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Review

An Analysis of Global Trends from 1990 to 2022 of Microbial Fuel Cells: A Bibliometric Analysis

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Abstract: Microbial fuel cells have undergone several modifications since their creation, mainly due to the different substrates that can be used as fuel for the generation of electrical energy. In this research, a deep and updated analysis of the characteristics of the literature published in the Scopus database from 1990 to 30 December 2022 has been carried out, finding 7055 documents indexed. The most used keywords are microbial fuel cells, performance, and electricity generation. From 2011 to the present, 5289 article-type documents were published; the article entitled "Microbial Fuel Cells: Methodology and Technology" by Logan B. E. et al., 2006 from Pennsylvania State University, USA in the *Environmental Science and Technology* journal of the ACS publisher was the most cited (4496 citations). On the other hand, in recent years, Chinese universities have begun to produce and highlight a number of documents positioning in the top ten, with six universities having the greatest presence in publications and as the country with the highest number of published and indexed documents (2773) in Scopus. Research on microbial fuel cells tends to grow, with China as a leading country on the subject, written by the author Wang X. It is observed that the new cell research trends deal with the modification and fabrication of electrodes with nanomaterials in order to improve their power and reduce costs to show their viability on a larger scale.

Keywords: microbial fuel cells; biometric analysis; research trend; organic waste

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1. Introduction

The accelerated increase in human society in the last decade has generated fossil fuels, which have become the main source of electricity generation worldwide, and have also become one of the causes of global warming and climate change [1,2]. In this context, organic wastes have become a potential source for the generation of bioenergy in an environmentally friendly way through their use as fuel in microbial fuel cell (MFC) technology [3,4]. This technology started to be investigated in 1911 by Potter, but more intensively in the last years through various manufacturing methods and design methods [3]. Nowadays, MFCs have expanded their applications beyond electricity generation to bioremediation, wastewater treatment, and biosensors [5]. Their basic components are two chambers (anodic and cathodic) joined internally by a proton exchange membrane and externally by a circuit through which electrons flow from the anodic to the cathodic chamber [6–8]. MFCs can use the catalytic bacteria present in the different substrates used (organic wastes, wastewater, etc.) to generate bioelectricity by means of the conversion of chemical to electrical energy through the oxidation and reduction process that occurs within the system [9,10]. A large number of substrates used are rich in sugars, minerals, vitamins, amino acids, polyphenols,

aromatic compounds, carotenoids, fibers, and phytosterols to be used by microorganisms as food for their metabolic activity [11–13]. The MFCs mainly base their electricity generation operation on the ability of bacteria to transfer electrons, within the wide variety of microbial community present in different kinds of wastes some mechanisms that can be attributed to the transfer of electrons from organic matter placed on the anode to the cathode electrode [14]. The main mechanisms so far accepted are direct electron transfer, by means of direct contact between the cell surface and the electrode, and indirect electron transfer, where a mediator interferes. Additionally, bacterial cells are immobilized as mediators on the electrodes to increase their number in the formed biofilms in order to improve their performance [15,16]. Within the different types of microbial fuel cells, there is a variety of microbial fuel cell architectures (see Figure 1), with single- and dual-chamber microbial fuel cells being the most widely used [14,17–19].

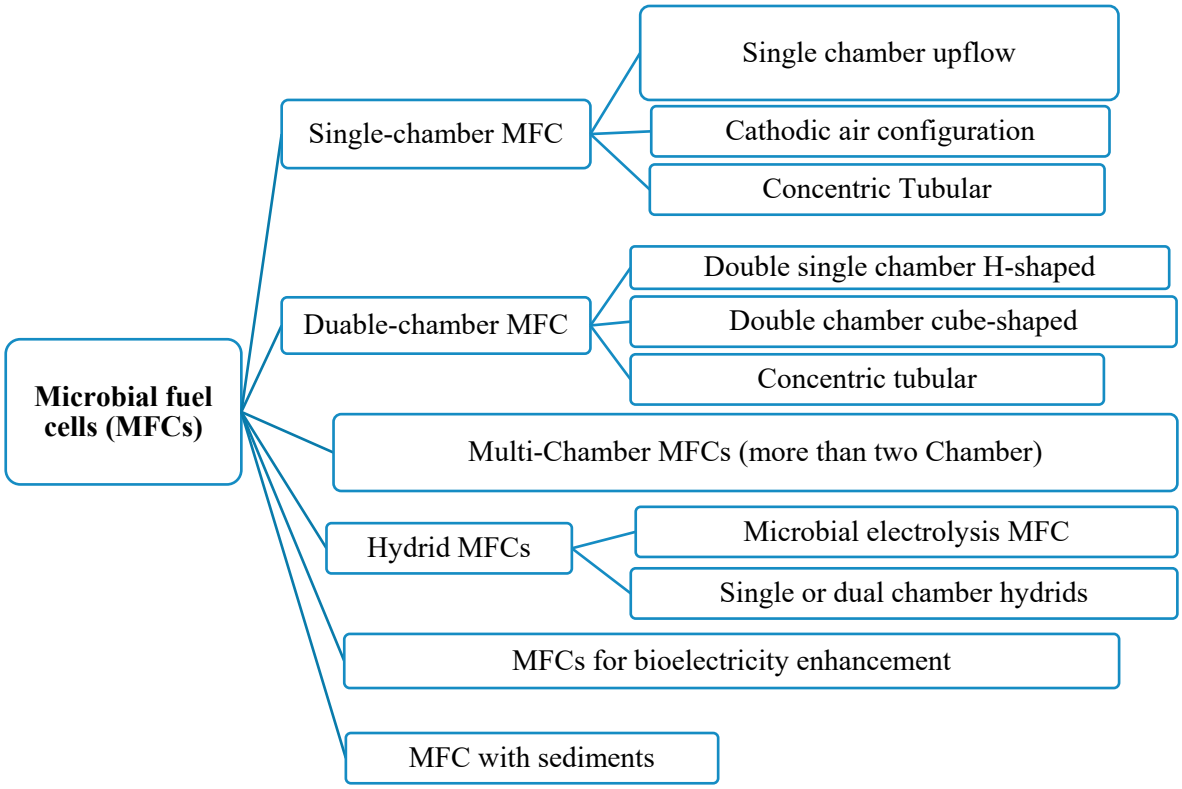

Figure 1. Types of microbial fuel cells.

In recent years, bibliometric analysis has begun to be used as a strategy to evaluate the trend of research areas and thus observe the existing gaps [20]. For this reason, bibliometric analysis is being used to evaluate scientific production through observable products; for example, citations, books, keywords, authors, published journals, etc. [21,22]. This type of analysis effectively measures the influences of authors and institutions, and publications predict and describe the processes of the scientific community [23,24]. Similarly, the WoS and Scopus databases, the largest globally recognized databases, have a high degree of overlapping journals, i.e., research that is published in journals and indexed in Scopus and WoS at the same time; but the Scopus database is recognized as the largest database of literature citations and peer-reviewed abstracts and covers a wide range of subject areas [25,26].

Although MFCs have been used to generate bioenergy in different ways and with a wide variety of substrates, very little research has been conducted on the bibliometric analysis of scientific publications from a global approach in the literature review [27]. Ni et al., 2021 presented their trend research on bibliometric analysis (BEA) for a period of 18 years from 2001 to 2018, where they investigated the cumulative number of publications inti-

mately related to industrialization and commoditization along with environmental issues, with an emphasis on the global challenges of microbial fuel cells using the Web of Science (WoS) database as a source [28]. Similarly, Naseer et al., 2021 conducted their research on MFCs and their trend of publication history, leading journals, leading countries, and leading organizations through bibliometric systems (BES) from 1970 to 2020 in the WoS database [29].

The aforementioned studies lack the use of the Scopus database, which is why our objective is to (i) analyze the temporal distribution of publications in journals dealing with MFCs; (ii) reveal the contributions of the most productive countries, academic institutions, and authors; (iii) show the most used terminology and research topics; and (iv) determine the most influential countries according to the main applications; all of this using the Scopus database.

2. Materials and Methods

A targeted bibliometric analysis was performed on articles and reviews indexed under the topic "microbial fuel cell" or "MFC" or "MFCs" in the Scopus core collection between 1990 and 2022, updated as of 30 December 2022; only in the English language. Scopus is a widely used catalog due to its extensive coverage of journals of recognized relevance, which reaches 7055 titles in its core collection [30]. In addition, it presents a lower number of errors in metadata recording compared to other databases [31]. The files downloaded from the Scopus database were preprocessed to improve data quality and later reorganized in Microsoft Excel 16, considering titles, years, journals, categories, authors, affiliated institutions, countries, keywords (KEY), and citations received. The author and keywords assigned by Scopus were standardized using a thesaurus (bioenergy, renewable energy, biomass) that allowed unifying equivalent terms and safeguarding their consistency in the different records and computer tools used for processing (see Figure 2).

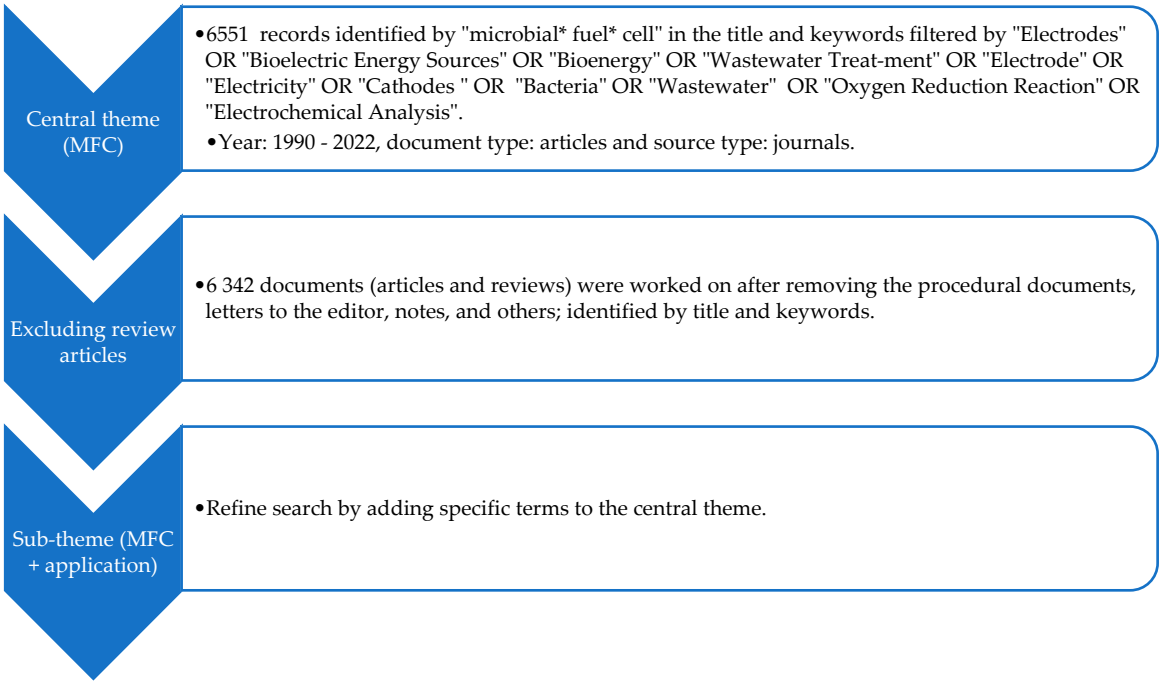

Figure 2. Flowchart of data collection of the central and secondary documents.

Figure 2 shows a flowchart that shows the analysis carried out in this investigation that includes (a) production indicators, the number of documents, their percentages, and distribution quantified, as well as the number of large producers with 10 or more documents in the area [32]; (b) impact indicators, such as citations received in Scopus, the H-index (HI) [33], the quartile of the journals in which the documents were published ac-

cording to the Journal Citation Reports [34], and the citation structure by year, countries and supra-regions obtained by grouping articles according to the ranges of citations received [20]; (c) the occurrence of MFCs, to establish their frequency of use; and (d) the co-occurrence of MFCs, to map the domain of study and categorize the topics in a strategic diagram with centrality and density as axes to locate the driving topics of the area, cross-cutting topics, emerging or disappearing topics, and specialized topics [35]. The strategic diagram integrated second-generation relational indicators that combined the themes and their impact [23].

Both the analysis and visualization of the thematic network were performed with VOSviewer 1.6.15, normalizing the graph according to the strength of association [22].

3. Results and Analysis

Figure 3a shows the research published from 1990 to 2021, showing an exponential increase in the research carried out in recent years, reaching a total of 6342. Almost in the last decade 69.85% (4382) of publications have been made from the year 2011 to 2020 (see Figure 3b), its first publication in the year 1993 [36], and then no publication is registered in the Scopus database until 1999 but its exponential ascent begins in the year 2004, with 141 types of research made; these increases made from the year 2000 have made a constant increase in the total accumulated publications to date. Since 2008, the annual publications have increased by approximately more than 100 articles, which would make us foresee that in the coming years, the rate of research will continue to increase, even more so since nowadays there is a constant search for new ways to generate energy in a clean and renewable way; considering that the microbial fuel cells occupy great amount in this area [37–39].

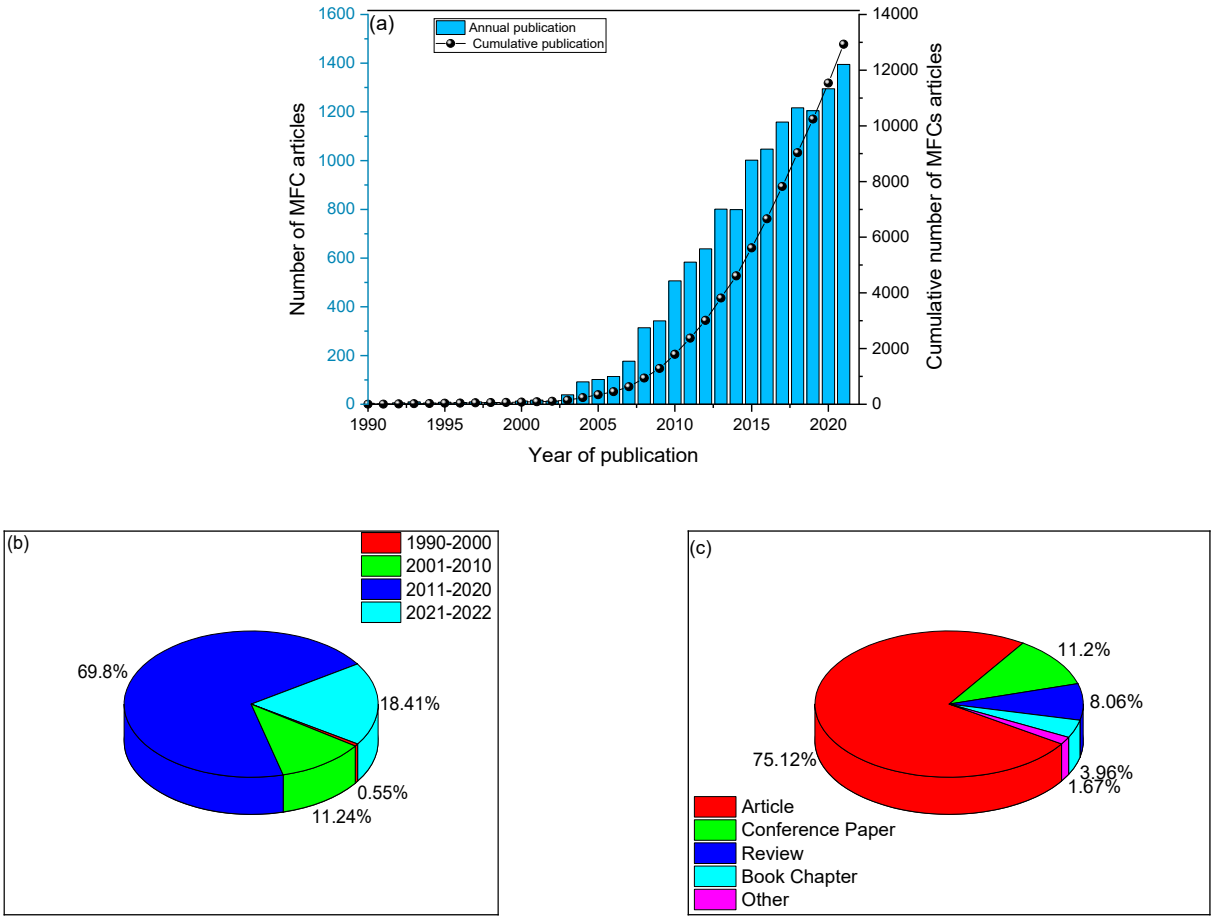

Figure 3. Graph of the (**a**) number of articles, (**b**) percentages of publications per 10 years, and (**c**) type of publication.

One of the most outstanding data found is the large number of articles that are not freely available, a negative point because an article offered for free to the scientific community would receive a greater number of citations by users than those that would have to make some kind of payment; only 38.18% of the registered publications are open access, although the percentage has increased to 2.3% (94 articles) [40]. The highest percentage of publications made are research articles (75.12%), conference papers (11.20%), reviews (8.06%), book chapters (3.96%), and others (1.67%), with 4764, 710, 511, 251, and 106 publications, respectively, as seen in Figure 3c.

Table 1 was categorized using Crane's method [41], where it was observed that 75 countries have produced some type of publication, with China being the country with the highest number of publications (2773), producing approximately 275% more than the second country (United States) which follows with 1008 publications; while Japan has only published 226, placing it in eighth place. Likewise, it has been observed that 1548 affiliations have been responsible for all the publications, Pennsylvania State University (USA) being the affiliation with the highest number of publications (195), followed by Southeast University (Republic of Korea) with 152. As can be observed, Chinese Universities are the institutions with a greater presence, placing six institutions in the top 10, but in the year 2020, it was reported that the Chinese Academy of Sciences was number one for numerous publications [30,42]. Likewise, it is also shown that the author with the highest number of publications is Logan B.E. with 162 publications on the subject of microbial fuel cells, his publication on electrogenic bacteria used as fuel in MFCs as the one with the highest number of citations; it is because it clearly explains the interaction mechanism between the biofilm formed on the anode electrode and its area with the power density found in its cells, as well as the value of the potential found experimentally, was very close to the theoretical potential calculated. He also shows all the microorganisms found in his previous work, showing all the electrogenic bacteria activated for the generation of bioelectricity [43,44].

Table 1. Main authors, institutions, and producing countries.

Author (a)	TD	R	University	TD	R	Country	TD
Logan B.E.	162	1	Pennsylvania State University	195	1	China	2773
Wang X.	58	3	Southeast University, Republic of Korea	152	3	United States	1008
Liu Y.	61	1	Chongqing University, China	187	1	India	962
Wang Y.	60	2	Nankai University, China	161	2	Republic of Korea	536
Ghangrekar M.M.	51	4	Tianjin University, China	131	4	United Kingdom	374
Zhang X.	50	5	Guangzhou University, China	129	5	Malaysia	271
Li Y.	47	6	Indian Institute Of Technology Kharagpur, India	111	6	Taiwan	261
Li X.	43	7	South China University Of Technology, China	92	7	Japan	226
Zhang Y.	43	8	University Of The West Of England, Reino Unido	78	8	Italy	218
Li J.	40	9	Nanjing Tech University, China	75	9	Iran	203

TD: total document; R: ranking.

Figure 4 shows the collaborations of the main authors with more than 25 publications, showing that Logan B. has a greater number of collaborations with Zhang X. and Wang X.; while Zhang X. has a greater number of collaborations with Liang P. and Huang X., and likewise Wang X. has a larger circle of collaborative research Zhang Y., Li X., Wang Y., Liu J., Feng Y., Ren N., Liu Y., and Li Y. It was also observed that the peak of Logan B.'s publications was between 2000 and 2008 and that Wang X. is currently the researcher with the most publications. Figure 5 shows the main collaborations between the institutions

with the greatest presence in scientific papers on the subject of microbial fuel cells, where Pennsylvania State University in the United States has a very close relationship of collaboration with the Dalian University of Technology, Tianjin University, and Nankai University, while Chongqing University has research collaborations with Sichuan University and the Beijing University of Technology mainly. Currently, Pennsylvania State University is the institution with the greatest projection in manufacturing MFCs on a large scale due to the large number of researchers working on topics related to bioreactors, microbial fuel cells, reactors, etc. Another study shows the largest air-cathode MFC of 850 L, which was used to generate electrical power while treating wastewater [45].

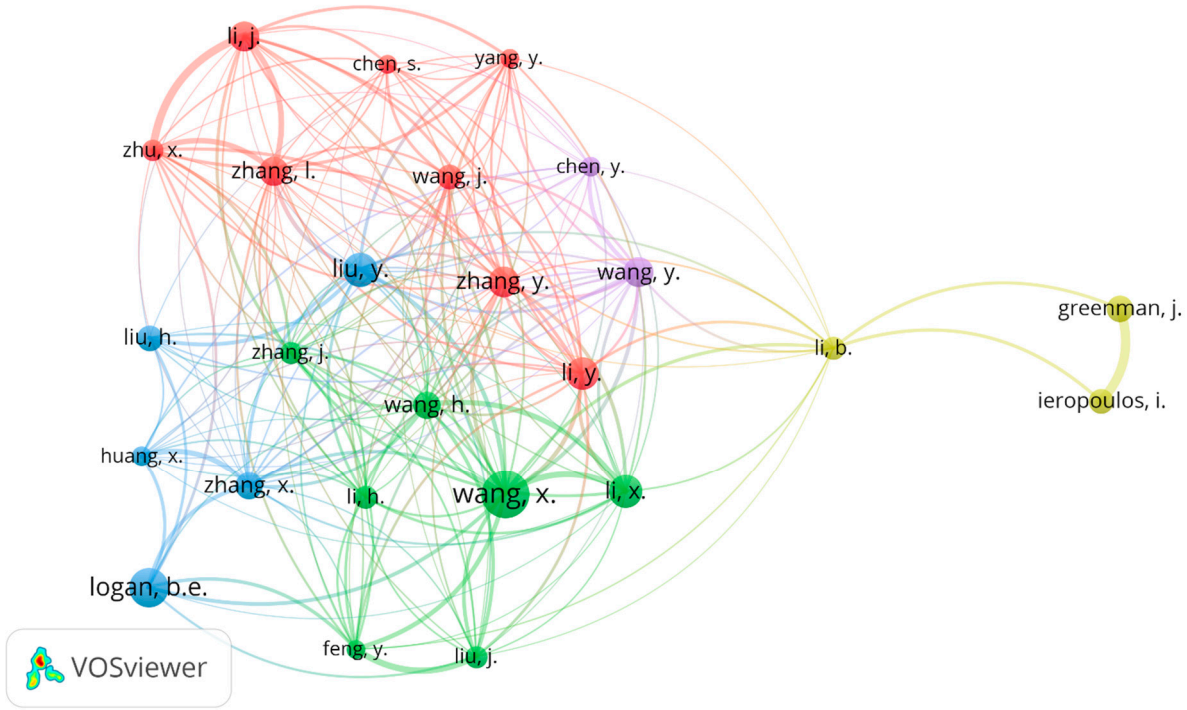

Figure 4. Leading researcher organizations in MFC research.

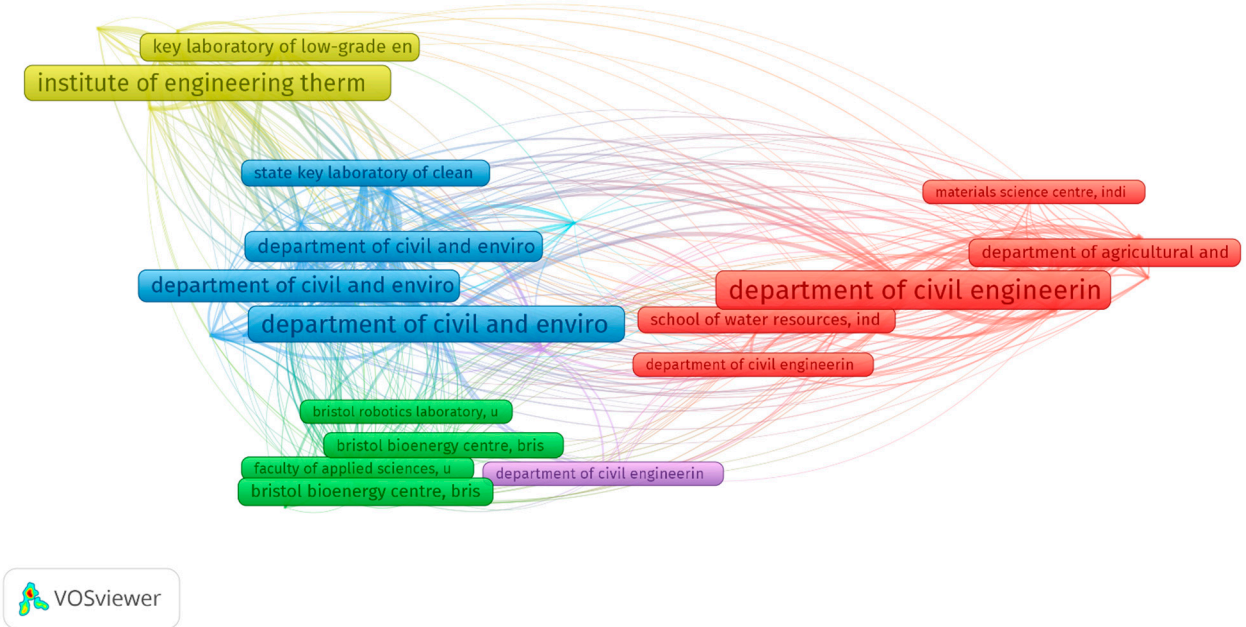

Figure 5. Leading organizations in MFC research.

In Table 2, the annual citation structure is shown, from 2012 to 2022, managing to observe 10,271 documents, the article with the highest number of citations was the one published by Santoro et al.,2017 entitled "Microbial fuel cells: From fundamentals to applications. A review" in the Journal of Power Sources with 884 citations, a review of the last 15 years (it was published in 2017) was made, explaining the electrochemical mechanisms for the generation of bioelectricity, which is generated mainly by the formation of electroactive biofilms and by the electrocatalysis process due to the reduction reaction of oxygen in the cathode chamber [43]. The article entitled "Towards sustainable wastewater treatment by using microbial fuel cells-centered technologies" by Li et al., 2014 and published in the journal Energy and Environmental Science (Royal Society of Chemistry) was the second most cited with 635 citations, which proposed a form of hybrid MFCs using wastewater as a substrate; it would be regenerated in a process in which it would generate electricity using the struvite precipitation and the proton exchange membrane as a filter [44].

Table 2. Annual citation structure in Scopus.

Year	>200	>100>	>50>	>20>	>10>	>5>	>1>	0	*TD*
2012	83	127	284	191	84	77	116	90	1052
2013	17	40	149	185	85	53	81	56	666
2014	13	43	121	191	102	59	83	39	651
2015	13	46	134	267	131	75	124	79	869
2016	11	32	123	261	177	94	112	43	853
2017	9	22	91	319	213	112	134	50	950
2018	8	20	76	321	213	155	176	82	1051
2019	4	7	64	298	261	186	175	61	1056
2020	0	2	26	208	288	221	260	81	1086
2021	0	2	5	64	172	286	471	180	1180
2022	0	0	0	1	18	60	326	452	857
Sum	158	341	1073	2306	1744	1378	2058	1213	10,271

The year 2021 shows the highest number of citations with only one citation (286) and no paper with more than 50 citations; this can be explained due to the short time elapsed since its publication. The same behavior was observed in the year 2019 with citations greater than 200; while, in the year 2013, the highest number of cited documents (83) greater than 200 was observed. It has been observed that the advantage of collaborations is not limited to the exchange of knowledge, expansion of the network, and shared experience; if not also to a strategy to rank up until now effective, as demonstrated lines above. The document with the greatest impact in 2022 was the one published by Wang et al., 2022, in which they used pig wastewater waste in single-chamber MFCs with anaerobic digestion, managing to generate electrical current peaks of approximately 20 mA in 16 days; they likewise identified at the genus level the species *Methanobacterium*, *Methanocorpusculum*, *Methanosarcina*, and *Methanoculleus* mainly [46].

In Table 3, the 10 journals with the highest number of publications on Microbial Fuel Cell are shown; it is able to observe that the environmental science and technology magazine is located in first place with 578 publications and 35,053 citations, with its publication entitled "Microbial Fuel Cells: Methodology and Technology" having 4496 citations as the influential ACS editor. This document was published in 2006 and has served as a theoretical and design basis for several investigations because it shows all types of MFCs with different types of electrodes used (the graphite and carbon electrode were the most used). Likewise, it explains the formulas to carry out the measurements of efficiency, electron transfer, COD balance, and others, and their applications on larger scales [42]. The second journal with the highest number of documents was the Journal of Power Sources with 374, 36% less than the journal located in the first place. This journal belongs to the Elsevier publishing house, whose document with the most citations is the one entitled "Microbial fuel cells: From fundamentals to applications. A review", whose content is very similar to the one mentioned above but with more updated information since it was published in

2017. This updated document already mentions electrodes embedded with nanomaterials to increase efficiency in the different types of cells. Likewise, it explains more clearly the generation of bioelectricity through the biofilm formed by the microorganisms of the different substrates used [47].

Table 3. Top 10 most productive journals on MFCs research with their most cited article.

	Journal	TP	TC	CiteScore (2021)	Most Cited Article (Reference)	Times Cited	Publisher
1	Environmental science and technology	578	35,053	11.357	Microbial Fuel Cells: Methodology and Technology [43]	4496	ACS
2	Journal of power sources	374	27,458	15.4	Microbial fuel cells: From fundamentals to applications. A review [44]	883	Elsevier
3	International journal of hydrogen energy	316	22,218	10	Non-Pt catalyst as oxygen reduction reaction in microbial fuel cells: A review [42]	229	Elsevier
4	Biosensors and bioelectronics	143	22,218	20.2	Operational parameters affecting the performance of a mediator-less microbial fuel cell [47]	870	Elsevier
5	Electrochimica acta	139	10,398	12.3	Non-catalyzed cathodic oxygen reduction at graphite granules in microbial fuel cells [48]	225	Elsevier
6	Chemical engineering journal	127	6106	6.7	Electricity generation from starch processing wastewater using microbial fuel cell technology [49]	334	Elsevier
7	Chemosphere	121	8182	11..7	A comprehensive overview on electro-active biofilms, role of exo-electrogens and their microbial niches in microbial fuel cells (MFCs) [50]	104	Elsevier
8	Science of the total environment	117	5684	14.1	Challenges in the application of microbial fuel cells to wastewater treatment and energy production: A mini review [51]	137	Elsevier
9	Rsc advances	114	6462	5.9	Graphene supported α-MnO_2 nanotubes as a cathode catalyst for improved power generation and wastewater treatment in single-chambered microbial fuel cells [52]	112	Royal Society of Chemistry
10	Bioelectrochemistry	109	4354	8.7	Effect of electrolyte pH on the rate of the anodic and cathodic reactions in an air-cathode microbial fuel cell [53]	283	Elsevier

TP: total publications; TC: total citations; ACS: American Chemical Society.

Table 4 shows the most cited documents from 1990 to 2022, showing that the article entitled "Microbial fuel cells: Methodology and technology" by Logan, B. E et al., 2006 was presented in the journal with the largest number of documents published [43]. Additionally, Logan, B. E. together with his team of researchers, have managed to place four articles [44,54–56] as the most cited in the top ten, achieved 8608 citations only from these four documents. Similarly, Liu Hong, together with his collaborators, managed to place two papers in the top ten, obtaining 2970 citations, the article entitled "Electricity Generation Using an Air-Cathode Single Chamber Microbial Fuel Cell in the Presence and Absence of a Proton Exchange Membrane" was the most cited, in which he investigated single chamber MFC and using wastewater as a substrate, in which he managed to generate 0.5 V in the first 5 h and a peak power density of 500 mW/m^2 [56–59].

Table 4. Most cited articles from 1990 to 2022.

Author	Year	Title of the Document	TC	TC per Year
Logan et al. [44]	2006	Microbial fuel cells: Methodology and technology.	4496	264.47
Logan et al. [54]	2009	Exoelectrogenic bacteria that power microbial fuel cells.	1730	123.57
Rabaeay et al. [55]	2005	Microbial fuel cells: novel biotechnology for energy generation.	1686	93.67
Liu et al. [56]	2004	Electricity generation using an air-cathode single chamber microbial fuel cell in the presence and absence of a proton exchange membrane.	1686	88.74
Logan et al. [57]	2008	Microbial fuel cells.	1378	91.87
Pant et al. [58]	2010	A review of the substrates used in microbial fuel cells (MFCs) for sustainable energy production.	1301	100.08
Liu et al. [59]	2004	Production of electricity during wastewater treatment using a single chamber microbial fuel cell.	1284	67.58
Chaudhuri et al. [60]	2003	Electricity generation by direct oxidation of glucose in mediatorless microbial fuel cells.	1222	61.10
Du et al. [61]	2007	A state of the art review on microbial fuel cells.	1181	73.81
Logan et al. [62]	2007	Graphite fiber brush anodes for increased power production in air-cathode microbial fuel cells.	999	62.44

TC: total citations.

Figure 6 shows the top 15 keywords in decreasing order of occurrence, which were microbial fuel cell (with a total of 4795 occurrences), performance (with a total of 856 occurrences), electricity generation (with a total of 536 occurrences), wastewater (with a total of 523 occurrences), generation (with a total of 463 occurrences), anode (with a total of 409 occurrences), wastewater treatment (with a total of 357 occurrences), microbial fuel cells (with a total of 324 occurrences), removal (with a total of 316 occurrences), application (with a total of 300 occurrences), treatment (with a total of 299 occurrences), carbon (with a total of 252 occurrences), bioelectricity generation (with a total of 234 occurrences), catalyst (with a total of 221 occurrences), and material (with a total of 217 occurrences). This set of reported keywords is evidence of the most used subject matter related to microbial fuel cells. Although the vast majority of substrates used in MFCs are in the liquid phase, semi-solid or solid phase substrates with a high organic matter content have been reported. Keywords such as "sludge" or "waste" have obtained a large number of occurrences, and words such as organic waste, excess sludge, food waste, and anaerobic sludge have been found. The results presented show that approximately 18% of the total words are described by the waste in the liquid phase and that the reduction in different types of bacteria has been exploited in these types of substrates to improve the bioelectrochemical process (increasing the Coulombic efficiency). On the other hand, the word catalyst is frequently mentioned because of its relation to the processes of catalytic activity, photocatalysis, bioelectrocatalysis, and electrocatalysis.

Actually, the MFCs have developed great advances in their technology with the purpose of taking it to larger scales. There are investigations that have managed to generate voltage greater than one volt in 100 mL cells for periods longer than 30 days, but there are still bottlenecks for its scaling. These are mainly the concentration of certain microorganisms present in the substrate for good performance, as well as the appropriate pH for its operation and the most suitable electrodes so that their maintenance is not too expensive [45,63,64]. On the other hand, MFCs have been used for the bioremediation of different types of toxic metals and the generation of bioelectricity at the same time, giving good indications that this technology will be a reality for society in the near future.

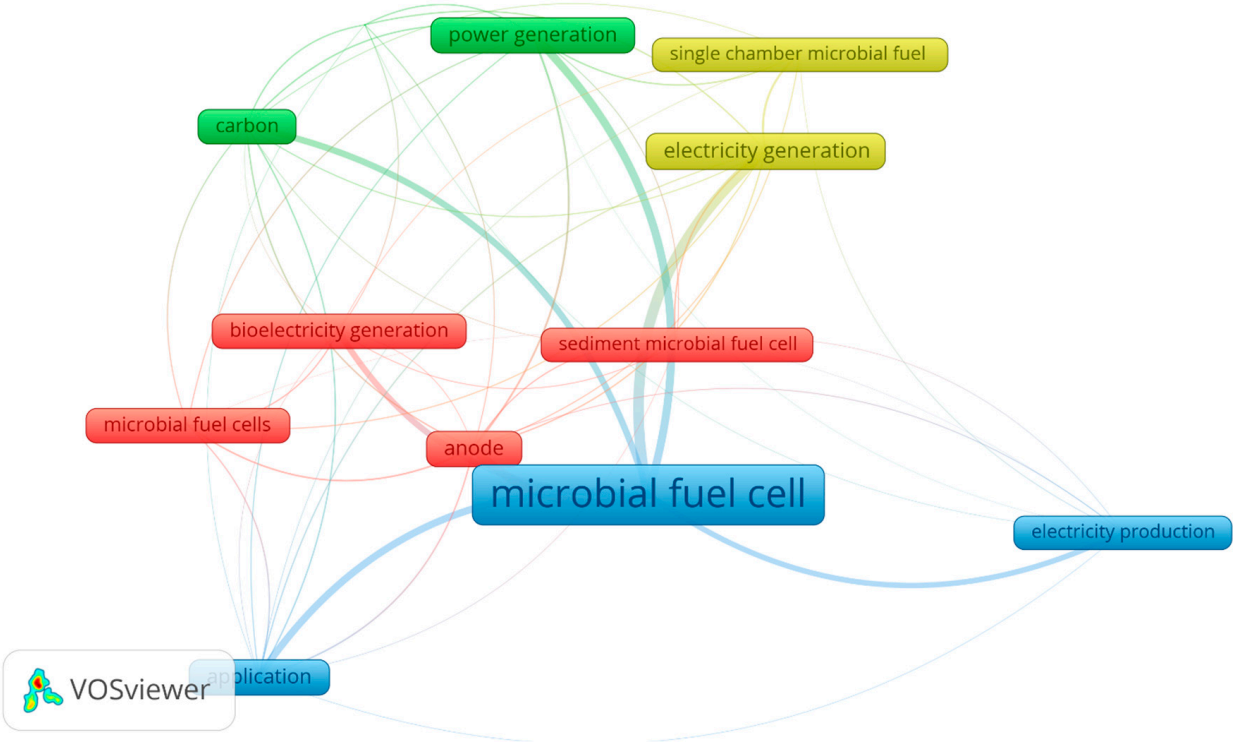

Figure 6. Thematic network of the main keywords used in microbial fuel cell research.

Current electrochemical technologies: Logan et al., 2022 are currently investigating the use of air cathodes to produce electricity while treating wastewater on a pilot scale, managing to generate voltage and current peaks of 0.43 V and 4 A for 6 days at a pH of approximately 8; and managing to reduce the initial concentrations of BOD (biochemical oxygen demand) and COD (chemical oxygen demand) of 2.31 kg/day and 0.47 kg/day. The research is carried out with new researchers in the area [65]. Likewise, it has been found that Yang W., Wang W., Logan B., and others (2021) have jointly investigated the use of a new catalyst (Fe-N-C conjugated with chitosan) on the activated carbon cathode electrode, managing to increase the power density (DP) generated by 33% of its initial value (1.8 ± 0.03 W/m^2), increasing the DP, and increasing the possibility that they are economically viable because they were manufactured with low-density materials cost [66]. Likewise, it was possible to observe that in 2022, the author with the largest number (8) of published documents is Kundu P. P., whose research is carried out on the use of nanostructures of different materials in microbial fuel cells for the generation of bioelectricity. The most cited is the research carried out with Dhillon S. and Kundu P. P. (2022) in when they carried out highly efficient electrocatalysts using air cathodes made with Fe/NC, managing to show a resistance of the cells of 132.5 Ω achieving an output PD of 637.53 mW/m^2, which is 33% higher than using a conventional Pt/C cathode electrode [67]. In this sense, as can be seen in Figure 7, the terms wastewater treatment, electricity, microbial fuel cells, electrolytic reduction, and oxygen are the most used by researchers for the preparation of manuscripts, although the authors with the most citations and most citations over the last thirty-two years are working with electrodes modified with nanostructures in wastewater treatment. The method of anaerobic digestion combined with chemical and thermochemical processes is the most used in water treatment; for example, in the extraction of lipids by thermochemistry [58–63,67,68]. Other types of combined technologies are those that include pyrolysis, liquefaction, and gasification for the production of fuels through wastewater [63,64].

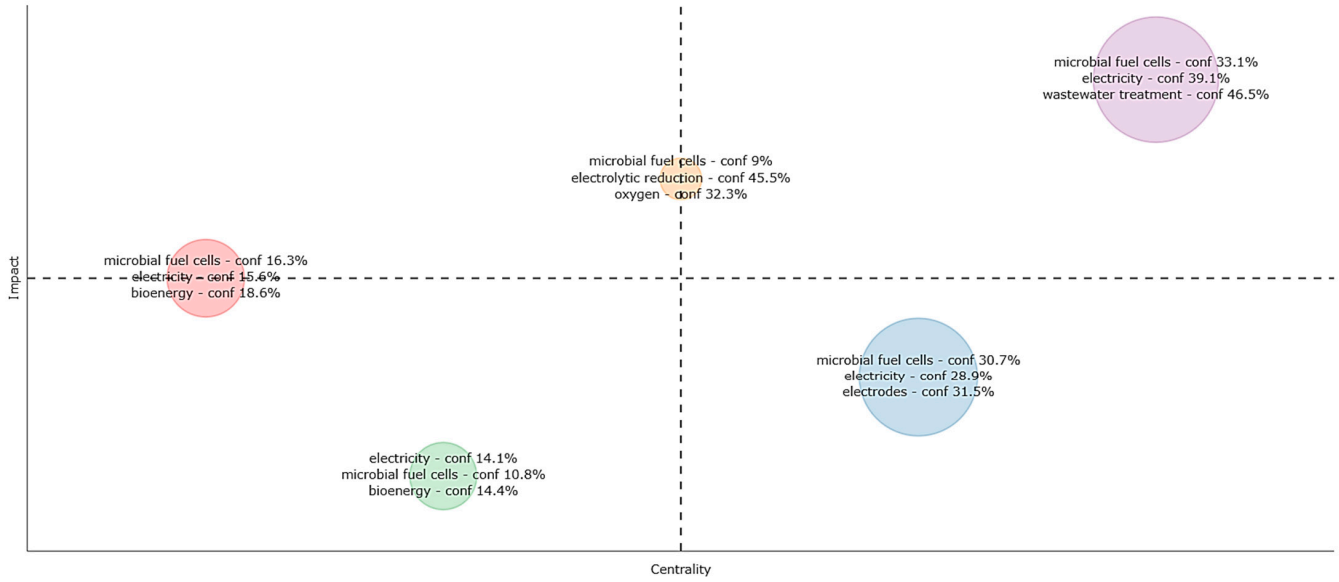

Figure 7. Map of the keywords with the greatest impact based on their centrality in the year 2022 alone.

4. Discussion

A great increase in published documents has been observed in the last decade (see Figure 3a,b), concentrating basically on experimental research articles. This is due to the great changes that have arisen in the environment, which has led universities, institutes, and research centers to focus on finding new ways to generate electricity without causing harm to the environment [67,69,70]. The USA is the country with the most research carried out; this is precisely due to the number of researchers working in this field. One of the key points for these research centers is the development of large-scale MFCs technologies, with Dr. Logan, B.E. from Pennsylvania State University as one of the pioneers in this field for as long as he has been researching. He is currently conducting work testing wastewater as fuel in MFCs, combined with more complex electrical circuits to increase the potential of their reactors, managing to generate electrical current peaks of 6 A and constant values of 3.5 A [45]. Much of his current research is due to the incorporation of nanostructured materials into the carbon felts used. According to his published documents, this is due to the fact that metal nanostructures have suitable properties to better conduct the electrons that generate electric current; some of the nanoparticles used are those from iron, nickel, and copper [45,71,72]. As well Dr. Logan, Dr. Wang X. from Southeast University, Republic of Korea (see Table 1) is also one of the most prominent researchers worldwide. His research area is microbial fuel cells from the point of view of microorganisms that generate electric currents and proton exchange membranes. One of his recently published papers deals with the effect of anaerobic sludge on the generation of bioelectricity using *Geobacter* and different types of concentrations in different media [73,74].

Many of the principal investigators work in collaboration; this has been observed in Figure 4, which shows that Wang X., Logan B.E., and Liu Y. are those who have a greater number of collaborations with other researchers from European and Asian countries. One of the main reasons that Logan B.E. has a large number of citations (Table 2) in his published documents is that he is the one with the most experience in the area, but the new researchers have been increasing their published documents rapidly and gradually. The area of greatest research is the oxygen variations in the cathode chambers (because it is the environment where the reduction occurs), electrolytic reduction, and the different types of large-scale designs of the MFCs, wastewater being the most used substrate. Figure 7 shows the centralized quantified measures based on their impact. As can be seen in the upper right part, there are the most transversal topics in the scientific field. The most de-

veloped topic is that of wastewater treatment (46.5%) and the document carried out by Liu and Logan (2004) is the one with the greatest impact (by its number of citations, 1724 citations), in which the bacteria present in domestic water were used as biocatalysts, managing to generate a maximum power density of 262 ± 10 mW/m^2 and thus showing the first indications of the use of the bacteria as biocatalysts and the use of a proton exchange polymeric membrane [56]. On the other hand, in the lower left part, you can see the most isolated topics, such as electricity (14.1%), bioenergy (14.4%), and microbial fuel cells (10.8%) due, in part, to the fact that most of the documents do not usually use microbial fuel cells or bioenergy as keywords, instead they are used in the title. Additionally, the topics of microbial fuel cells, electrolytic reduction, and oxygen are words with greater impact and centrality; these are found to be well-developed and essential themes. While the fields in the lower right quadrant are emerging or quasi-isolated topics, their evolution will depend on discoveries that are made in the short term. According to the reviewed literature, it will depend on the investigations on the microorganisms isolated in different types of waste, as these microorganisms are being used as a substrate (fuel) to observe their potential to generate bioelectricity in MFCs, where electrolytic reduction plays an important role for the generation of ions and electrons [75,76].

Thus, microorganisms isolated from different types of waste are also being studied. These microorganisms are being used as a substrate (fuel) to observe their potential to generate bioelectricity in MFCs [75,76].

5. Conclusions

5.1. Research Conclusions

This study provided a comprehensive analysis of the characteristics of the literature on microbial fuel cells using bibliometric methods during the period from 1990 to 2022 (30 December 2022). Information was obtained from the Scopus database, and a total of 7055 articles published and indexed in Scopus were analyzed, of which 4599 articles were published from 2011 to 2020, with an exponential growth curve, and 74.97% of the total documents are research articles. Likewise, China is located in the first position, with 2773 published documents, followed by the United States with 1008 documents, but Logan B.E. of Pennsylvania State University (United States) was the one observed with the highest number of published documents (162) on the subject. Logan B.E. has a close collaboration with Wang X. and Liu Y. from Southeast University and Chongqing University located in Bangladesh and China, respectively. It was also observed that older papers have a higher number of citations but in recent years, a higher number of papers published with one citation has been noted. The journal with the highest number of published documents was Environmental Science and Technology, with a total of 578, with the article entitled "Microbial Fuel Cells: Methodology and Technology" with 4496 citations from the ACS publishing house; this document was published by Logan B.E. in 2006, whose research reviews all the processes of electricity generation in a microbial fuel cell. Finally, it was observed that the most used keywords in the different documents were microbial fuel cell, performance, and electricity generation with 4795, 856, and 536 occurrences, respectively.

5.2. Research Limitations

As can be seen, researchers are beginning to lean toward the use of nanostructured materials (because they increase electrical conductivity) in their different forms to modify the anode and cathode electrodes of microbial fuel cells, in order to improve power densities in a simple and low-cost way and be sustainable over time. The improvement of the anode electrode is one of the main limitations in the application of MFCs on a large scale due to its economic cost; whose commercial scaling has led to the use of different types of conventional materials in recent years in order to minimize costs; however, these materials have not been effective in generating the required electrical power. On the other hand, the design of the MFCs and the configuration of the electrodes are presented as another limitation: they influence the definition of the anodic surface for the formation of the bacterial

biofilm and for other required actions. A poor selection of the configuration or design of the anodic electrode will disturb the growth of the bacteria and impair the flow of electrons making it less efficient. In this sense, it is important to improve the durability of the anodic electrode, thus maintaining mechanical and chemical stability for long periods of work and minimizing costs.

5.3. Future Research Direction

For future work, research should be focused on the manufacturing of anode electrodes from natural biomass as a promising source, in order to obtain low-cost and high-quality electrodes. On the other hand, the catalysts used so far have been chemical. It is recommended to investigate the use of biocatalysts such as bacteria or yeasts; these microorganisms use carbon-rich sources for their metabolisms. Many organic wastes used as substrates in MFCs contain high concentrations of carbon and other components that would help the proliferation of these microorganisms.

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