao [46] has been cited the most times by later studies among the topmost cited articles. The links highlighted in Table 5 constitute the cross citation between the top articles whether such articles are being cited by the top articles or the top articles cite any of the articles within the league of the topmost cited articles thereby contributing to the citation counts of the articles.

3.6 Subject area contributions in the research for cathode development in SOFCs

From the bibliometric data retrieved from the Scopus database, based on the search algorithm for articles focused on cathode development for intermediate to low temperature operating solid oxide fuel cells, there are about 13 distinct subject areas. The top contributing subject area is chemistry accounting for about 594 research documents. This is closely followed by Energy with a total number of 572 research documents and then the other subject areas which constituted the top five (5) subjects that contribute the most to cathode development in SOFCs, including Material Science (516), Engineering (410), and Physics and Astronomy (351). Figure 10 illustrates the contributions of various subject areas for cathode development for intermediate to low temperature operating SOFCs.

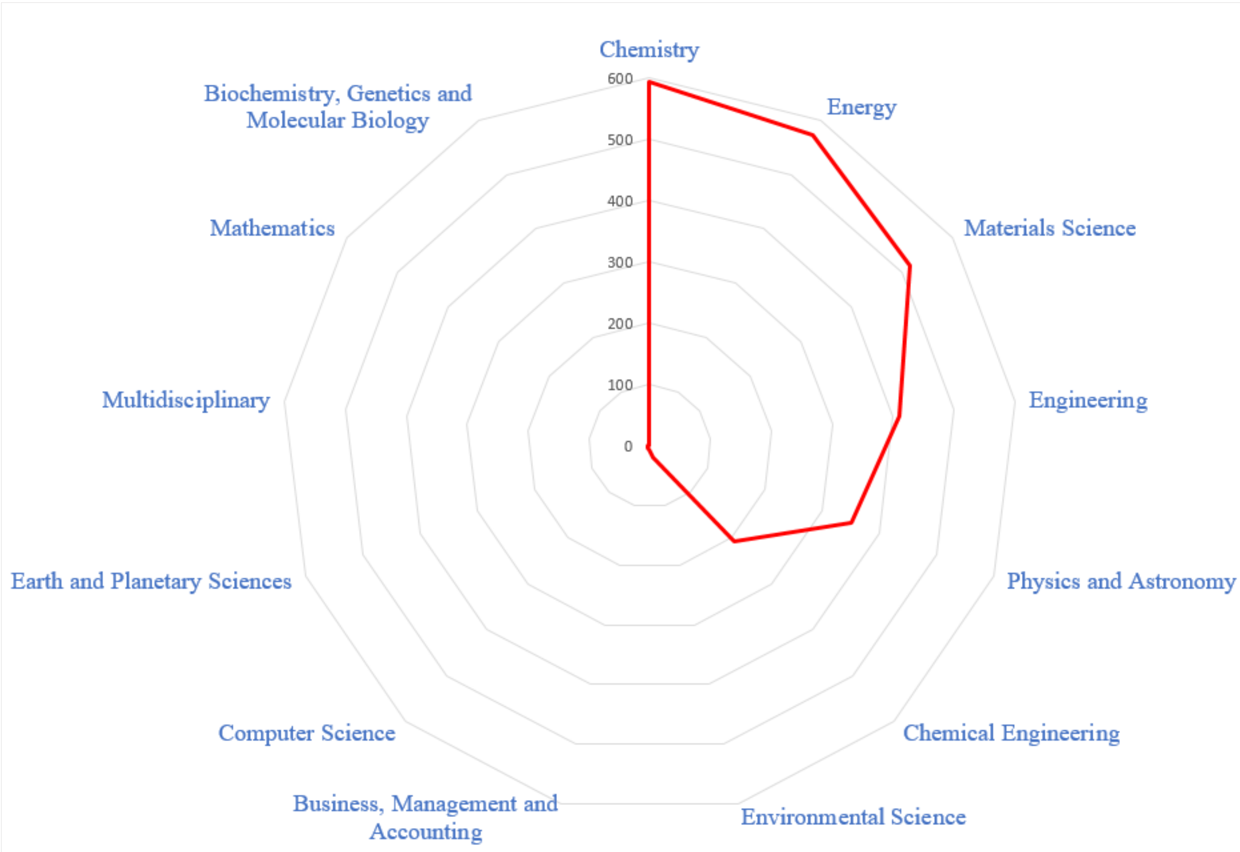

Figure 10: Contributions of various subject areas to cathode development for intermediate to low temperature operating SOFCs.

Table 6 illustrates the respective contributions of each subject area to the development of cathode for intermediate to low-temperature operating SOFCs. Sometimes, more than one discipline can be involved in cathode development since SOFC cathode development is a multidiscipline research area.

Table 6: Contribution of different subject areas to cathode development for intermediate to low-temperature operating SOFCs

SUBJECT AREA	Documents
Chemistry	594
Energy	572
Materials Science	516
Engineering	410
Physics and Astronomy	351
Chemical Engineering	207
Environmental Science	19
Business, Management and Accounting	5
Computer Science	4
Earth and Planetary Sciences	4
Multidisciplinary	4
Mathematics	3
Biochemistry, Genetics and Molecular Biology	2

3.7 Active countries in the research for cathode development in SOFCs

Based on geographical region, some countries are more active than others in promoting research that could lead to the commercialization of SOFCs, thereby solving one of the problems that threaten the survival of the present and future generations (i.e., excessive emission of GHGs into the atmosphere caused by heavy reliance and use of fossil fuels). Different reasons could make researchers in any country prioritize focusing on the development of SOFCs, but it is essential that different and more countries jointly work on this research by pulling resources together through funding and grants to promote research activities in this area. Figure 11 illustrates countries that contribute the most to the development of cathodes for intermediate to low-temperature solid oxide fuel cells. It is imperative to state that this is not motivated by any political gains but purely based on research outputs in terms of citations, collaborations, and co-citations as shown in Table 7. To generate Figure 11, the minimum number of documents and corresponding citations were set to

10 and 50, respectively. Out of the 56 countries involved in this research area, only 22 fulfilled the criteria set above. Furthermore, out of the 195 countries on earth, only 56 of them are into this research area which is equivalent to 29% and just approximately 39% of this percentage are the topmost productive countries with a minimum of 5 research articles and an overall minimum of 50 citations.

The respective sizes of the nodes in Figure 11 depict the contribution of individual countries to the development of cathodes for SOFCs. For example, China appears to dominate research in this area (based on the research output) with a very wide margin surpassing all other countries followed by the United States, South Korea, Japan, France, Australia, United Kingdom, Spain, etc. There appears to be an emergence of several divergent clusters in the network with each having a deep connection with China. The different colors represent variant clusters as clearly depicted in Figure 11.

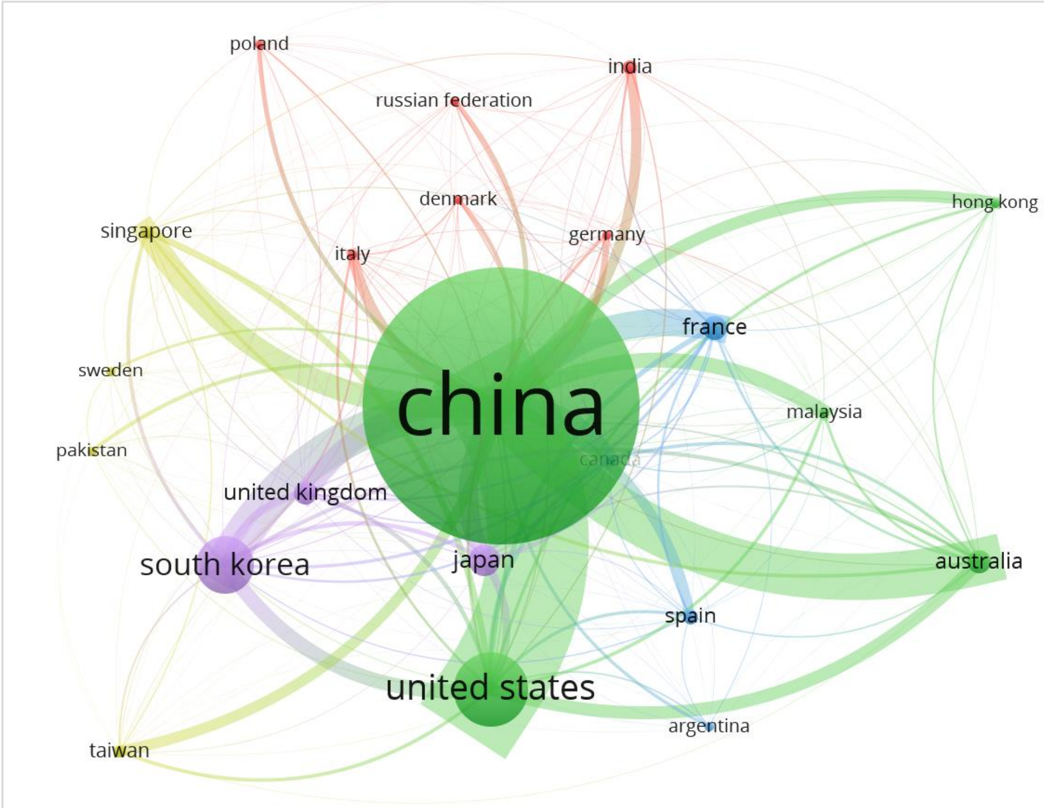

Figure 11: Countries with the most contributions towards the development of high-performance cathode for intermediate to low-temperature SOFCs.

Table 7 shows that there is variation when the ranking is solely based on research outputs or citations. For instance, in terms of research output, the top five (5) most productive countries are China (594), United States (159), South Korea (124), Japan (68), and France (53). There is a slight deviation in the ranking pattern when it is only based on citations. The ranking of the top five (5) will then be in the following order China (14489), United States (9117), South Korea (2778), United Kingdom (2671), and Singapore (2171). However, if the two metrics are combined (i.e., average citations), Singapore with an average citation of 78 tops the list followed by Canada (73) Denmark (60), United States (57), and Germany (54)

Table 7: Most active countries in the research for the development of cathodes for intermediate to low-temperature SOFCs

Country	Continent	Documents	Citations	Av. Citations	Total link strength
China	Asia	594	14489	24	5681
United States	North America	159	9117	57	2676
South Korea	Asia	124	2778	22	1290
Japan	Asia	68	2167	32	680
France	Europe	53	1397	26	806
Australia	Oceania	51	2032	40	1259
United Kingdom	Europe	50	2671	53	694
Spain	Europe	32	1530	48	366
India	Asia	31	506	16	304
Singapore	Asia	28	2171	78	682
Taiwan	Asia	26	494	19	313
Italy	Europe	20	558	28	351
Malaysia	Asia	20	277	14	423
Canada	North America	19	1386	73	547
Germany	Europe	19	1023	54	260
Argentina	South America	18	380	21	128
Denmark	Europe	17	1014	60	189
Poland	Europe	17	253	15	145
Russian Federation	Europe and Asia	16	208	13	175
Pakistan	Asia	14	126	9	124
Sweden	Europe	12	261	22	99
Hong Kong	Asia	11	460	42	342

Every continent has at least one representative country contributing to this research area. However, the least contributing continent is Africa and the continent with the most contribution is Asia followed by North America as shown in Figure 12.

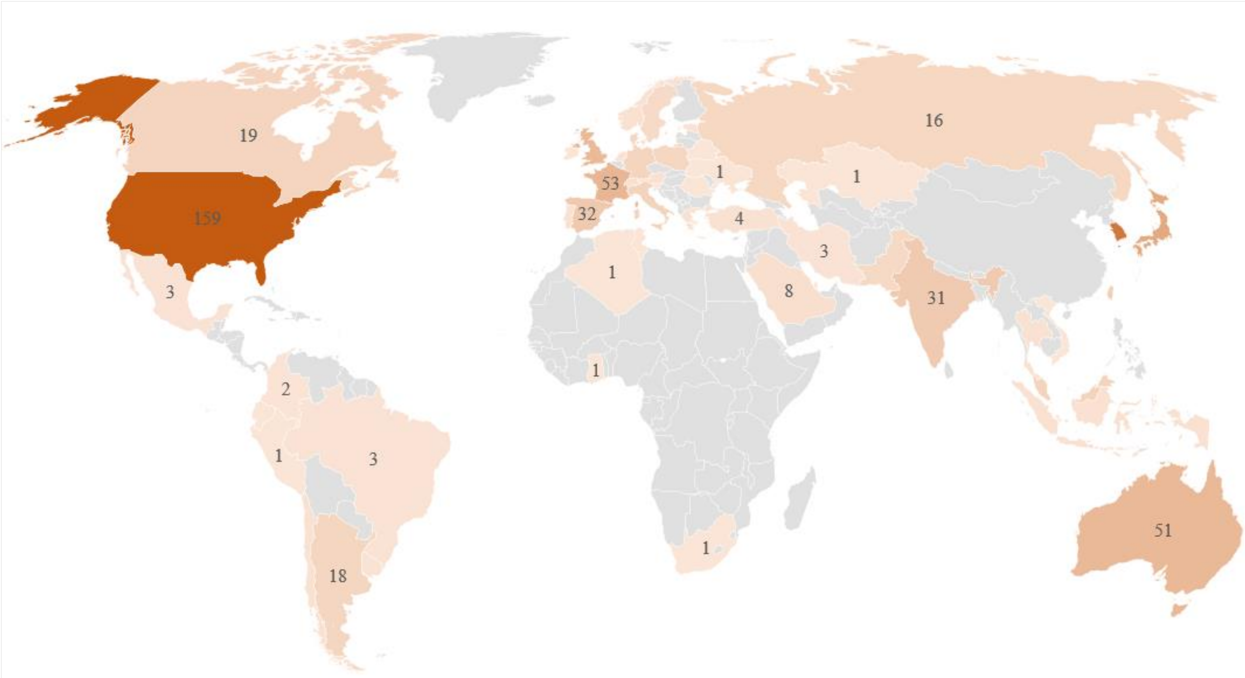

Figure 12: Geographical distribution of research contributions of countries in the development of cathodes for intermediate to low-temperature SOFCs.

3.8 Focus assessment areas on the development of cathode materials for intermediate to low-temperature SOFCs.

The cathode is one of the key components of a fuel cell. Asides from the fact that this cell component is the pathway through which oxygen is being continuously fed into the cell, it also receives electrons (i.e., through an externally connected circuit) from the anode and reduces this oxygen to produce oxygen ions that eventually migrate through the ion-conducting electrolyte to the anode for the oxidation of the fuel being fed through the anode. The cathodes are often made from relatively cheap available perovskite-based compounds[65–73].

In the early years of SOFC development, the cathodes were mainly electronic conductors which was a basic requirement that time to fulfill the requirement for exchange reactions at the electrode-electrolyte-oxidant interface commonly referred to as the triple-phase boundary (TPB) [61]. Lanthanum Sr-doped manganite (LSM) was popularly used as cathode material because of its good electronic conductivity and good activity towards oxygen reduction reaction (ORR).

Later, mixed ionic and electronic conductors (MIEC) were developed as a cathode as the electrochemical reaction region can be extended from the TPB to the entire surface of the MIEC cathode [112–121]. To shed light on this aspect, Adler [85] has extensively discussed mechanisms on how ORR takes place at the cathode and the roles material properties and microstructure play in this regard.

In the 1990s and early 2000s, lanthanum strontium manganite (LSM) was one of the highly investigated cathode electrode materials for SOFCs [61,86,87]. LSM is a good cathode material for high-temperature SOFCs but not for intermediate or low-temperature SOFCs. For a cathode material to be considered excellent for intermediate to low temperature SOFCs, it must possess high activity within the temperature ranges of 400 – 750 degrees Celsius. In this regard, it is expected that the area-specific resistance (ASR) should not exceed 0.3 Ω cm^2 to achieve the desired peak power density (PPD) of 1.0 W cm^{-2} [5]. Furthermore, the material should be able to maintain a high activity at this temperature with good durability. This implies that the ASR should be low and stable without undergoing phase transition when it encounters impurities. The cathode material should also possess sufficient electronic conductivity to a minimum of 100 S cm^{-1} to prevent the additional contribution of an ohmic drop from the electrode [82,88]. It is also essential that the material used as cathode be affordable with good reproducible performance.

To identify the parameters that are popularly reported in research articles concerning the development of cathodes for intermediate to low-temperature solid oxide fuel cells, a co-occurrence analysis was executed on VOSviewer with the bibliometric data of all the 1101 quality-related research articles from 1990 to 2021. Concerning this approach, Su and Lee [33] remarked that to study the research trends in a given research field, mapping the keywords is very essential [42]. Keywords often reflect the focus and content of a research theme. The co-occurrence network earlier generated was for the network of keywords but the present co-occurrence analyses cut across the essential terms in the article titles and abstracts as illustrated in Figure 13.

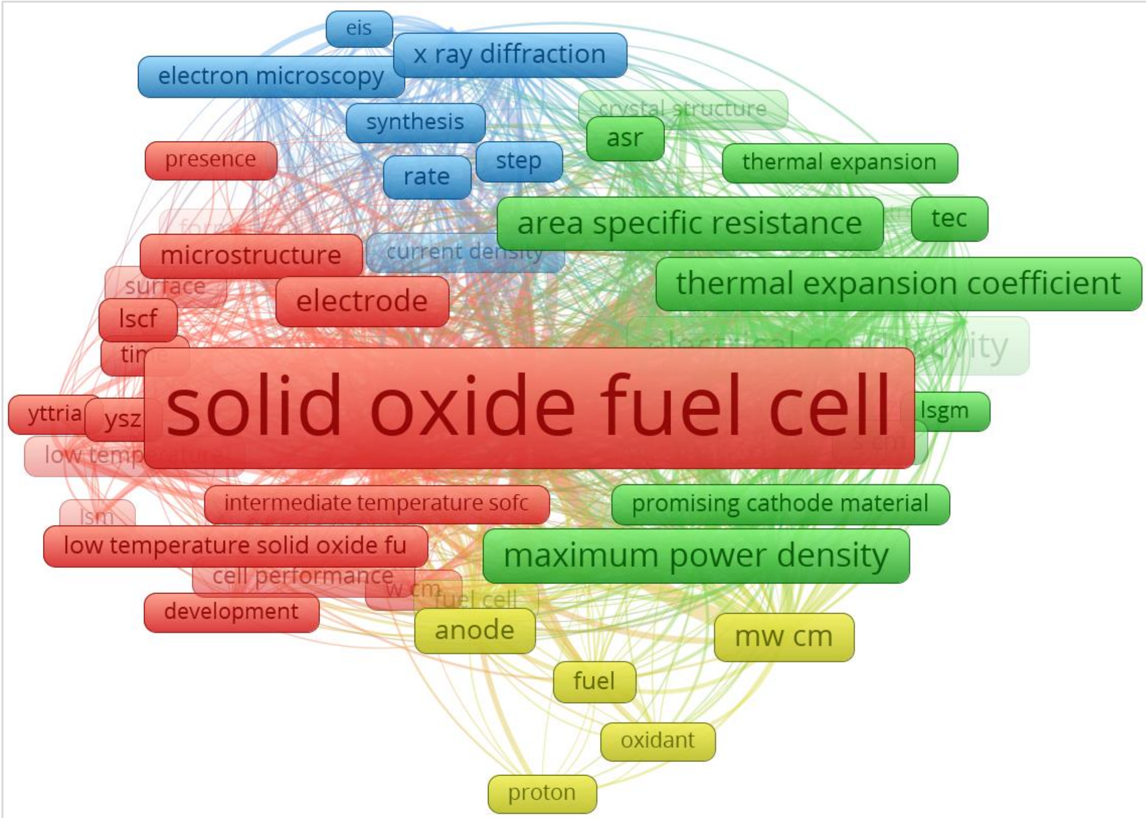

Figure 13: Clusters of cathode development focused areas in intermediate to low temperature operating solid oxide fuel cells.

To achieve this, the binary counting method was selected with the minimum number of occurrences of a term set to 40. Out of 14360 terms analyzed, 485 met this threshold. The relevance score was then computed. After this, the most relevant terms were identified and selected. This was estimated to be 68 which is equivalent to 60% of the most relevant terms (a default value set by VOSviewer). The key areas that need to be focused on in the development of cathodes for intermediate to low-temperature SOFCs based on results of the co-occurrence analysis in Figure 13 are illustrated in Figure 14. It is clear from Figure 13 that there are four (4) clusters, red, blue, yellow, and green. The red and most prominent cluster consists of terminologies that pertain to various descriptive materials and properties used in intermediate to low temperature operating

SOFC. This includes microstructure, surface, intermediate temperature, low temperature, oxygen reduction reaction, development, LSCF, LSM, YSZ, etc. The blue cluster consists majorly of various characterizations carried out on the resulting synthesized cathode materials such as x-ray diffraction, SEM, electrochemical impedance spectroscopy, and electron microscopy. The green cluster consists of the assessments of resulting fabricated cathode material which include the following: area-specific resistance, thermal expansion coefficient, maximum power density, electrical conductivity, and crystal structure. The yellow cluster consists of vital components that are needed for the proper functioning of the cell which are the anode, fuel, oxidant, and proton. It can also be deduced that the most used electrolyte for intermediate to low-temperature SOFCs is the doped ceria, especially, SDC. Furthermore, it can also be inferred that most of the experiments and analyses carried out in cathode development for SOFCs are mostly on single cells since it has a high occurrence score (199) with a relevance score of 0.7778. The table of the top recurring terms analyzed from the title, abstract, and author keywords of the 1101 articles studied are presented with the relevance score of each recurring term.

Table 8: Top recurring terms used in articles focused on the development of cathodes for intermediate to low temperature operating SOFCs.

Term	Occurrences	Relevance score
Solid oxide fuel cell	981	0.1593
SOFC	401	0.2387
Electrical conductivity	283	1.0001
Maximum power density	235	0.6486
Area specific resistance	228	0.326
Thermal expansion coefficient	224	1.4714
Oxygen reduction reaction	217	0.6721
Single cell	199	0.7778
Electrode	197	0.4841
SDC	178	0.5483
Mw cm	177	1.2334
Sample	149	0.6812
Anode	141	0.2372
ASR	135	0.2948
S cm	135	1.4278
TEC	133	1.8711
Microstructure	126	0.7817
X ray diffraction	125	0.609
XRD	122	0.7781
ORR	120	0.9817
Work	120	0.5325
Intermediate temperature	115	0.2266
Peak power density	115	0.2602
Perovskite oxide	114	0.8853
Rate	113	0.8031
LSCF	111	1.6504
YSZ	108	2.6233
Formation	105	0.757
Surface	103	1.3616
Chemical compatibility	101	0.9437

The important terminologies in the red clusters are often assessed qualitatively while those key terminologies in the blue and green clusters are assessed quantitatively based on measurements taken from the cathode material before and during testing.

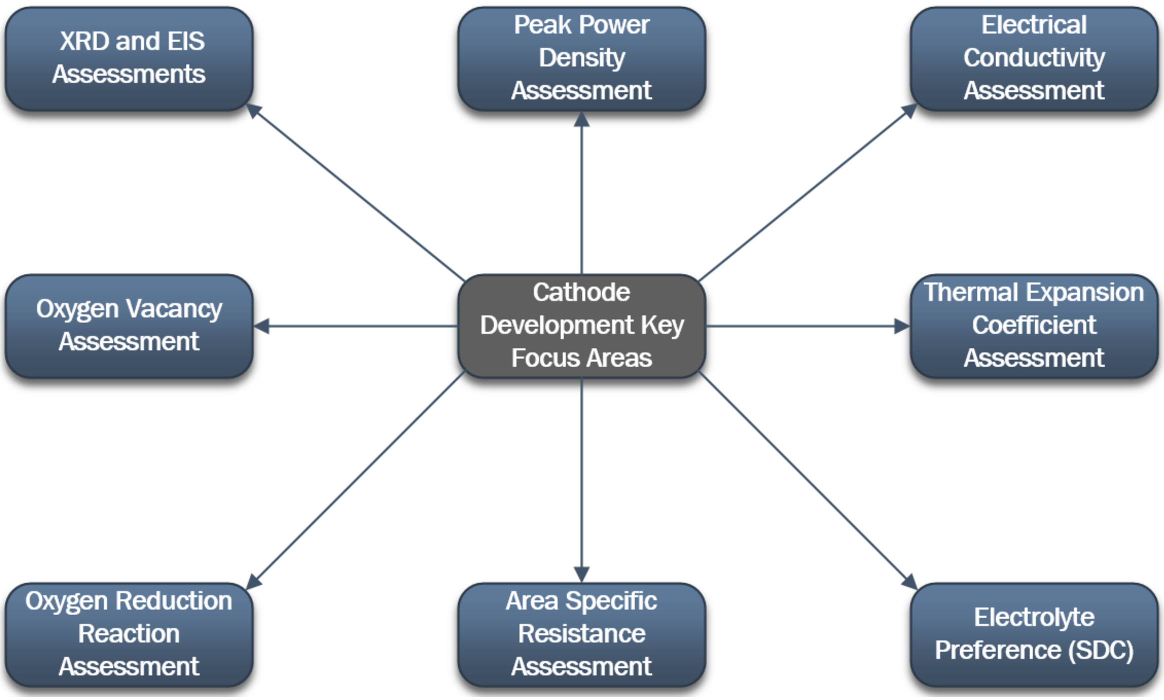

Figure 14: Framework of key focus areas for cathode development in intermediate to low-temperature SOFCs.

Cathode materials that have been subjected to developmental procedures to improve their performance, activity, stability, morphology, and durability are often being assessed or tested based on the webbed list in Figure 14. Each of those assessments was found to be commonly reported in most of the articles under the area of cathode development for intermediate to low temperature operating SOFCs. Table 9 shows the various quantitative assessments of the latest 20 publications in the development of cathode materials for intermediate to low-temperature SOFCs.

Table 9: Assessment of various latest cathode material developments for intermediate to low-temperature SOFCs (where σ = electrical conductivity, PPD = peak power density, ASR = area-specific resistance, TEC = thermal expansion coefficient)

Cathode material	**σ** ($\mathbf{S\ cm^{-1}}$)	**PPD** ($\mathbf{W\ cm^{2}}$)	**ASR** ($\mathbf{\Omega\ cm^{-1}}$)	**TEC** ($\mathbf{10^{-6}\ K^{-1}}$)	**Temp** (℃)	**Ref.**
$BaCo_{0.8}Nb_{0.1}Sc_{0.1}O_{3-\delta}$		0.481	0.0373	18.67	650	[89]
$Ba_{0.5}Sr_{0.5}Co_{0.7}Fe_{0.28}Pr_{0.02}O_{3-\delta}$		1.083	0.026	16.4	700	[90]
$La_{1.8}Sr_{0.2}CoFeO_{5+\delta}$	37		0.42	19.4	700	[91]
$Nd_{1.9}Ce_{0.1}CuO_4$	52.7	0.283	0.66	11.79	700	[92]
$PrBa_{0.5}Sr_{0.5}Co_{1.5}Fe_{0.5}O_{5+\delta}$	420	0.59	0.067		800	[93]
$Bi_{0.5}Sr_{0.5}Fe_{0.95}P_{0.05}O_{3-\delta}$		0.56	0.18	13.5	700	[94]
$LaBaCo_2O_{5+\delta}$			0.046	27	700	[95]
$Pr_{0.94}Ba_{0.7}Ca_{0.3}Co_2O_{5+\delta}$	832	1.202	0.022		700	[96]
$LaNi_{0.4}Co_{0.6}O_{3-\delta}$	1200	0.45			650	[97]
$La_{1.2}Sr_{0.8}CoO_{4\pm\delta}$		0.630	0.062	15	800	[98]
$LaCoO_3$		0.812	0.34		800	[99]
$SrCo_{0.95}Ir_{0.05}O_{3-\delta}$	30	0.6		16.36	800	[77]
$SmBa_{0.1}Ca_{0.9}Co_2O_{5+\delta}$			0.07		700	[100]
$Ba_2YCu_3O_{6+\delta}$	>74	0.175	0.29		650	[101]
$Sm_{0.5}Sr_{0.5}CoO_{3-\delta}$			0.035		650	[102]
$Sr_{0.9}Y_{0.1}CoO_{3-\delta}$		0.3533	0.044	19	700	[103]
$YBa_{0.5}Sr_{0.5}Co_{1.4}Cu_{0.6}O_{5+\delta} - Sm_{0.2}Ce_{0.8}O_{1.9}$		0.432	0.034	11.2	800	[104]
$La_{0.7}Sr_{0.3}Ti_{0.1}Fe_{0.6}Ni_{0.3}O_{3-\delta}$	318	0.402	0.047		800	[105]
$Bi_{0.5}Sr_{0.5}Fe_{0.9}Sn_{0.1}O_{3-\delta}$		0.960	0.09	12.9	700	[106]
$BaCe_{0.1}Zr_{0.2}Fe_{0.6}O_{3-\delta}$		0.24	0.21		700	[107]

3.9 Knowledge gaps and future research consideration

Based on the various high-impact articles and researchers in the field of cathode development for intermediate to low-temperature SOFCs, it is recommended that the operating temperatures should be maintained within the range of 400 – 650 ^{o}C [82,108]. The cathodic polarization resistance of the cells should be within the acceptable limits at this temperature range. Since the choice of the cathode material depends on the electrolyte selected, care must be exercised in selecting an appropriate electrolyte material that will be compatible with electrodes in terms of its thermal expansion coefficient, ohmic polarization, and chemical stability. The cost of the cathode material should also be affordable to ease the commercialization process. From the scientometric analysis in this study, it can be deduced that the material mostly used as electrolyte material is the doped ceria (i.e., either Samarium or Gadolinium). For the past 30 years, enormous effort has been exerted by researchers to achieve an efficiently mixed conductivity in cathode electrodes to extend electrode activity from the TPB to the entire electrode surfaces. It is believed that this effort will facilitate the ORR substantially.

One of the most explored cathode materials due to its MIEC is LSCF. From the co-occurrence network of keywords before fine-tuning it to the present level reported, we noticed that LSCF came up in many instances. This confirms a level of greenlighting the material has given researchers to explore various configurations of the material. Several articles also show the potential of cobalt-based perovskites as promising electrodes to achieve an excellent electrode activity due to the level of oxygen vacancy concentration it could create. Hence, more research is recommended in this area to explore various doping techniques to achieve this feat. Since better ORR requires an improvement in the amount of oxygen vacancy concentration and oxygen mobility, various electrode developmental strategies should be employed. Some of those strategies as highlighted by Yang et al. [5] include: reducing the bond energy between cation and oxygen, increasing the cell volume, and creating a deficiency in the stoichiometry of the A-cation which can all be achieved by prolific combination and selection of the A and B-site cations as well as the dopants.

Efforts should also be intensified in the development of cathodes for protonic SOFCs because they have better chances of functioning more efficiently at intermediate to low temperatures due to the good proton conductivity of typical protonic electrolyte materials. However, one of the key challenges identified with protonic SOFCs is the lower power output compared to anion conducting SOFCs. Although there have been significant efforts by researchers to improve the cathode for proton-conducting ceramic fuel cells (PCFC), also known as proton-conducting solid oxide fuel cells as reported in some recent classic articles [4,5,109–123], more strategic and collaborative efforts need to be exercised to develop cathodes with efficient triple conductivity (i.e proton, electron, and oxygen ion conduction capacity). Another major challenge identified with protonic SOFCs is the formation of water at the cathode which is not good for the cell. Cathode materials should therefore be developed to effectively manage the possible flooding tendency at the cathode.

4. Conclusion

The race to achieve an efficient, clean, and cheaper alternative energy source has motivated researchers to research the development of solid oxide fuel cells. One of the problematic areas that are under study is the cathode. A potential solution to this problem is to design a working and efficient cathode for both oxygen ion and proton-conducting SOFCs. To study the research trend and progress in this area, we have conducted a scientometric review of all quality research articles in the development of cathodes for intermediate to low-temperature SOFCs for the past 30 years. We retrieved bibliometric data of 1101 research articles published in the top journal outlets. The analysis shows that the first noticeable increase in this research area was in the year 2000 even though the first recorded research article from the database was in 1990. After this, researchers began trooping into this research area which caused a significant rise in the research outputs. This was followed by a sinusoidal trend after exactly a decade but in general, there was continuous progress in the research.

Furthermore, the analysis showed that the top 5 (five) research outlets that are most cited and highly influential in the development of cathode for intermediate to low-temperature SOFCs are *Journal of Power Sources (8870), International Journal of Hydrogen Energy (3775); Journal of the Electrochemical Society (2566); Solid State Ionics (2419) and Electrochimica Acta (1487)*. The research output from these outlets ranges between 53 and 229. Based on the co-occurrence frequency and total link strength, we found that "cathode", "solid oxide fuel cell", "solid oxide fuel cells", "electrochemical performance", "oxygen reduction reaction", "composite cathode", "perovskite", and "SOFC" were the top 10 (ten) author most used keywords.

Geographical analysis showed that just a few countries are 56 (29%) of the 195 countries on planet earth are into the area of cathode development for SOFCs. This shows that the regional coverage of research in this area is low. In terms of research output, the top five (5) most productive countries are China (594), United States (159), South Korea (124), Japan (68), and France (53). The ranking of the top five (5) countries when it comes to the number of citations are China (14489), United States (9117), South Korea (2778), United Kingdom (2671), and Singapore (2171). However, if the two metrics are combined (i.e., average citations), Singapore with an average citation of 78 tops the list followed by Canada (73) Denmark (60), United States (57), and Germany (54).

Based on the co-occurrence mapping of keywords from the article titles and abstracts, we generated a list of quantitative assessment criteria often used to report the outcome of most cathodic developmental processes and we identified them to be electrochemical conductivity, area-specific resistance, thermal expansion coefficient, operation temperature, and peak power density. We illustrated this by reporting the research outcomes of the latest 20 research articles in the field. We also identified areas least studied, cathode and electrolyte materials mostly used for intermediate to low temperature operating solid oxide fuel cells.

Therefore, this study presents a general overview of the background and progress in cathode development for intermediate to low-temperature solid oxide fuel cells. This can be useful to enthusiasts in this research area such as graduate students, government, industry, energy policymakers, and funding bodies. The research challenges and less investigated areas highlighted in this study can be further explored and attended to by researchers. Notwithstanding, it is imperative to mention that the results from this study were discussed under certain limiting conditions. At first, the manual reading of all the 1101 retrieved articles was not feasible and so certain important pointers might have been missed during the discussions. However, a stupendous effort was exerted to ensure proper coverage of important articles, especially those with the most citations. Lastly, the captured data spans between 1990 and 2021.

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