Energy Reports 7 (2021) 4126–4138

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Mapping the field of microbial fuel cell: A quantitative literature review (1970–2020)

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ARTICLE INFO

Article history:
Received 26 March 2021
Received in revised form 21 June 2021
Accepted 25 June 2021
Available online 10 July 2021

Keywords:
Microbial fuel cell
Research trend
Global attention
Research topics
Bibliometric analysis
Quantitative review

ABSTRACT

Microbial fuel cell (MFC) has received much attention in the last decade as a promising technology to simultaneously generate electricity and decontaminate wastewater. This study aims to quantitatively review the published literature on MFC, published in the period of 1970–2020, based on the Web of Science (WoS) database. For the first time in literature, a comprehensive quantitative review of MFC has been conducted by employing the technique of bibliometric and content analyses. A total of 11,397 publications have been retrieved from WoS, out of which 81.6% are research articles. The evaluation in the field of MFC has been mapped in various categories, such as publication history, publication distribution, subject category distribution, leading journals, leading countries and leading organizations in MFC research. Additionally, content analysis has been conducted to unearth the research trends in MFC; and some hot research topics in MFC have been spotted. Results depict that the period 2011–2020 has been the most appreciating era for MFC research, as it contributed 87% of the total publications. Among the subject categories, energy fuel and microbiology lead with contributions of 26.5% for each, but the overall growth of the energy fuel category in the last decade has been the highest. Out of 1,147 journals publishing MFC research, *Bioresource Technology* is the leading one; and countries like China, USA and India are the main hub of MFC research with 26.47%, 16.95% and 7.69% contributions in publications, respectively. The hottest topics in MFC research are nanoparticles, catalysts, air electrodes, graphene electrodes, power enhancement, air cathode and nitrogen removal. Moreover, major research areas are engineering, energy fuels and biotechnology with each contribution 26.5% of the total publications.

1. Introduction

The growing population of the world and an ever-increasing quest for industrialization have made global water access and energy demand the preferential topics of discussion (Stern et al., 2016; Kober et al., 2020). The population is increasing at an enormously high rate and is anticipated to increase by 21% by 2040 (Kober et al., 2020). In order to meet this growing energy demand, fossil fuels are a major contributor that dominates about 80%–85% of the global energy production market (Liu, 2015). According to recent research, our planet has entered a new era called the Anthropocene era (Stern et al., 2016; Crutzen, 2006; Lewis and Maslin, 2015; Ruddiman, 2013; Keys et al., 2019; Wagner, 2020). Anthropocene refers to changes in the earth's environment, ecosystem and lifecycle due to the anthropogenic activities of humans. Several anthropogenic activities are responsible for Anthropocene, but according to many studies fossil fuel burning and accompanied release of CO_2 are the main contributors (Stern et al., 2016; Ruddiman, 2013; Council, 2011; Change, 2013). Therefore, to ensure a sustainable future, clean and green energy sources are required.

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https://doi.org/10.1016/j.egyr.2021.06.082

Another eminent issue faced globally is water scarcity. With increasing population, global water demand is increasing but resources are depleting at a higher pace. In the next decade, freshwater availability may decrease by 40% (Gupta et al., 2020). In this regard, waste treatment has obtained much attention. But existing waste treatment technologies require a lot of energy and also lack the work–energy ratio for effluents discharge (Gupta et al., 2020; Siddiqi et al., 2018). Since organic waste serves as a viable source of energy (Zaidi et al., 2018; Siddiqi et al., 2019; Mushtaq et al., 2016; Siddiqi et al., 2020), wastewater (that contains organic wastes) can be seen as a renewable source of energy that has minimal detrimental impacts on the environment (Gupta et al., 2020; Cai et al., 2019). In this regard, microbial fuel cell (MFC) has emerged as a promising technology. In nutshell, MFC can be touted as a single solution catering to two eminent global issues, renewable energy production and fulfillment of water demand.

Microbial fuel cell is a bio-electrochemical cell that generates electricity by imitating natural bacterial interactions. In other contexts, it can be referred as a fuel cell in which catalytic reactions of microorganisms assist to convert the chemical energy of the substrate to electrical energy. The name "bio-electrochemical" owes to the involvement of microorganisms, usually bacteria, and their chemical reaction(s) (Kim et al., 2007; Rahimnejad et al., 2015).

The phenomena involved in MFC dates back billions of years as microorganisms present in nature were degrading organics. During the study of this natural phenomenon of microbial degradation, Prof. Potter of Durham University-UK explored for the first time that microbes can produce voltage. He was striving to discover the agents that contribute to the oxidation of insoluble substances (for example, charcoal) in soil, and revealed the phenomenon of bioelectricity during the same study in 1908 (Potter, 1908). Foregoing in view, in the year of 1911, by utilizing the electrical potential of microbes (*Saccharomyces*), the first microbial cell was discovered by him (Potter, 1911).

For the next two decades, the idea of MFC was under a shade, until in 1931, when a researcher from Cambridge University, Prof. Cohen, introduced an MFC that produced 35 V. Cohen connected several MFCs to obtain this voltage. It was the first experiment to generate a substantial amount of voltage by adopting the method of stacked MFCs (Singh and Songera, 2012a; Cohen, 1931). In 1963, a new path in the development of MFC was introduced. DelDuca et al. (1963) for the first time introduced *Clostridium Butyricum* in the anode chamber for hydrogen generation. This method was not much successful due to the instability of the production, but it opened a path for forthcoming research works. One year later, this instability issue was resolved by the research group of Prof. Suzuki, and the first MFC for hydrogen production was introduced (Karube et al., 1976).

Later on, the quest of Prof. Allen (Mercer, 2015) to ensure low-cost energy for third-world countries brought many design amendments of MFC to light. The optimization of the electron transport mechanism enabled others to propose optimized MFCs. It was soon realized that the main issue associated with the cost of MFC was mediator cost that created a hurdle in its commercialization. In 1999, Kim and his co-workers resolved the issue by introducing the first mediator-less MFC (Kim et al., 1999). Afterward, a major milestone was created by researchers from the University of Queensland-Australia. A joint project between these researchers and Foster Brewing has led them to convert brewery waste to $CO_2$by constructing a MFC prototype (Staff, 2020). Since then, MFC became a hot topic among researchers, and it is witnessed revolutionization each subsequent year. This fact is evident from the development of MFCs in various forms, such as microbial desalination cell, microbial wetland cell, microbial waste treatment cell and microbial metal extraction cell (Huang et al., 2019). Moreover, certain products of MFC, such as extracted metals, have found multiple applications, like in capacitors and MOSFETs (Metal oxide semiconductor field effect transistor) (Wahab et al., 2020a,b; Abdul Wahab et al., 2020).

It has been realized that the published literature contains very few quantitative studies that dealt with the mapping of the MFC evolution. The most recent study was done by Ji et al. (2020), and it was the first study that quantitatively measured the aspect of constructed wetland MFC. This study involved conduction of a bibliometric analysis on the constructed wetland MFC, using the Web of Science (WoS) database for the years of 2008–2020. Another recent study has been performed by Zhao et al. (2020). In this study, content analysis and bibliometric techniques have been applied to quantitatively map microbial electrolysis cells for hydrogen production, using the WoS database, covering the period of 2008–2020. The first comprehensive quantitative analysis of MFC was done by Khudzari et al. (2018), whereby the Scopus database was used to conduct bibliometric analysis, covering the period of 1962–2018. As per the knowledge of the authors, until date, there is no comprehensive quantitative literature review published that uses the WoS database to map the MFC field from 1970–2020. Hence, conduction of the first content analysis of the complete MFC literature (indexed in WoS), published in the last 50 years, is a notable novelty of this review paper. The main objectives of this study are as follows:

- To map the history of MFC research, so that emergence of various research tracks can be unearthed.
- To provide a stepping stone for novices to understand and choose a significant and fast-growing area within the MFC research field.
- To provide the current focus of MFC research and map the future research directions.

2. Research methodology

WoS is a potential journal indexing database (Thelwall, 2018). The core collection of WoS is a hub of 21,100 high-quality and peer-reviewed journals that are further distributed into 250 fields, and are accessed widely. It provides access to more than 53 million publications and 1.18 billion cited references. Therefore, this database was exploited to search the relevant literature on MFCs (Clarivate, 2021).

A total of 11,397 publications were extracted from WoS that are relevant to the MFC field, out of which the major portion comprised of journal articles (81.6%) followed by review articles (11.35%). Further study on these articles have been focused on the publication history, publication distribution, subject category distribution, leading journals, leading countries, leading organizations, leading authors and research trends.

2.1. Bibliometric analysis

Bibliometric analysis is a quantitative technique to review the literature of any particular field. This technique is an effective method to statistically evaluate the most prolific published literature and map out the evolution of the field as a function of time (Hui et al., 2020; Iftikhar et al., 2019). Therefore, this study employs a bibliometric analysis technique to map the recent developments of MFC. Similar studies of different topics, including marine water environment monitoring (Di Ciaccio and Troisi, 2021), solar cells (Yeo and Jeong, 2020), CO_2 capture (Omoregbe et al., 2020), energy security (Zhou et al., 2018), wind energy (Madvar et al., 2019), 3D printing (Muhammad et al., 2021) and many others (Losse and Geissdoerfer, 2021; Miot et al., 2020; Zeng et al., 2021) are present in the literature.

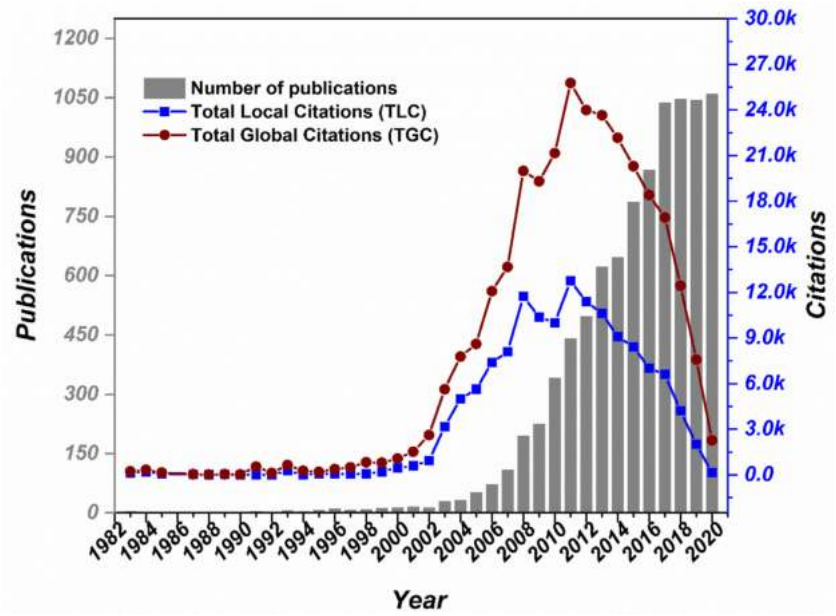

Fig. 1. Number of publications and citations in MFCs.

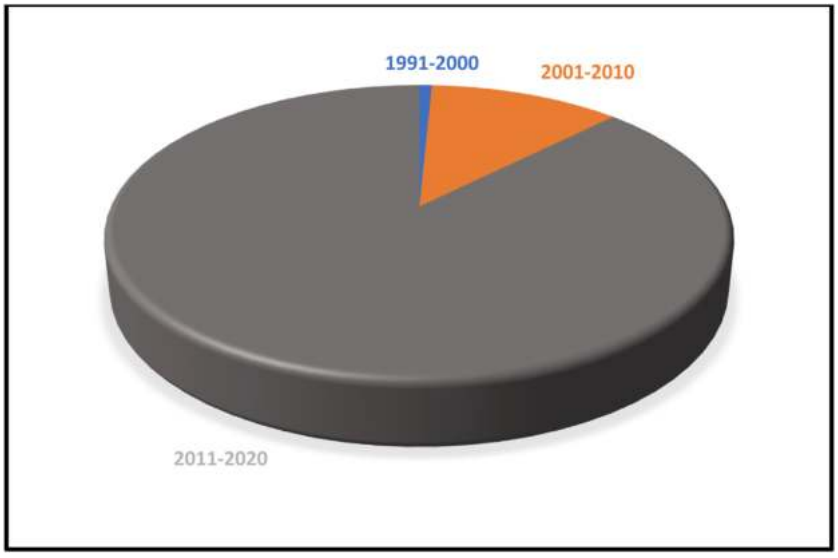

Fig. 2. Publication distribution over the decades.

2.2. Content analysis

Content analysis is a technique to map out certain keywords or concepts in a particular literature domain, in a quantitative manner. It allows researchers to study the emergence of different keywords and their correlation as a function of time. This technique is employed in this study to map the most frequent keywords involved in MFC-based publications. Additionally, future directions of MFC research have also been highlighted based on content analysis.

3. Results and discussion

3.1. Publication history of MFC

The MFC has been a topic of keen interest within the research community. The very first publication on the topic of MFC was reported in 1983; however, for almost a decade since then, MFC failed to get much attention. Starting in 2003, the number of publications and citations related to this field got boosted, and it kept on increasing each passing year. The year 2020 showed the highest number of publications in this field, i.e., 1074; while, the highest number of total local citations (TLCs) and total global citations (TGCs) were detected in 2011 (Fig. 1). The three decades involving publications on MFCs (i.e., 1990s, 2000s and 2010s) contributed 1%, 12% and 87%, respectively, of the total publications (see Fig. 2).

3.2. Publications distribution

Out of the 11,397 publications available in WoS, the research articles count was found to be 9,236, followed by review articles, with a count of 1,267. Fig. 3 depicts the contribution of various document types published in literature on MFCs. The contribution share of research articles, reviews, proceeding papers, book chapters, meeting abstracts, early access, editorials, corrections

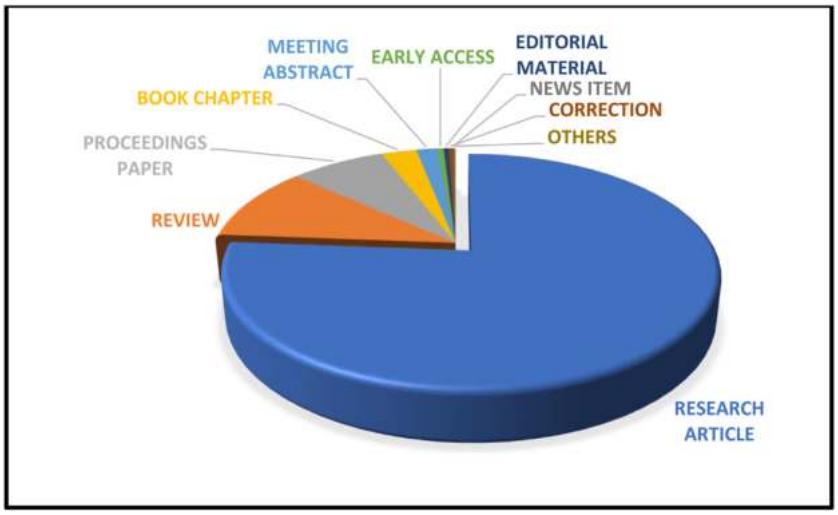

Fig. 3. Publication distribution in MFCs.

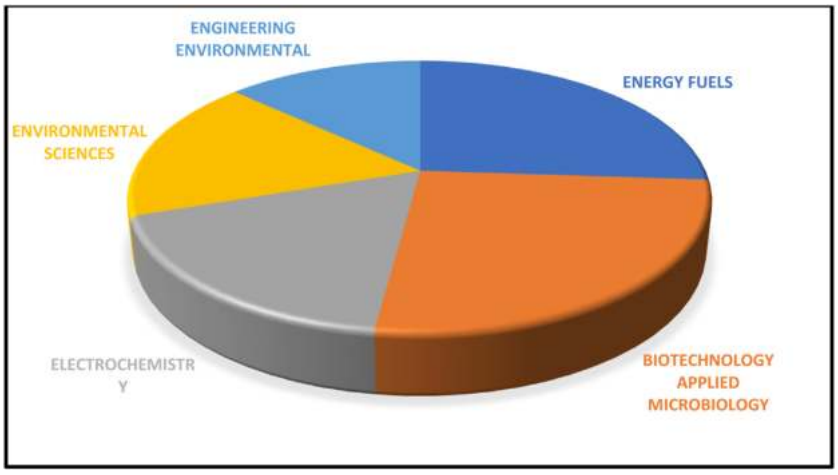

Fig. 4. Top five subject categories in MFC research.

and others is 81.6%, 11.135%, 8%, 2.9%, 1.75%, 0.57%, 0.41%, 0.28% and 0.3%, respectively. The "others" include news items, letters, retracted publications, books, biographies, notes and retractions, with 0.16%, 0.053%, 0.035%, 0.018%, 0.009%, 0.009% and 0.009% contribution, respectively.

3.3. Subject category distribution

The literature on MFCs, available in WoS, can be classified into 145 subject categories. The top 5 subject categories are energy fuels, biotechnology and applied microbiology, electrochemistry, environmental sciences, and engineering environmental with 26.5%, 26.5%, 17.9%, 17.5%, and 13.3% contributions, respectively, see Fig. 4.

Energy fuels category deals with the production, utilization and management of combustible nonrenewable fuels and all renewable energy sources. This category does not include the studies related to the nuclear science. Biotechnology and applied microbiology spans over the multitude of topics related to living organisms and their applications to solve human problems. Other than biology-specific topics (genetic engineering, therapeutic techniques, etc.), this category also covers the section of bio energy, where MFC overlaps. Electrochemistry deals with the chemical changes caused by electricity. Since the basic phenomenon in MFC is to create electricity, it got much attention from electrochemists to spot related chemical changes. Environmental sciences category deals with the study of environment health, toxicology, monitoring and management. Lastly, Engineering Environmental covers the studies related to anthropogenic impacts on environment and their remedies. It also covers incineration, sludge management and policy development. As MFC has emerged as a green resource of energy that do not have substantial anthropogenic impacts on the environment, it became a hot topic for researchers involved in environment related fields.

The energy fuel category got tremendous attention after 2011, as it contributed 92.52% of the publications from the year 2011 to 2020. Meanwhile, biotechnology has witnessed an almost steady growth since 2010, with 5%–9% contribution per year. For electrochemistry, 2017–2019 was the most popular era, resulting in 37.2% contribution. The "others" field, such as Environmental science and engineering environmental showed a high number of publications in 2017–2019. Fig. 5 depicts a detailed evolution of different subject categories over the last two decades.

3.4. Leading journals publishing MFC research

Another technique used for quantitative literature review on MFCs was to carry out analysis of journals. Different journals were investigated by setting a filter of a minimum of 80 publications and 100 citations. The results depict that 22 out of a total of

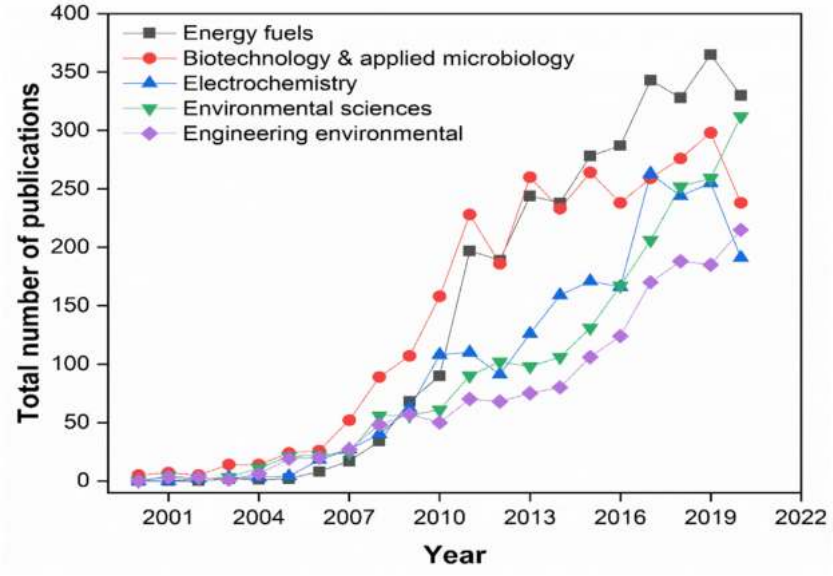

Fig. 5. Evolution of MFC subject categories.

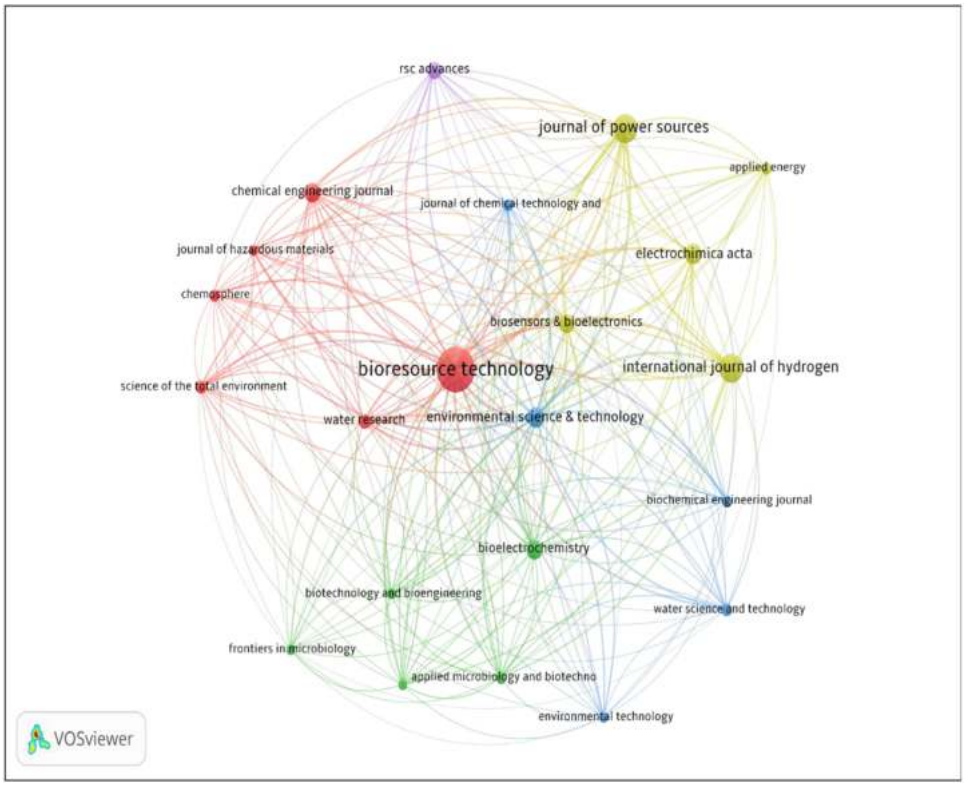

Fig. 6. Leading journals in MFC research.

1147 journals met the threshold criterion, as depicted in Fig. 6. *Bioresource Technology* was observed to have the highest impact, followed by the *Journal of Power Sources* and *International Journal of Hydrogen Energy*.

Table 1 presents "individual documents published" and "citations received" by the top 15 journals that account for 85.44% of the documents published and 85.58% of the citations received so far in the field of MFCs.

3.5. Leading countries involved in MFC research

The country-based analysis was performed for this quantitative literature review, using the web of science; and it was found that 98 countries are working on MFC-based technologies. A minimum benchmark of 30 document publications and 100 citations was set for filtering the leading contributors. This resulted in 45 countries meeting the threshold conditions, see Fig. 7. In Fig. 7, the size of the circle shows the contribution of a country, while the connecting lines show the collaboration between two countries.

Table 1
Top 15 journals in MFC research.

Source	Documents	Citations	Documents contribution	Citation contribution
Bioresource Technology	834	32346	20.27%	18.71%
Journal of Power Sources	406	16353	9.87%	9.46%
International Journal of Hydrogen Energy	398	11589	9.67%	6.70%
Environmental Science & Technology	229	32660	5.57%	18.89%
Electrochimica Acta	220	6188	5.35%	3.58%
Bioelectrochemistry	208	5324	5.05%	3.08%
Chemical Engineering Journal	196	5142	4.76%	2.97%
Biosensors & Bioelectronics	195	11415	4.74%	6.60%
RSC Advances	171	2462	4.16%	1.42%
Water Research	135	9380	3.28%	5.43%
Science of The Total Environment	117	1353	2.84%	0.78%
Water Science and -Technology	110	2538	2.67%	1.47%
Journal of Chemical Technology and Biotechnology	100	2146	2.43%	1.24%
Applied Microbiology and Biotechnology	99	6494	2.41%	3.76%
Biochemical Engineering Journal	98	2559	2.38%	1.48%

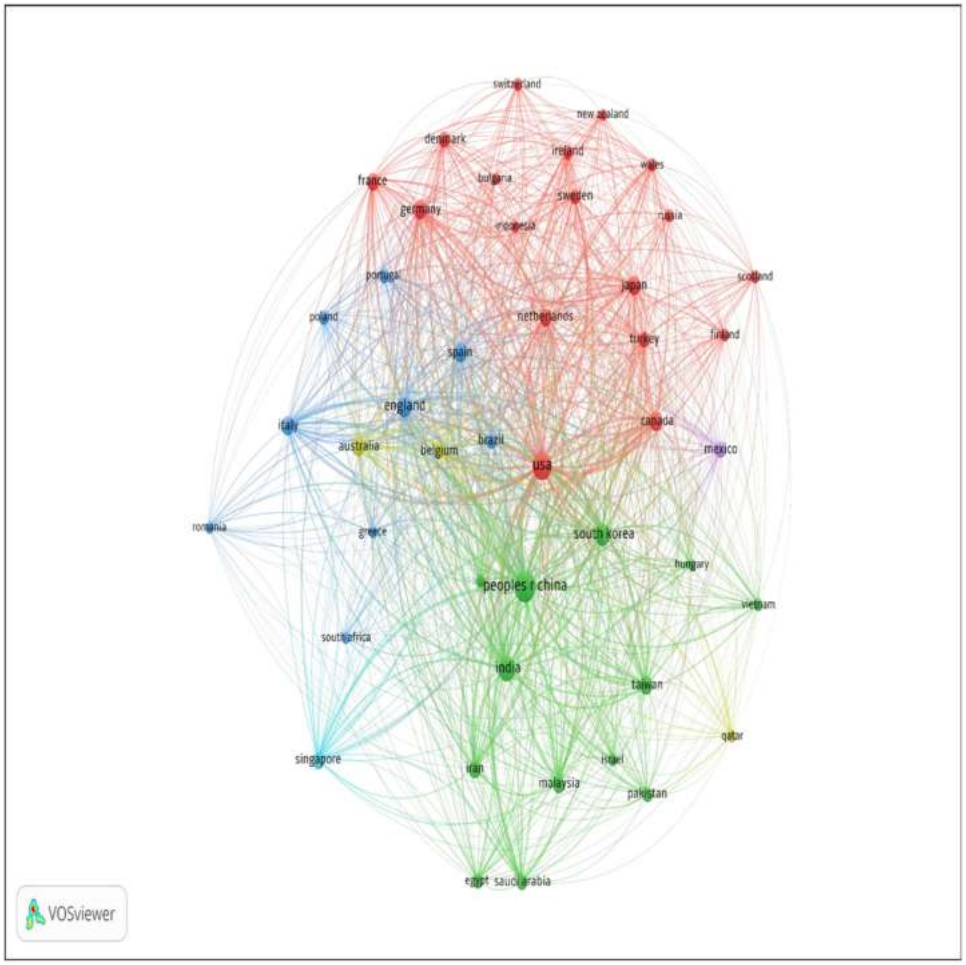

Fig. 7. Leading countries in MFC research.

It was also found that among the 98 countries, 15 countries produced the highest contributions in MFC field (accounting for 80.38% documents and 88.32% citations), with China as the leading country with 26.74% publications and 21.04% citations. The next country in the category is USA, with 16.95% publications and 29.70% citations, followed by India (7.69% publications and 4.16% citations). The individual contribution of 15 countries has been given in Table 2.

3.6. Leading research organizations involved on MFC research

Globally, there are 3866 organizations working in the domain of MFC. These organizations were filtered by setting a minimum threshold condition of 60 documents and 100 citations. 34 organizations were found to meet the required criteria, as depicted in Fig. 8. The top 15 organizations have contributed about 63.91% of the documents and 56.67% of the citations. Chinese Academy of Sciences, followed by Penn State University and Harbin Institute of technology are the top contributors. The individual

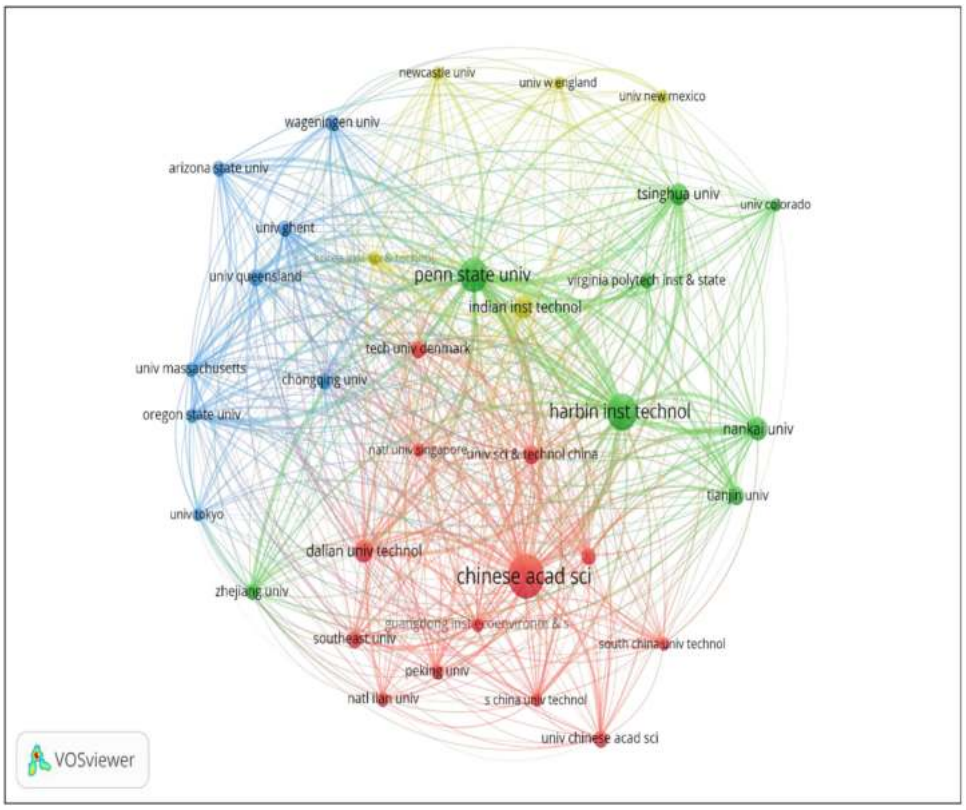

Fig. 8. Leading organizations in MFC research.

Table 2
Top 15 countries in MFC research.

Country	Documents	Citations	Documents contribution	Citation contribution
China	3147	80196	26.74%	21.04%
USA	1995	113213	16.95%	29.70%
India	905	15868	7.69%	4.16%
South Korea	597	22152	5.07%	5.81%
England	425	14786	3.61%	3.88%
Japan	322	9994	2.74%	2.62%
Germany	317	11906	2.69%	3.12%
Spain	313	7641	2.66%	2.00%
Taiwan	275	4755	2.34%	1.25%
Italy	252	7153	2.14%	1.88%
Australia	238	10391	2.02%	2.73%
Canada	238	7662	2.02%	2.01%
France	229	6693	1.95%	1.76%
Malaysia	204	3819	1.73%	1.00%
Iran	203	3294	1.72%	0.86%

contribution of the top 15 organizations has been depicted in Table 3.

3.7. Leading authors in MFC research

A quantitative literature review on author analysis has been performed to find the leading authors in the field of MFC. A minimum benchmark of 100 citations and 50 documents was set, and only 37 authors met the required conditions as depicted in Fig. 9. It is to be noted that most of the authors are Chinese as China is the main hub for MFC research, as observed in the above mentioned country analysis. Out of these 37 authors, the contribution of the top 15 is 50.66% in publications and 65.46% in citations. The individual contribution of each author has been depicted in Table 4.

The analysis of the top leading authors of the field reveals that China is the country with the highest number of authors in the list of top 15 leading authors. In fact, 7 out of the 15 authors in Table 4 belongs to China, which verifies the facts stated in the country analysis. In addition, it is also pertinent to mention that some leading authors have affiliation to universities from both China and USA.

3.8. MFC research directions

3.8.1. MFC research evolution

There are various techniques available to map the research directions of a field. Data mining technique is usually employed to extract the author's keyword or keyword plus. The author's keyword analysis only analyzes the title and abstract of articles, while keyword plus analysis analyzes the whole article to find the most frequent keywords. Therefore, in this study, the keyword plus technique has been employed to map the research trend in MFC.

For quantitative analysis of MFC literature, by employing the keyword plus technique, 9404 keywords have been extracted under the filter of "articles" only. Some of the keywords were less frequent; therefore, a filter has been applied here as well. The minimum occurrence of keywords was set to 100 and the resulting number obtained was 105 keywords. Fig. 10 depicts the mapping of these keywords. The bigger the circle, the more frequently it appears. On the other hand, the thicker the connection line, the higher is the frequency of co-occurrence.

It has been found that the most frequently used keyword is "performance", followed by "electricity-generation". Fig. 10 further elaborates that the period of 2015–2016 was an emerging era for microbial fuel cells, as depicted by the vast contribution of color noted for this era. Moreover, from 2017 onwards, MFC research has increasingly involved the fields of nanoparticles, air cathode, catalyst, nitrogen removal and graphene.

Table 3
Top 15 organizations in MFC research.

Organization	Documents	Citations	Documents contribution	Citations contribution
Chinese Academy of Sciences	458	11262	11.53%	6.11%
Harbin Institute of Technology	342	11467	8.61%	6.23%
Penn State University	312	35774	7.85%	19.42%
Nankai University	160	4867	4.03%	2.64%
Indian Institute of Technology	156	4166	3.93%	2.26%
Tsinghua University	152	5702	3.83%	3.10%
Dalian University of Technology	144	4038	3.62%	2.19%
University of Science & Technology China	114	5261	2.87%	2.86%
Tianjin University	112	2488	2.82%	1.35%
Southeast University	104	1709	2.62%	0.93%
The University of Queensland	101	7478	2.54%	4.06%
University of the Chinese Academy of Sciences	98	1245	2.47%	0.68%
Chongqing University	96	1291	2.42%	0.70%
Technical University of Denmark	96	2994	2.42%	1.63%
Nanyang Technological University	94	4630	2.37%	2.51%

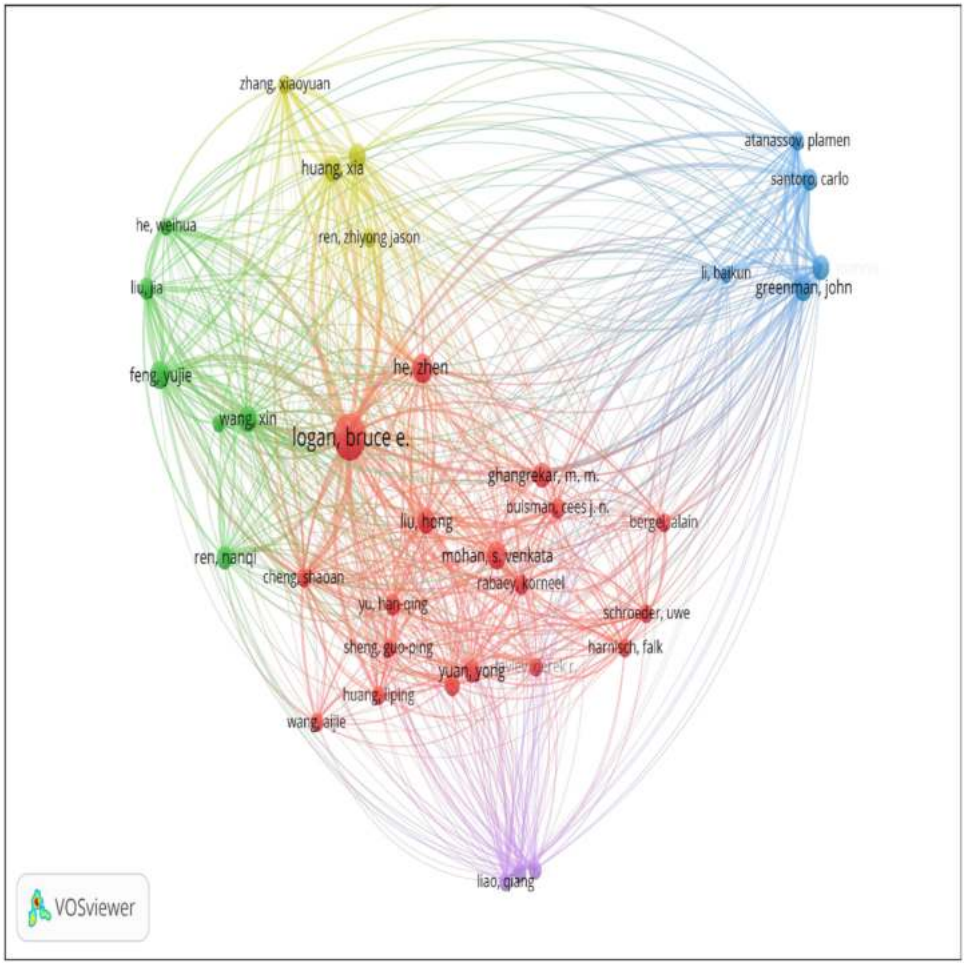

Fig. 9. Leading authors in MFC research.

Out of the 105 keywords, top keywords were selected and analyzed to determine the contributing percentage of occurrence of each keyword, see Table 5. The performance of MFC is the main challenge toward its applications in industrial sector. Low power density and difficulties in reproducibility of the experiments are the main limiting factors for MFCs (Jadhav et al., 2020). From the published literature, it is evident that researchers have demonstrated interest in improving the MFC performance by proposing various methods, such as employing algae (Khandelwal et al., 2020), nanoparticles (Jiang et al., 2021), nanotubes (Tsai et al., 2009) and many others (Li et al., 2018; Hu et al., 2021; Aiyer, 2021). MFC has widely been used as a source of clean energy production, and over the time it has evolved as a renewable energy source. Owing to this fact, energy production application is mostly discussed in literature (Obileke et al., 2021); and therefore, appears among the most frequently used keywords. With respect to applications, waste water treatment is the second most discussed application of MFC. A range of heavy metals, including Cr, Cu, Co, V and Hg, have been reported to be reduced by employing MFC-based technology (Ezziat et al., 2019; Chonde, 2014).

Table 4
Top 15 authors in MFC research.

Author	Documents	Citations	Document contribution	Citation contribution	Affiliation
"Logan, Bruce E."	241	20539	9.08%	15.59%	Penn State University
"Lovley, Derek R."	53	7145	2.00%	5.42%	University of Massachusetts
"Rabaey, Korneel"	62	6789	2.34%	5.15%	Ghent University
"Cheng, Shaoan"	57	6745	2.15%	5.12%	Zhejiang University
"He, Zhen"	115	5862	4.33%	4.45%	Virginia Polytechnic Institute and State University
"Wang, Xin"	91	5035	3.43%	3.82%	Nankai University
"Buisman, Cees J. N."	60	4652	2.26%	3.53%	Wageningen Universit
"Huang, Xia"	90	4113	3.39%	3.12%	Tsinghua University
"Schroeder, Uwe"	57	3833	2.15%	2.91%	Technical University of Braunschweig
"Mohan, S. Venkata"	104	3827	3.92%	2.91%	Council of Scientific and Industrial Research
"Liu, Hong"	82	3753	3.09%	2.85%	Beihang University
"Ren, Nanqi"	78	3682	2.94%	2.80%	Harbin Institute of Technology
"Feng, Yujie"	99	3526	3.73%	2.68%	Harbin Institute of Technology
"Liang, Peng"	85	3374	3.20%	2.56%	Tsinghua University
"Yu, Han-Ging"	71	3360	2.67%	2.55%	King Abdullah University of Science and Technology

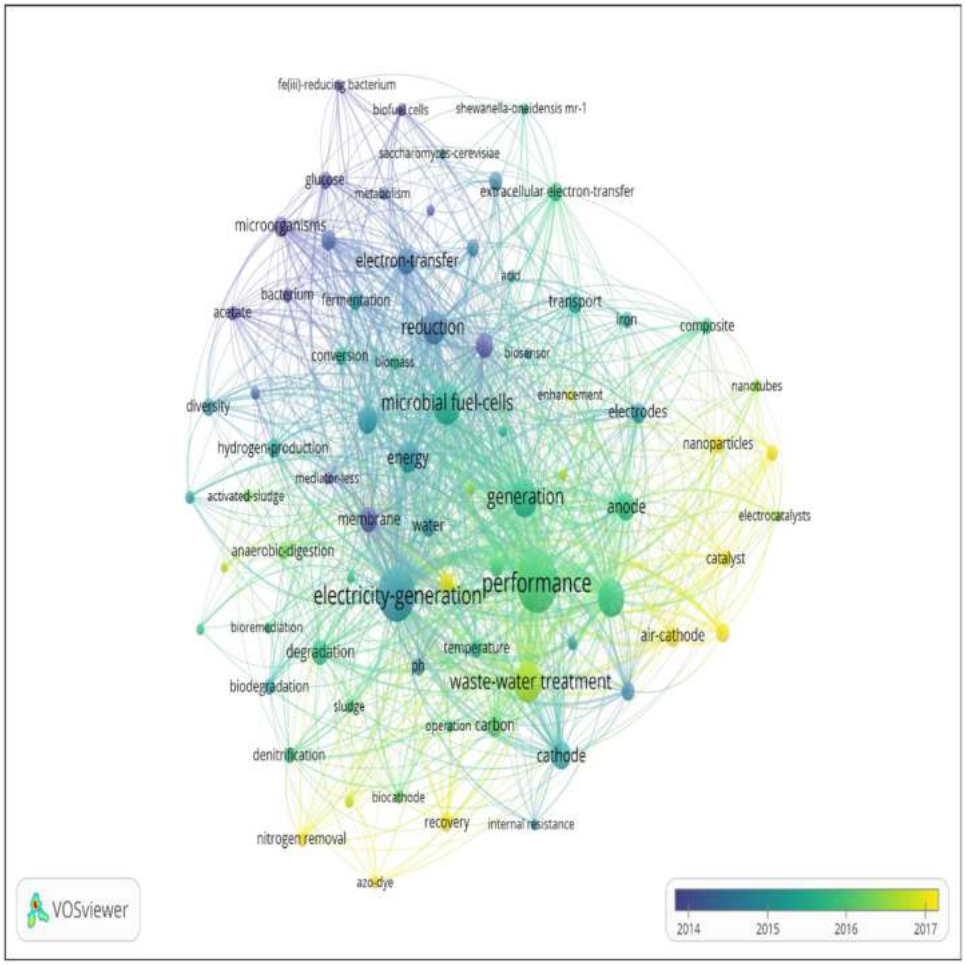

Fig. 10. Most frequent keywords used in MFC publications.

MFC primarily uses organic waste to produce electricity, treating the waste-containing water in the process (Singh and Songera, 2012b). In this way, it has become a promising technology for waste reduction. Different wastes used n MFC as the substrate are agricultural waste, cassava waste, vegetable waste, brewery waste, chocolate industry waste, domestic waste, starch processing waste water, chicken feather, azo dyes and rice straw waste (Chaturvedi and Verma, 2016). With respect to MFC design modification and performance enhancement, electrodes (cathode and anode) and type of microbes used play a vital role. Adequate selection of material and design of electrodes has always been a topic of interest in all types of fuel cells (Bessel et al., 2001). References (Hamed et al., 2020; Kalathil et al., 2017; Konovalova et al., 2018; Cao et al., 2019) provide a detailed look into the effects of electrodes (Hamed et al., 2020; Kalathil et al., 2017) and microbes (Konovalova et al., 2018; Cao et al., 2019) on the MFC performance.

Additionally, the topic of electron transfer and membrane conductivity in MFCs are among the most discussed topics of the field. In the study (Chaturvedi and Verma, 2016), after reviewing recent literature it was concluded that low electron transfer and membrane selection/design are among the main drawbacks of

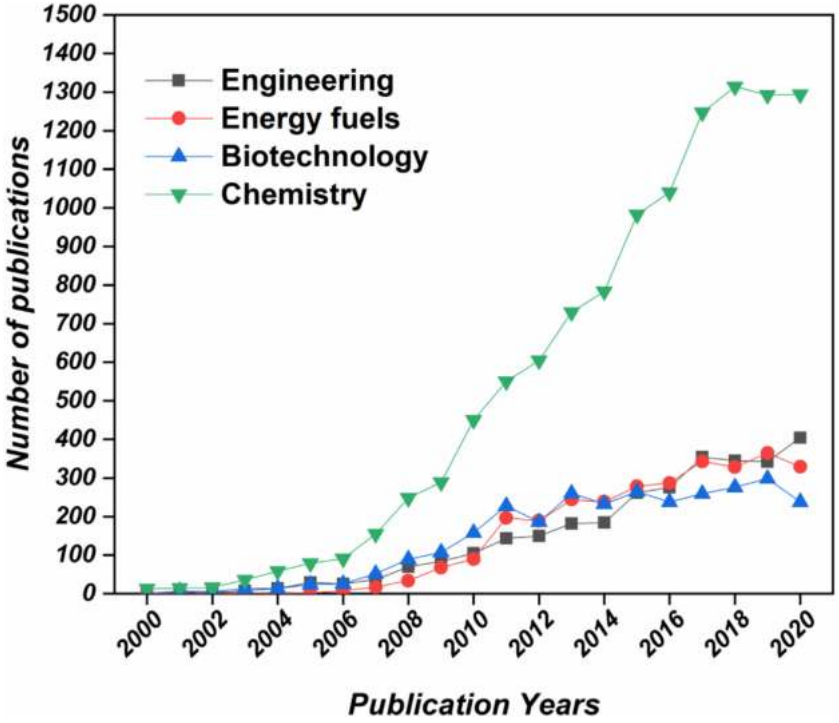

Fig. 11. Microbial fuel cell research areas.

Table 5
Most frequent keywords used in the MFC field.

Keywords	Frequency of occurrence (%)
Performance	9.92
Electricity generation	8.19
Microbial fuel cell	4.67
Waste water treatment	4.31
Waste reduction	3.13
Anode	2.13
Cathode	2.10
Bacteria	2.09
Electron transfer	2.05
Degradation	1.85
Membrane	1.71
Oxidation reaction	1.66

MFCs that needs more attention to commercialize this technology. The field of electrochemical modeling of MFC is also widely discussed, especially in the current era. MFC has several electrochemical models, but these are difficult to understand. Therefore, to predict the MFC performance accurately, research community is active to propose easily understandable models of MFC.

3.8.2. Most cited articles

The most cited articles of a field provide a deep insight into the fundamental and crucial aspects of the field. Therefore, the top 10 most cited articles on MFCs have been sorted and listed in Table 6.

3.8.3. Major research areas

In MFC research, about 94 major areas have been identified; and the leading research areas include engineering, energy fuels, biotechnology and chemistry with contributions of 26.6%, 26.5%, 26.5% and 24.8% (% of the total publication), respectively. The evolution of these top research areas over the timeline of 2000–2020 has been depicted in Fig. 11. Table 7 can be referred to realize the top 20 areas in MFC research.

The engineering area deals with the overall design of MFCs, and includes chamber design, innovation in configurations, etc. Energy fuels cater to the development, optimization, application and management of renewable and nonrenewable sources. In the case of MFC, it refers to the green energy production aspect of MFCs. Biotechnology deals with implementation of various microbes, as well as developing or optimizing mathematical models such as biofilm models. The chemistry research area covers all aspects of chemical reactions that take place in MFCs. It has been observed that since 2008 a substantial growth rate has taken place in all of the top 4 areas. It is pertinent to note that in the last two decades, the research area of MFC has grown at the highest rate.

3.8.4. Recent hot topics

There are six prolific papers available in WoS related to the MFC field, see Table 8. Out of these 6 papers, 4 are review articles and 2 are research papers. These prolific articles focused on the use of MFC for waste treatment. Meanwhile, optimization of the MFC performance is the main hot research topic. Additionally, as aforementioned in the keyword analysis section (Fig. 10), keywords such as nanoparticles, catalysts, air electrodes, graphene electrodes, power enhancement, air cathode, nitrogen removal and metal recovery have got increased attention recently, and is still under the development phase. Therefore, these mentioned keywords serve as the current hot topics of the field.

4. Conclusion

In this study, a quantitative analysis of the MFC literature has been performed. About 11,397 publications available in WoS, covering a time period of 1970–2020, have been analyzed. The major findings can be summarized as:

- Year 2020 witnessed the highest number of publications (1074) in the history of MFC research, while the highest numbers of total local and total global citations were received in 2011.

Table 6
Top 10 most cited papers in MFC research.

Citations	Title	Ref
2730	Microbial Fuel Cells: Methodology and Technology	Logan et al. (2006)
1070	Electricity Generation Using an Air-Cathode Single Chamber Microbial Fuel Cell in the Presence and Absence of a Proton Exchange Membrane	Liu and Logan (2004)
1008	Microbial fuel cells: novel biotechnology for energy generation	Rabaey and Verstraete (2005)
968	Electricity Production by *Geobacter sulfurreducens* Attached to Electrodes	Bond and Lovley (2003)
926	Exoelectrogenic bacteria that power microbial fuel cells	Logan (2009)
747	Production of Electricity during Wastewater Treatment Using a Single Chamber Microbial Fuel Cell	Liu et al. (2004)
729	A review of the substrates used in microbial fuel cells (MFCs) for sustainable energy production	Pant et al. (2010)
703	Microbial fuel cells	Logan (2008)
678	Increased performance of single-chamber microbial fuel cells using an improved cathode structure	Cheng et al. (2006)
642	Electricity generation by direct oxidation of glucose in mediator-less microbial fuel cells	Chaudhuri and Lovley (2003)

Table 7
Major research areas in MFC.

Research area	Publications	% of Total publications
Engineering	3031	26.639
Energy fuels	3024	26.578
Biotechnology applied microbiology	3019	26.534
Chemistry	2822	24.802
Environmental sciences ecology	2055	18.061
Electrochemistry	2048	18
Science technology other topics	1281	11.259
Materials science	1119	9.835
Agriculture	1031	9.061
Biochemistry molecular biology	659	5.792
Microbiology	616	5.414
Water resources	518	4.553
Biophysics	480	4.219
Physics	332	2.918
Life sciences biomedicine other topics	254	2.232
Polymer science	127	1.116
Food science technology	118	1.037
Instruments instrumentation	109	0.958
Thermodynamics	87	0.765

- The decade of 2011–2020 has contributed the most toward MFC research, accounting for 87% of all MFC literature.
- Out of the total publications, 81.6% were research articles while 11.135% were review articles.
- 145 subject categories are involved in the domain of MFC, with energy fuel and microbiology appearing as the leading subjects with 26.5% contribution each.
- About 1147 international journals have been involved in MFC-related publications , with Bioresource Technology, Journal of Power Sources and International Journal of Hydrogen Energy serving as the leading ones.
- China appears at the top of the list in MFC research with respect to the number of publications, while USA is at the top of the list with respect to the number of citations.
- Chinese Academy of Sciences, Penn State university and Harbin Institute of Technology are the leading research organizations in the MFC field.
- The main focus of research in MFC from 1970–2020 has been to optimize the performance of MFC. With respect to MFC applications, researchers have focused on electricity generation and waste treatment. To improve the performance of MFC, the most discussed topics are electrodes (material and design) and microbes used in MFCs.
- A total of 94 major research areas have been found to lie within the domain of MFC research, with engineering, energy fuels, biotechnology and chemistry serving as the top contributing fields.
- Nanoparticles, catalysts, air electrode, graphene electrodes, power enhancement, air cathode, nitrogen removal, and metal recovery have been identified as hot research topics. These research topics are the future of MFCs. Employing nanoparticles has resulted in substantial enhancement of the MFC performance. In the days to come, MFC may find its applications in industry owing to nanotechnology utilization.

This study has employed the Web of Science database. No doubt, WoS is among the most trusted source of indexing;

Table 8
Hot papers in MFC research.

Title	Year	Ref
Control Strategy for Adaptive Active Energy Harvesting in Sediment Microbial Fuel Cells	2020	Ma et al. (2020)
Electroactive microorganisms in bioelectrochemical systems	2019	Logan et al. (2019)
Short Chain Fatty Acids (SCFAs)-Mediated Gut Epithelial and Immune Regulation and Its Relevance for Inflammatory Bowel Diseases	2019	Parada Venegas et al. (2019)
Microbial fuel cells: An overview of current technology	2019	Slate et al. (2019)
Start-Up Process Modeling of Sediment Microbial Fuel Cells Based on Data Driven	2019	Ma et al. (2019)
Heterogeneous electro-Fenton and photoelectro-Fenton processes: A critical review of fundamental principles and application for water/wastewater treatment	2018	Ganiyu et al. (2018)

however, it does not cover all the articles published in any specific year. Therefore, in future, similar studies can be performed using other trusted databases, such as Scopus, Dimensions and The Lens.

CRediT authorship contribution statement

Muhammad Nihal Naseer: Conception and design of study, Acquisition of data, Analysis and/or interpretation of data, Writing - original draft. **Asad A. Zaidi:** Conception and design of study, Analysis and/or interpretation of data. **Hamdullah Khan:** Acquisition of data, Analysis and/or interpretation of data. **Sagar Kumar:** Acquisition of data. **Muhammad Taha bin Owais:** Acquisition of data. **Juhana Jaafar:** Conception and design of study, Writing - review & editing. **Nuor Sariyan Suhaimin:** Writing - original draft. **Yasmin Abdul Wahab:** Analysis and/or interpretation of data, Writing - review & editing. **Kingshuk Dutta:** Conception and design of study, Writing - review & editing. **Muhammad Asif:** Writing - original draft. **S.F. Wan Muhamad Hatta:** Writing - original draft. **Muhammad Uzair:** Writing - original draft, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This work was supported/funded by the Ministry of Higher Education, Malaysia under Fundamental Research Grant Scheme (FRGS/1/2020/TK0/UTM/02/66). All the authors extend their appreciation to the National University of Sciences and Technology, Islamabad-44000, Pakistan for technical and financial support for conducting this research.

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