Research Trends of Microbial Fuel Cells in 1990-2022

Subjects: Biochemistry & Molecular Biology

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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. 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.

microbial fuel cells biometric analysis research trend

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][7][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][12][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, with single- and dual-chamber microbial fuel cells being the most widely used [14][17][18][19].

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 intimately 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].

2. Microbial Fuel Cells

Figure 1a 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 1**b), its first publication in the year 1993 [30], 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, 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 [31][32][33].

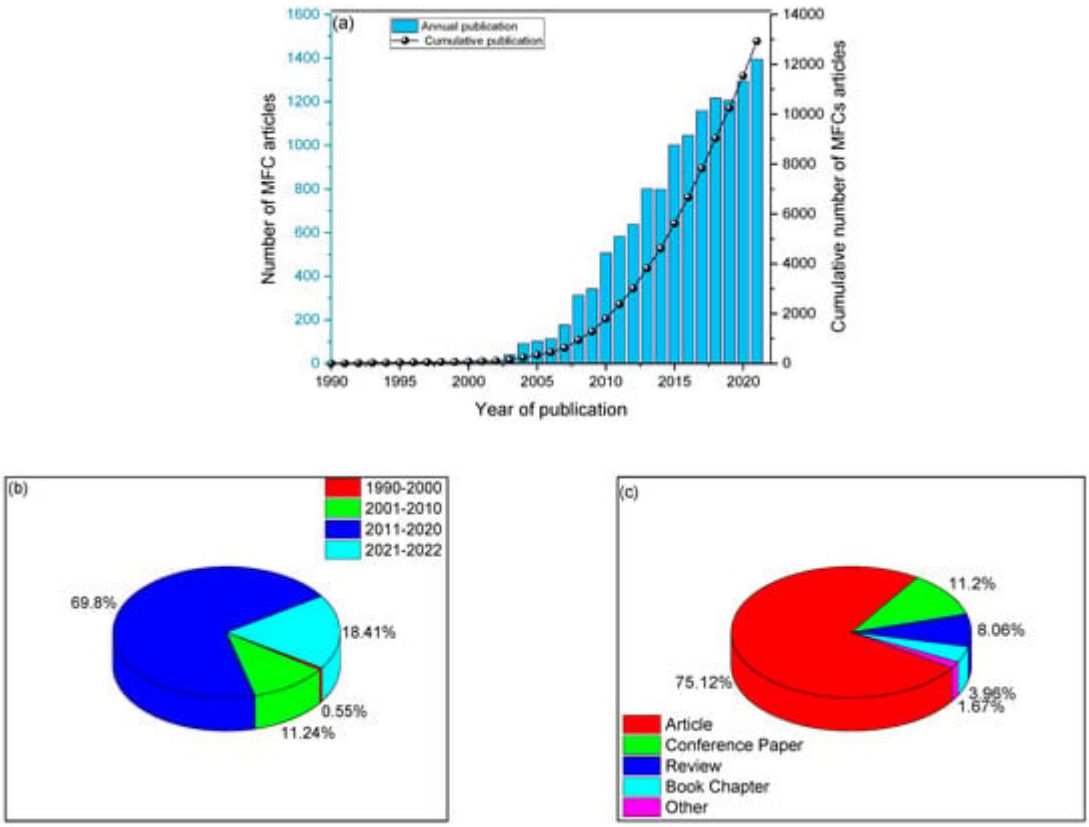

Figure 1. Graph of the (**a**) number of articles, (**b**) percentages of publications per 10 years, and (**c**) type of publication.

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) [34]. 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 1**c.

Table 1 was categorized using Crane's method [35], 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 [36] [37]. 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 [38][39].

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

Figure 2 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 3** 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 [40].

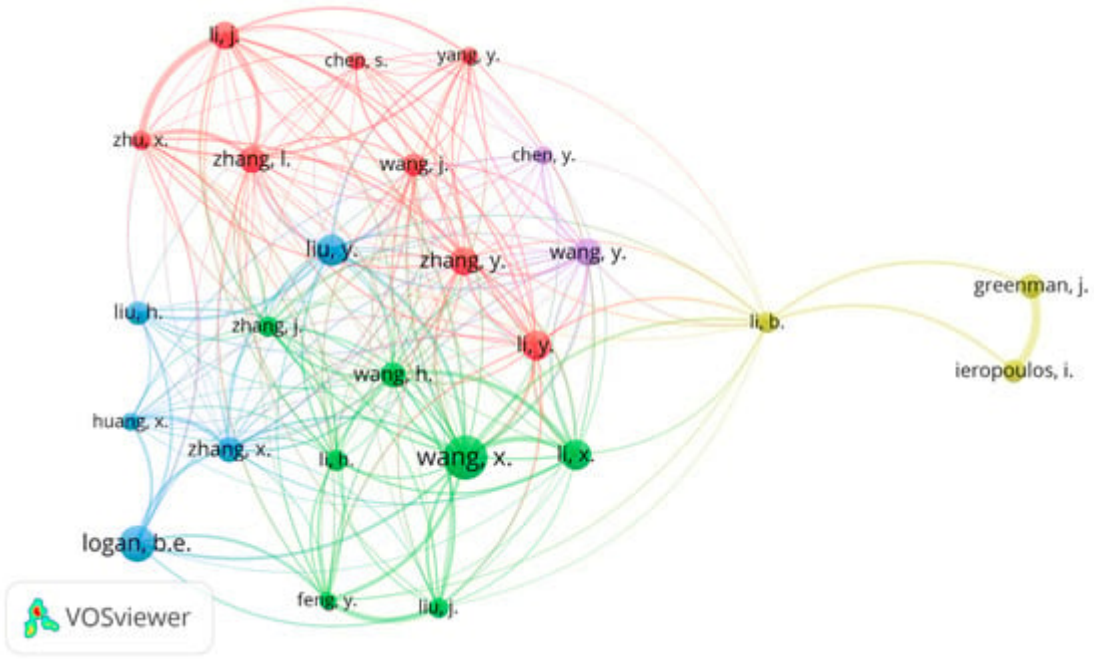

Figure 2. Leading researcher organizations in MFC research.

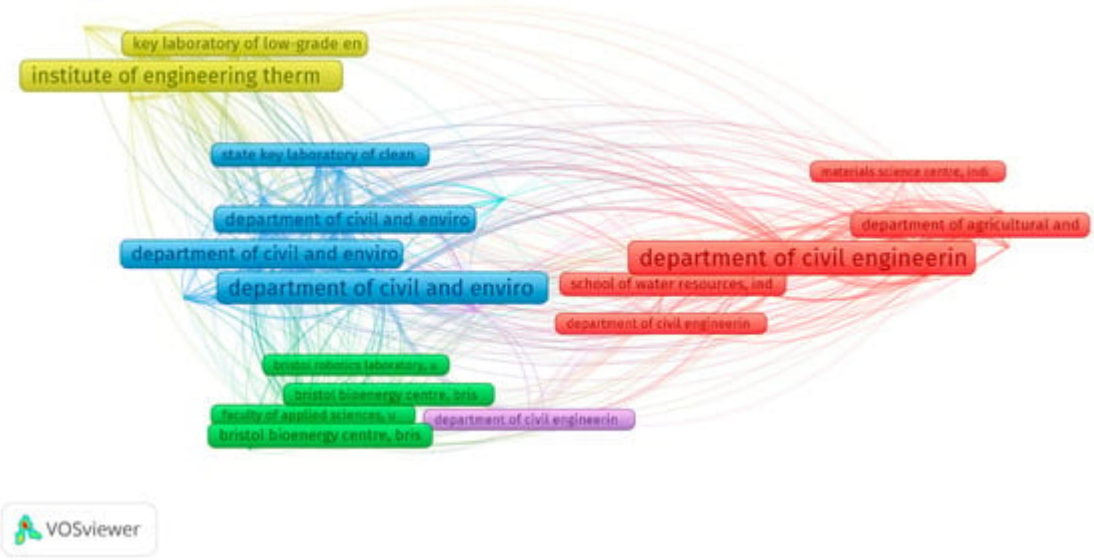

Figure 3. Leading organizations in MFC research.

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 [38]. 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 [39].

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 [41].

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 [37]. 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 [42].

Figure 4 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.

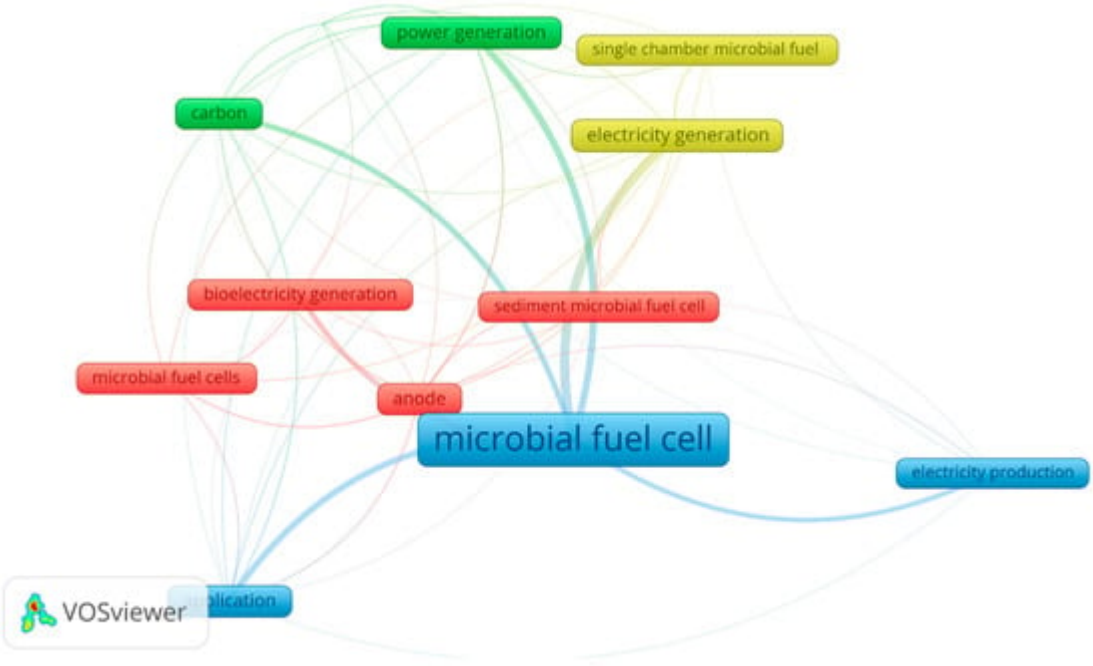

Figure 4. Thematic network of the main keywords used in microbial fuel cell research.

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 [40][43][44]. 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.

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 [45]. 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 [46]. 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.

References

1. Burda, Y.; Edwards, H.; Pathak, D.; Storkey, A.; Darrell, T.; Efros, A.A. Large-scale study of curiosity-driven learning. arXiv 2018, arXiv:1808.04355.
2. Cook, R.I.; Woods, D.D. Operating at the sharp end: The complexity of human error. In Human Error in Medicine; CRC Press: Boca Raton, FL, USA, 2018; pp. 255–310.
3. Chen, T.; Zhang, S.; Yuan, Z. Adoption of solid organic waste composting products: A critical review. J. Clean. Prod. 2020, 272, 122712.
4. Sivasankar, V.; Mylsamy, P.; Omine, K. (Eds.) Microbial Fuel Cell Technology for Bioelectricity; Springer International Publishing: Cham, Switzerland, 2018.
5. Munoz-Cupa, C.; Hu, Y.; Xu, C.; Bassi, A. An overview of microbial fuel cell usage in wastewater treatment, resource recovery and energy production. Sci. Total. Environ. 2020, 754, 142429.
6. Sazali, N.; Wan Salleh, W.N.; Jamaludin, A.S.; Mhd Razali, M.N. New Perspectives on Fuel Cell Technology: A Brief Review. Membranes 2020, 10, 99.
7. Wang, Y.; Seo, B.; Wang, B.; Zamel, N.; Jiao, K.; Adroher, X.C. Fundamentals, materials, and machine learning of polymer electrolyte membrane fuel cell technology. Energy AI 2020, 1, 100014.
8. Xu, H.; Shang, H.; Wang, C.; Du, Y. Recent Progress of Ultrathin 2D Pd-Based Nanomaterials for Fuel Cell Electrocatalysis. Small 2021, 17, e2005092.
9. Zakaria, Z.; Awang Mat, Z.; Abu Hassan, S.H.; Kar, Y.B. A review of solid oxide fuel cell component fabrication methods toward lowering temperature. Int. J. Energy Res. 2019, 44, 594–611.
10. Do, M.H.; Ngo, H.H.; Guo, W.; Chang, S.W.; Nguyen, D.D.; Liu, Y.; Varjani, S.; Kumar, M. Microbial fuel cell-based biosensor for online monitoring wastewater quality: A critical review. Sci. Total. Environ. 2019, 712, 135612.
11. Li, M.; Zhou, M.; Tian, X.; Tan, C.; McDaniel, C.T.; Hassett, D.J.; Gu, T. Microbial fuel cell (MFC) power performance improvement through enhanced microbial electrogenicity. Biotechnol. Adv. 2018, 36, 1316–1327.
12. Zhang, Y.; Liu, M.; Zhou, M.; Yang, H.; Liang, L.; Gu, T. Microbial fuel cell hybrid systems for wastewater treatment and bioenergy production: Synergistic effects, mechanisms and challenges. Renew. Sustain. Energy Rev. 2018, 103, 13–29.
13. Wu, Q.; Jiao, S.; Ma, M.; Peng, S. Microbial fuel cell system: A promising technology for pollutant removal and environmental remediation. Environ. Sci. Pollut. Res. 2020, 27, 6749–6764.

14. Yuan, W.; Lu, S.; Xiang, Y. Pt-based nanoparticles on non-covalent functionalized carbon nanotubes as effective electro-catalysts for proton exchange membrane fuel cells. RSC Adv. 2014, 4, 46265–46284.
15. Yuan, W.; Cheng, Y.; Shen, P.K.; Li, C.M. Significance of wall number on the carbon nanotube support-promoted electrocatalytic activity of Pt NPs towards methanol/formic acid oxidation reactions in direct alcohol fuel cells. J. Mater. Chem. A 2015, 3, 1961–1971.
16. Gupta, S.K.; Rachna; Singh, B.; Mungray, A.K.; Bharti, R.; Nema, A.K.; Pant, K.; Mulla, S.I. Bioelectrochemical technologies for removal of xenobiotics from wastewater. Sustain. Energy Technol. Assess. 2021, 49, 101652.
17. Guan, C.-Y.; Tseng, Y.-H.; Tsang, D.C.; Hu, A.; Yu, C.-P. Wetland plant microbial fuel cells for remediation of hexavalent chromium contaminated soils and electricity production. J. Hazard. Mater. 2019, 365, 137–145.
18. Sharma, S.C.D.; Li, J.; Hu, A.; Chang, C.-C.; Yu, C.-P. Integration of pre-colonized and mediator immobilized mixed culture for the improvement of electricity production of microbial fuel cells. Environ. Technol. Innov. 2021, 22, 101514.
19. Cao, Y.; Mu, H.; Liu, W.; Zhang, R.; Guo, J.; Xian, M.; Liu, H. Electricigens in the anode of microbial fuel cells: Pure cultures versus mixed communities. Microb. Cell Factories 2019, 18, 39.
20. Moral-Muñoz, J.A.; Herrera-Viedma, E.; Santisteban-Espejo, A.; Cobo, M.J. Software tools for conducting bibliometric analysis in science: An up-to-date review. Prof. Inf. 2020, 29, e290103.
21. Guo, Y.; Hao, Z.; Zhao, S.; Gong, J.; Yang, F. Artificial Intelligence in Health Care: Bibliometric Analysis. J. Med. Internet Res. 2020, 22, e18228.
22. Kumar, S.; Pandey, N.; Lim, W.M.; Chatterjee, A.N.; Pandey, N. What do we know about transfer pricing? Insights from bibliometric analysis. J. Bus. Res. 2021, 134, 275–287.
23. Khanra, S.; Dhir, A.; Kaur, P.; Mäntymäki, M. Bibliometric analysis and literature review of ecotourism: Toward sustainable development. Tour. Manag. Perspect. 2020, 37, 100777.
24. Pranckutė, R. Web of Science (WoS) and Scopus: The Titans of Bibliographic Information in Today’s Academic World. Publications 2021, 9, 12.
25. Vera-Baceta, M.-A.; Thelwall, M.; Kousha, K. Web of Science and Scopus language coverage. Scientometrics 2019, 121, 1803–1813.
26. Khurana, P.; Sharma, K. Impact of h-index on authors ranking: A comparative analysis of Scopus and WoS. arXiv 2021, arXiv:2102.06964.
27. Budimir, G.; Rahimeh, S.; Tamimi, S.; Južnič, P. Comparison of self-citation patterns in WoS and Scopus databases based on national scientific production in Slovenia (1996–2020). Scientometrics 2021, 126, 2249–2267.

28. Ejsmont, K.; Gladysz, B.; Corti, D.; Castaño, F.; Mohammed, W.M.; Martinez Lastra, J.L. Towards ‘Lean Industry 4.0’—Current trends and future perspectives. Cogent Bus. Manag. 2020, 7, 1781995.
29. Ni, J.; Steinberger-Wilckens, R.; Jiang, S.; Xu, M.; Wang, Q. Novel study on microbial fuel cells via a comprehensive bibliometric and dynamic approach. Rev. Environ. Heal. 2021, 37, 13–27.
30. Shah, S.H.H.; Lei, S.; Ali, M.; Doronin, D.; Hussain, S.T. Prosumption: Bibliometric analysis using HistCite and VOSviewer. Kybernetes 2019, 49, 1020–1045.
31. Tanaka, K.; Vega, C.A.; Tamamushi, R. Thionine and ferric chelate compounds as coupled mediators in microbial fuel cells. J. Electroanal. Chem. Interfacial Electrochem. 1983, 156, 289–297.
32. Chakraborty, I.; Sathe, S.; Dubey, B.; Ghangrekar, M. Waste-derived biochar: Applications and future perspective in microbial fuel cells. Bioresour. Technol. 2020, 312, 123587.
33. Grattieri, M.; Minteer, S.D. Microbial fuel cells in saline and hypersaline environments: Advancements, challenges and future perspectives. Bioelectrochemistry 2018, 120, 127–137.
34. Khudzari, J.M.; Kurian, J.; Tartakovsky, B.; Raghavan, G. Bibliometric analysis of global research trends on microbial fuel cells using Scopus database. Biochem. Eng. J. 2018, 136, 51–60.
35. Wang, G.; Wang, C.; Guo, Z.; Dai, L.; Wu, Y.; Liu, H.; Li, Y.; Chen, H.; Zhang, Y.; Zhao, Y.; et al. Integrating Maxent model and landscape ecology theory for studying spatiotemporal dynamics of habitat: Suggestions for conservation of endangered Red-crowned crane. Ecol. Indic. 2020, 116, 106472.
36. Naseer, M.N.; Zaidi, A.A.; Khan, H.; Kumar, S.; bin Owais, M.T.; Jaafar, J.; Suhaimin, N.S.; Wahab, Y.A.; Dutta, K.; Asif, M.; et al. Mapping the field of microbial fuel cell: A quantitative literature review (1970–2020). Energy Rep. 2021, 7, 4126–4138.
37. Santoro, C.; Arbizzani, C.; Erable, B.; Ieropoulos, I. Microbial fuel cells: From fundamentals to applications. A review. J. Power Sources 2017, 356, 225–244.
38. Li, W.-W.; Yu, H.-Q.; He, Z. Towards sustainable wastewater treatment by using microbial fuel cells-centered technologies. Energy Environ. Sci. 2013, 7, 911–924.
39. Logan, B.E.; Hamelers, B.; Rozendal, R.; Schröder, U.; Keller, J.; Freguia, S.; Aelterman, P.; Verstraete, W.; Rabaey, K. Microbial Fuel Cells: Methodology and Technology. Environ. Sci. Technol. 2006, 40, 5181–5192.
40. Rossi, R.; Hur, A.Y.; Page, M.A.; Thomas, A.O.; Butkiewicz, J.J.; Jones, D.W.; Baek, G.; Saikaly, P.E.; Cropek, D.M.; Logan, B.E. Pilot scale microbial fuel cells using air cathodes for producing electricity while treating wastewater. Water Res. 2022, 215, 118208.

41. Rossi, R.; Evans, P.J.; Logan, B.E. Impact of flow recirculation and anode dimensions on performance of a large scale mi-crobial fuel cell. J. Power Sources 2019, 412, 294–300.
42. Ben Liew, K.; Daud, W.R.W.; Ghasemi, M.; Leong, J.X.; Lim, S.S.; Ismail, M. Non-Pt catalyst as oxygen reduction reaction in microbial fuel cells: A review. Int. J. Hydrogen Energy 2014, 39, 4870–4883.
43. Segundo, R.-F.; Magaly, D.L.C.-N.; Benites, S.M.; Daniel, D.-N.; Angelats-Silva, L.; Díaz, F.; Luis, C.-C.; Fernanda, S.-P. Increase in Electrical Parameters Using Sucrose in Tomato Waste. Fermentation 2022, 8, 335.
44. Ghosh, P.; Das, S.P. Microbial Fuel Cells (MFC) and Its Prospects on Bioelectricity Potential. In Status and Future Challenges for Non-conventional Energy Sources; Springer: Singapore, 2022; Volume 2, pp. 157–176.
45. Yang, W.; Wang, X.; Rossi, R.; Logan, B.E. Low-cost Fe–N–C catalyst derived from Fe (III)-chitosan hydrogel to enhance power production in microbial fuel cells. Chem. Eng. J. 2019, 380, 122522.
46. Dhillon, S.K.; Kundu, P.P. Polyaniline interweaved iron embedded in urea–formaldehyde resin-based carbon as a cost-effective catalyst for power generation in microbial fuel cell. Chem. Eng. J. 2021, 431, 133341.