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Analisis Scientometri Penelitian Biofilm dalam Sel Bahan Bakar Mikroba: Wawasan tentang Area Penelitian Utama dan Tren yang Sedang Berkembang

Scientometric Analysis of Biofilm Research in Microbial Fuel Cells: Insights into Key Research Areas and Emerging Trends

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ABSTRAK: Sel bahan bakar mikroba (MFC) adalah sumber energi terbarukan yang menjanjikan dan metode yang efektif untuk mengolah limbah organik. Literatur tentang pengembangan biofilm di MFC dipetakan menggunakan teknik pemetaan scientometri. Studi ini menganalisis 16898 sumber literatur, termasuk 12571 artikel penelitian, 2554 makalah review, 465 makalah konferensi, 1189 buku dan bab buku, serta 119 publikasi lainnya. Analisis jaringan co-citation dan co-authorship mengungkapkan kelompok penelitian dan subtopik paling signifikan terkait dengan pengembangan biofilm. Karakterisasi dan interaksi dalam pembentukan biofilm, optimalisasi bahan elektroda dan geometri untuk pertumbuhan biofilm, serta pengembangan teknologi pemantauan dan pengendalian akan dipelajari dan dianalisis. Pengetahuan dari penelitian biofilm telah membuka jalan bagi pendekatan baru seperti rekayasa biofilm, elektroda yang dimodifikasi biofilm, dan teknik analisis canggih, memperluas potensi penerapannya di dunia nyata. Integrasi teknologi MFC ke dalam pembangunan berkelanjutan dan bioekonomi mengungkapkan potensi biofilm sebagai komponen sistem produksi energi yang ramah lingkungan dan ekonomis.
Kata Kunci: penulisan bersama; kejadian bersama; kolaborasi; bioenergi; tren penelitian

ABSTRACT: A scientometric investigation mapped the literature on biofilm development in Microbial Fuel Cells (MFCs), revealing promising renewable energy prospects and waste treatment solutions. The analysis encompassed 16898 sources, predominantly research articles (12571), along with review papers, conference papers, books, and other publications. Network analysis highlighted key research clusters and subtopics, including biofilm characterization, electrode optimization, and monitoring/control technologies. Insights from biofilm research have led to innovative approaches like biofilm engineering and advanced analytical techniques, enhancing real-world applications. Integration of MFCs into sustainable development underscores biofilms' potential as eco-friendly and economically viable components of energy production systems.
Keywords: bioenergy; co-authorships; collaboration; co-occurrences; research trends

1. Introduction

Microbial Fuel Cell (MFC) is an innovative technology that has gained considerable attention in the field of environmental engineering over the past few decades. It is a bio-electrochemical system that utilizes microorganisms to convert chemical energy into electrical energy through a process called microbial electrogenesis (Rahimnejad et al., 2015). MFCs have the potential to generate renewable energy from a wide range of organic wastes, such as wastewater, sludge, and agricultural by-products, while also treating these wastes (Santoro et al., 2017; Jaya et al., 2022). There are some advantages of MFCs. MFCs offer a unique opportunity to generate renewable energy from various

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organic wastes (Palanisamy et al., 2019). Unlike other renewable energy sources like solar and wind, MFCs require little maintenance (Winfield et al., 2013). The system can operate continuously without much human intervention (Olias & Di Lorenzo, 2021). MFCs can be highly efficient in converting organic matter into electricity (Gude, 2016). MFC technology can be scaled to meet the specific energy needs of a community or even a large-scale industrial operation (Ge et al., 2015). The modular design of MFCs makes it possible to stack multiple units to increase energy production (Kim et al., 2015). MFC technology can be used to treat wastewater and other organic wastes, reducing their impact on the environment (Santoro et al., 2020).

By converting organic waste into electricity, MFCs can potentially reduce greenhouse gas emissions and lessen the reliance on fossil fuels. On the other hand, there are some disadvantages accompany the MFCs. MFCs are not yet capable of producing large amounts of power (Oliveira et al., 2013). The current power output of MFCs is limited, making them unsuitable for large-scale energy production. The cost of constructing an MFC system can be high, making it a less attractive option for some communities and industries (Boas et al., 2022). The lifespan of MFCs can be limited due to the degradation of electrodes and membranes (Wei et al., 2011; Rozendal et al., 2006). This means that the technology may not be a long-term solution for energy production (Zhang et al., 2011). The performance of MFCs can be affected by various factors such as temperature, pH, and microbial activity (Goswami & Mishra, 2018). This variability can make it difficult to optimize the energy output of MFC systems. While MFC technology can treat organic waste, it may not be as efficient as other treatment methods. MFCs may not remove all pollutants from wastewater, making it necessary to use additional treatment methods. MFC technology offers a promising solution for generating renewable energy while treating organic waste. While there are some disadvantages to this technology, such as high capital costs and limited power output, the benefits of MFCs outweigh these drawbacks. With continued research and development, MFCs have the potential to become an important source of renewable energy and a valuable tool for treating organic waste.

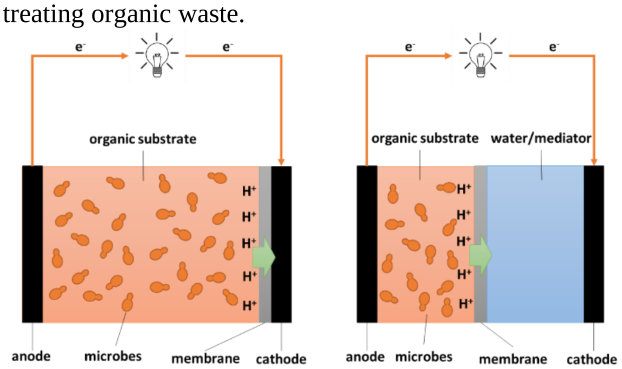

Figure 1. Schematic diagram of single (left) and double chambers (right) MFCs

The working principle of MFCs is based on the ability of microorganisms to transfer electrons to an electrode through a process called microbial electrogenesis. The mechanism of MFCs involves a complex interaction between microorganisms, organic matter, and electrodes. The core of an MFC consists of an anode and a cathode separated by a membrane. The anode is typically made of a conductive material, such as carbon fiber or graphite, and serves as the electron acceptor (Hindatu et al., 2017). The cathode, on the other hand, is made of a material that is a good electron donor, such as platinum, and serves as the electron donor (Lu & Li, 2012). The membrane that separates the anode and cathode is typically made of an ion exchange material that allows the transfer of ions but prevents the mixing of the two compartments (Rahimnejad et al., 2014). In the anode compartment, microorganisms are introduced into the system.

These microorganisms, typically bacteria, can be either free-floating or attached to the surface of the anode (Mashkour et al., 2017). As the microorganisms consume the organic matter, they release electrons that are transferred to the anode which is known as oxidation. The electrons produced by the oxidation of organic matter are then transported to the cathode through an external circuit, where they react with oxygen and protons to produce water, which is known as reduction. The schematic diagram of MFCs with single and double chambers can be shown in Figure 1. The overall reaction can be represented by the following equation (Logan, 2008):

$$\text{Organic matter} + O_2 \rightarrow CO_2 + H_2O + \text{energy}$$

The energy produced in the reaction is in the form of electricity and can be used to power external devices. The mechanism of electron transfer in MFCs is complex and involves a series of chemical reactions that occur between the microorganisms and the anode surface (He et al., 2017). The microorganisms produce extracellular electron transfer mediators that help transport electrons from the cell surface to the anode (Kumar et al., 2016). These mediators can either be secreted directly by the microorganisms or can be released by the degradation of extracellular polymeric substances. While produced protons move to cathode side by crossing the separator membrane (Nastiti & Hidayati, 2020; Hakim, 2018; Sitanggang, 2018; Sitanggang, 2017).

The electron transfer mechanism in MFCs is also influenced by the type of microorganisms present in the system. Some microorganisms are capable of directly transferring electrons to the anode, while others use mediators to facilitate electron transfer (Schröder, 2007). The type of microorganism present in the system can also impact the efficiency of the MFC. The working principle and mechanism of MFCs are still being studied, and there are several challenges that need to be addressed to optimize the performance of these systems. One of the primary challenges is the development of more efficient electron transfer mechanisms that can improve the energy output of MFCs (Nawaz et al., 2020). Another challenge is the optimization of the microbial community present in the system to enhance the efficiency of the conversion process (Srivastava et al., 2022). While there are still challenges to be addressed, MFCs have the potential to become an important source of

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renewable energy and a valuable tool for treating organic waste.

Biofilm plays a crucial role in the functioning of MFCs. Biofilm is a complex matrix of microorganisms that attach to a surface and secrete a matrix of extracellular polymeric substances (EPS) (Angelaalincy et al., 2018). These substances provide a protective layer for the microorganisms and facilitate electron transfer between them and the electrode surface in MFCs (Greenman et al., 2021). In MFCs, biofilm formation is critical for the efficient transfer of electrons from microorganisms to the electrode surface. The biofilm matrix provides a conductive pathway for electron transfer and enhances the overall performance of the system (Saratale et al., 2017). The EPS produced by the microorganisms can also serve as electron shuttles, facilitating the transfer of electrons from the microorganisms to the electrode surface (Naaz et al., 2023). Biofilm also plays a role in the selection of microorganisms that are well-suited for MFCs. Microorganisms that are able to form biofilm are more likely to thrive in MFCs and can outcompete other microorganisms that are unable to form a biofilm. This can lead to the development of a stable and efficient microbial community that is capable of producing electricity over extended periods (Prathiba et al., 2022).

The formation of biofilm in MFCs is influenced by several factors, including the nature of the electrode surface, the type of microorganisms presents in the system, and the operating conditions of the MFC (Franks et al., 2010). The electrode surface plays a critical role in the formation of biofilm, as it serves as the attachment point for the microorganisms (Mei et al., 2017). The surface properties of the electrode, such as its roughness and hydrophobicity, can influence the attachment and growth of microorganisms. The type of microorganisms present in the system also influences the formation of biofilm. Some microorganisms are more capable of forming biofilm than others, and the composition of the microbial community can impact the structure and function of the biofilm.

The operating conditions of the MFC, such as temperature and pH, can also impact the formation and stability of the biofilm (Picioreanu et al., 2007). The formation of biofilm in MFCs is not without its challenges. One of the primary challenges is the growth of biofilm on the electrode surface, which can lead to reduced performance of the system (Xu et al., 2019). Biofilm that is too thick or too dense can limit the diffusion of oxygen or nutrients, which can reduce the activity of the microorganisms and the overall power output of the MFC. As biofilm grows and thickens, it can block the pores of the electrode, reducing the availability of the electrode surface for microbial attachment and electron transfer. This can result in a decrease in the power output of the MFC and reduced overall efficiency. Biofilm growth on the cathode can lead to clogging of the electrode surface, reducing the ability of the microorganisms to transfer electrons to the electrode (Brunschweiger et al., 2020). This can lead to a decrease in the efficiency of the MFC. Biofouling occurs when the biofilm becomes contaminated with other microorganisms, such as bacteria and fungi, which can compete for nutrients and resources with the microorganisms that are actively producing electricity in the MFC. Overall, biofilm plays a critical role in the functioning of MFCs. In addition to clogging and biofouling, the development of biofilm in MFCs can also lead to the accumulation of toxic compounds. The formation of a stable and efficient biofilm is essential for the efficient transfer of electrons from microorganisms to the electrode surface. While there are challenges associated with biofilm growth, the development of strategies to optimize biofilm formation and control its growth on the electrode surface could lead to significant improvements in the performance of MFCs. Biofilm can be difficult to remove, and harsh cleaning methods can damage the electrode surface or remove essential components of the biofilm. Moreover, frequent cleaning can disrupt the formation of a stable and efficient biofilm, leading to reduced power output and decreased overall efficiency (Martinez Ostormujof et al., 2023). Strategies to mitigate these issues and optimize biofilm formation are essential for the development of efficient and sustainable MFCs.

Biofilm formation is a crucial part of the MFC process, and knowing its mechanism is key to understanding MFC performance. MFC biofilm production comprises numerous phases, including initial attachment, growth and maturation, and detachment (Read et al., 2010). Microorganisms attach to the anode surface at the first attachment stage and begin to manufacture extracellular polymeric substances (EPS), which form a matrix for biofilm development (Zhuang et al., 2022). EPS acts as a platform for communication and nutrition exchange between cells in the biofilm, aiding their survival and proliferation. The cells begin to proliferate as the biofilm grows, and the EPS matrix continues to expand, resulting in a thicker biofilm (Yao et al., 2022). Proteins, carbohydrates, and nucleic acids make up the EPS matrix, which aids in the creation of a cohesive and resilient biofilm structure (Rana & Upadhyay, 2020). Cells near the biofilm's base detach off the anode surface and are transported away by the flowing liquid during the detachment stage. Cell detachment may occur owing to a variety of reasons, including shear pressures, changes in environmental conditions, and cell death (Douville et al., 2011). The biofilm generation mechanism in MFCs is a complicated process involving electrochemical reactions and microbial interactions. The metabolic activity of the biofilm rises as it expands, resulting to an increase in electron transfer rates and power output (Jiménez Otero et al., 2021). Microbial interactions in the biofilm may potentially have an impact on biofilm production and MFC performance.

The development of biofilm in MFCs has been the subject of extensive research in recent years. To gain a comprehensive understanding of the research trends and patterns in this area, a scientometric approach was used to map the literature on biofilm development in MFCs. The study analyzed a large corpus of research articles published, using various bibliometric indicators and network analysis techniques. The analysis will also identify several key research topics and themes related to biofilm development in MFCs, such as the role of different microbial species in biofilm formation, the impact of operating conditions on biofilm development, and strategies for optimizing biofilm formation and performance (Logan, 2009). Furthermore, the study will identify the most influential authors, institutions, and countries in the field of biofilm development in MFCs. The most productive countries in this area, with a high level of collaboration among researchers from different countries and institutions also would be analyzed.

The study also highlighted the leading authors and institutions that have made significant contributions to the field. The network analysis of co-citation and co-authorship revealed the most significant research clusters and subtopics related to biofilm development in MFCs. The characterization of microbial communities and their interactions in biofilm formation, the optimization of electrode materials and geometries for biofilm development, and the development of new technologies for biofilm monitoring and control will be studied and analyzed. The scientometric mapping of biofilm development in MFCs provides a comprehensive overview of the research trends and patterns in this area, highlighting the most influential authors, institutions, and countries, as well as the key research topics and themes (Rojas-Flores et al., 2023; Naseer et al., 2021). The findings of the study can be used to guide future research efforts, identify research gaps and challenges, and inform policy decisions related to the development and application of MFC technology.

2. Data source and analyzing method

2.1. Data sources

This article evaluates the development of biofilm formation in microbial fuel cells (MFCs) using bibliometrics.

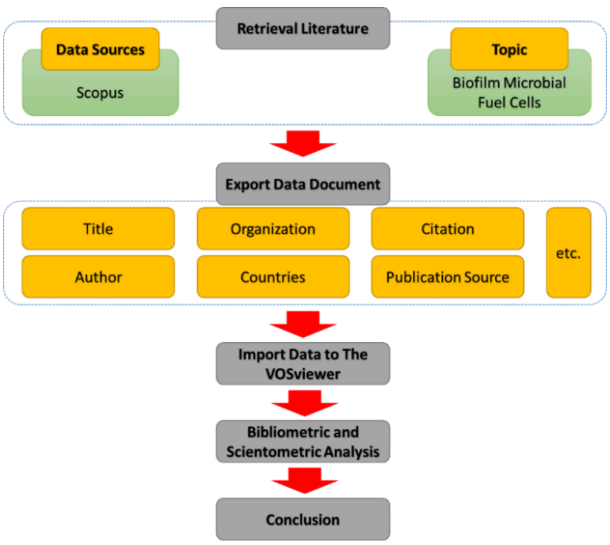

Figure 2. The schematic research processes

As shown in Figure 2, a statistical and visual analysis of the relevant literature published in recent years was accomplished. The Scopus core collection database was searched for field-related literature, and the results were exported to a .csv file (Christwardana & Khaerudini, 2022). For bibliometric analysis, the file was subsequently imported into visualization software (VOSviewer) (Van Eck & Waltman, 2010). Based on this procedure, the research produced analytical findings and conclusions.

Using the topic search method with the keywords "biofilm" and "Microbial Fuel Cells" with a cutoff date of June 30, 2023, data for this research were retrieved from the Scopus database. There were identified a total of 16898 literature sources, comprising 12571 research articles, 2554 review papers, 465 conference papers, 1189 books and book chapter, and 119 other publications form. The primary Scopus subject areas for the search were environmental science, chemical engineering, chemistry, and energy as mapped in Figure 3. The information on the literature, including author, publication date, year, citation frequency, etc., was exported in text document format for bibliometric analysis.

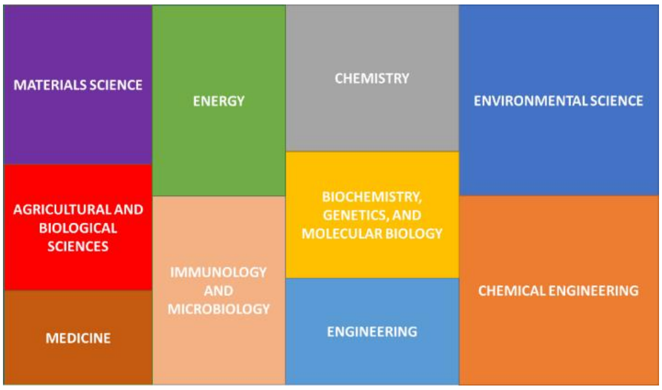

Figure 3. Top 10 subject areas related to biofilm research in microbial fuel cells

2.2. Analyzing Method

To understand the literatures that were found, the VOSviewer was utilized. The VOSviewer software was created at Leiden University's Research Center of Science and Technology in the Netherlands (Van Eck & L. Waltman, 2011; Van Eck & L. Waltman, 2013). The term "VOS" refers to visualization of similarities.

By the use of co-occurrence data, VOSviewer is able to visualize relationships between authors and journals, as well as between keywords and other topics (Chen et al., 2023). Using the correlation strength as a metric, VOSviewer determines how similar each pair of items in the co-occurrence data are to one another by constructing a similarity algorithm matrix. These efforts resulted in the creation of knowledge maps organized by countries, journals, keywords, and other criteria. To help researchers better comprehend the research development and hotspots in

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this discipline, a visual study of the publishing condition, research hotspots, and development trends was conducted.

3. Results and Discussion

3.1. Analysis of Annual Publication

Biofilms pertaining to microbial fuel cells (MFCs) have yielded a total of 16898 papers as of the 30th of June, 2023. In 1994, the first articles in this discipline were published, followed by a surge in 1997 and 1999. However, biofilm research on MFCs ceased until 2003, when it resumed. From 2003 to 2013, the quantity of annual papers increased progressively. During this time period, the study of biofilms on MFCs was still in its infancy, and researchers were investigating various facets of MFCs. In 2014, studies regarding biofilms on MFCs increased, albeit not significantly. During that year, MFC's research may have concentrated significantly on its application for wastewater treatment. However, from 2015 to 2018, the number of papers on biofilms on MFCs increased dramatically.

In 2019, the increase was not as pronounced. This increase in research was influenced by the 2016 implementation of the Paris Agreement, which led to a worldwide emphasis on renewable energy and clean technology, including hydrogen fuel cells (Bose et al., 2020). Due to rising environmental consciousness, the world's energy system has shifted from nonrenewable to renewable sources over the past two decades (Van Zalk & Behrens, 2018). Hydrogen energy, which is renowned for its high energy density and lack of pollution, has garnered significant interest from numerous nations (Rezaei-Shouroki et al., 2017). This focus may have contributed to the moderate increase in research on biofilms on MFCs in 2014, as MFCs' potential for hydrogen energy production was being investigated. From 2020 to 2023, biofilm research on MFCs is anticipated to increase significantly. This increase is attributable to the increasing prominence of hydrogen energy in the context of carbon neutrality objectives (Thulasinathan et al., 2021).

Researchers are concentrating on developing biofilms on MFCs for wastewater degradation and increasing bio-electricity production through the concept of waste-to-energy (Leininger et al., 2021; Sunny e tal., 2020). As a result, there has been a significant influx of researchers into the field, especially in the area of biofilm development and their interactions, resulting in accelerated advances in MFC science and technology. In general, the historical trend of research on biofilms on MFCs demonstrates periods of expansion, influenced by environmental consciousness, renewable energy initiatives, and international policies (Kižys et al., 2023). These factors have significantly influenced the trajectory of research in this field and have led to significant advances in the understanding and application of MFCs.

The annual citation frequency for research on biofilm development in microbial fuel cells (MFCs) has exhibited a consistent upward trend, with the exception of a minor decline in 2003. Since 2017, however, both the number of annual publications and the frequency of citations have increased exponentially, indicating significant advancements in the discipline over the past two decades. This increase in citations demonstrates the expanding prominence and significance of biofilm research in MFCs. In addition, the use of MFCs in the effluent treatment and bioelectricity production industries is expanding rapidly (Gul et al., 2021). The advances in biofilm development have played a crucial role in making these applications possible. This demonstrates that biofilm research in MFCs is not only acquiring scientific significance, but is also contributing to the development of practical solutions for sustainable waste management and renewable energy production (Khandaker et al., 2021). The extraordinary increase in both citation frequency and publications is indicative of the scientific community's strong interest in biofilm development in MFCs, as well as the potential for further advancements in the field. Researchers and practitioners are actively investigating novel approaches to improve biofilm performance and optimize MFC systems in an effort to fully exploit the technology's potential to resolve environmental challenges and meet energy needs (Tran et al., 2022; Kamel et al., 2020).

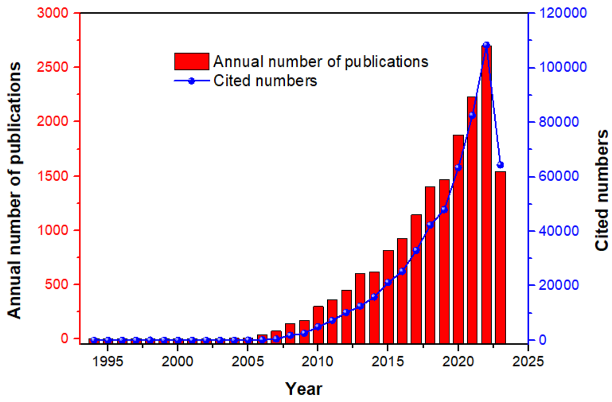

Figure 4. Annual trends in the number of publications and citations in the field of biofilm research in MFCs

3.2. Bibliometric analysis on countries

The map and analysis provide a global overview of the distribution of research efforts in the field of biofilms on MFCs, highlighting significant countries and their contributions over time. These results illustrate the global significance of biofilm research in the context of sustainable energy development and environmental preservation. This investigation compiled literature from 150 countries and regions. Figure 5 is a comprehensive map depicting the countries of the primary author that have contributed at least five articles, comprising 90 countries. The color-coded image illustrates the research timeline, with blue representing prior years and yellow representing current or more recent research.

The magnitude of each node corresponds to the number of publications produced, while the connections between nodes represent cooperative relationships between countries or regions. Several countries have made significant contributions to the study of biofilm formation in microbial fuel cells (MFCs), as depicted in Figure 5. China's robust scientific community and emphasis on renewable energy solutions have propelled it to the forefront of the field. The United States, which is renowned for its research and innovation capabilities, has also contributed significantly. India, a swiftly developing nation with a growing emphasis on renewable energy, has demonstrated a growing interest in MFC biofilm research. South Korea and Japan have engaged in a technological competition in East Asia, specifically in the field of MFCs. Beginning in 2003, South Korean researchers were among the first to investigate biofilm development and MFC technology. In addition, numerous South Korean researchers who pursued additional education or careers in the United States have substantially advanced biofilm research for MFCs in their home country. Malaysia, having relocated to Southeast Asia, has been at the vanguard of biofilm research in MFCs.

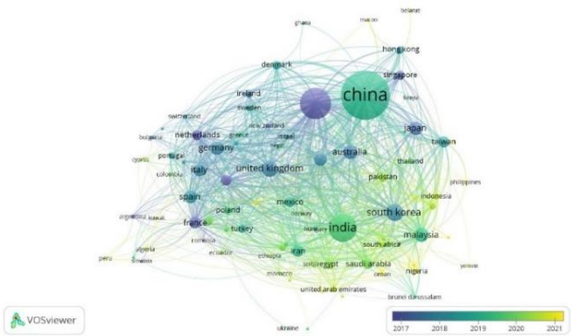

Figure 5. Co-occurrence maps of countries and regions with threshold 5 publications

Its equatorial location, which is characterized by abundant biodiversity and a variety of microorganisms, offers enormous potential for the use of biocatalysts in MFCs. Following Malaysia's lead, Indonesia's participation in biofilm research on MFCs has increased, capitalizing on its own biodiversity and expanding research infrastructure. In addition, it is noteworthy that countries such as Nigeria, Oman, the United Arab Emirates, and Pakistan have become increasingly interested in biofilm research on MFCs. Motivated by their own energy and sustainability objectives, these nations are actively investigating the application of MFCs and biofilm technologies.

Table 1 shows the frequency of citations and the number of publications on biofilms in MFCs in the top 10 countries. These 10 countries account for a significant 93% of all published articles, while the remaining nations contribute the remaining 7%. China, the United States, and India are the leaders in terms of publication volume, accounting for over 69% of all articles. Notable is the fact that the top 10 list is dominated by developed nations, with China and the United States holding significant positions. China, the United States, and India have the greatest total citation frequencies in the field of biofilms in MFCs, indicating their considerable impact on research. Moreover, South Korea, Australia, and the United Kingdom have the greatest average frequency of citations, indicating that their publications have a substantial impact. In addition, Germany and Malaysia stand out due to their high number of published articles, which demonstrates their active contributions to the field and their ability to generate citations per article.

Germany is ranked ninth in terms of the number of published research papers, but it ranks third in terms of the number of citations received by each paper. This indicates that German-published articles are of superior quality and influence. China rates high in both the number of published articles and total citations, but its average frequency of citations is relatively low at 26. Consequently, China ranks ninth among the top 10 countries in terms of the number of published articles, indicating a need to enhance the academic influence and quality of Chinese papers in the field.

Table 1. Top 10 countries in the number of publications

Country	Document	Citation	Citation per Document	Total Link Strength
China	6786	174439	26	2682
United States	2701	165415	61	1920
India	2228	53397	24	1531
South Korea	861	40990	48	1004
United Kingdom	739	32443	44	898
Australia	583	38239	66	861
Malaysia	561	17351	31	761
Germany	535	26212	49	549
Saudi Arabia	270	7357	27	540
Spain	499	17243	35	503

3.3. Bibliometric analysis on authors

The analysis of highly influential papers in the field of biofilm research in MFCs provides valuable insights into the research trends and directions. Figure 6 illustrates the primary authors who have made significant contributions, each having published at least five articles in this field. These authors formed 21 distinct clusters, with many of them having more than two core scholars. Notably, some of these scholars are among the top 1% of researchers, possessing extensive expertise in MFCs. One such eminent figure is Bruce E. Logan, a Professor of Environmental Engineering at The Pennsylvania State University. He is widely recognized for his ground-breaking work on MFCs, which are innovative devices that utilize bacteria's metabolic activity to convert organic matter into electrical energy (Logan et al., 2006). With a long-standing affiliation with the university's Department of Civil and Environmental Engineering, Logan's expertise and research contributions have significantly advanced the field. Another distinguished researcher is Derek R. Lovley, currently serving as a Distinguished Professor at the University of Massachusetts

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Amherst. Lovley's research revolves around the physiology and ecology of novel anaerobic microorganisms, focusing on their role in biogeochemical cycling and waste-to-electricity conversion (Lovley, 2008). His expertise in the field has led to valuable insights and advancements in understanding electroactive microorganisms. Moreover, Ioannis Ieropoulos is currently a Professor of Bioenergy and Self-Sustainable Systems at the Bristol BioEnergy Centre, University of the West of England (UWE Bristol) in the United Kingdom. He has been actively involved in research related to MFCs and bioenergy since the early 2000s. His work primarily focuses on harnessing the power of microorganisms to generate electricity and treat wastewater (Santoro et al., 2017). Ieropoulos has conducted extensive research on the design, optimization, and scale-up of MFCs, aiming to make them more efficient and commercially viable. Additionally,

Mostafa Rahimnejad, a Professor at Babol Noshirvani University of Technology (BNUT), has accumulated extensive experience in various areas of biotechnology, nanotechnology, fuel cells, biosensors, fermentation, and chemical engineering (Rahimnejad et al., 2014). These researchers, along with other significant contributors, form an influential cohort of scholars shaping the development of MFCs research. Their expertise, academic influence, and numerous publications establish them as key figures in the advancement of this field. Further investigation into their specific research contributions would provide a more comprehensive understanding of the ongoing progress in MFC research. Apart from these three, there are many more potential cores researchers in the field of MFCs biofilms.

Figure 6. Core authors with threshold 5 publications

Figure 7 contains a list of authors along with the number of documents they have produced related to biofilm research of MFCs, and the number of citations per document. Notably, D.R. Lovley and M. Rahimnejad stand out with 11 documents each, but their citation rates are vastly different, with Lovley's work accumulating an astounding 404 citations per document compared to Rahimnejad's 29. This highlights the significance and recognition that Lovley's research appears to have within the scientific community. Each of S. Bagchi, A.P. Barole, L. Liu, and I. Angelidaki has created seven documents. While Bagchi's work is cited 11 times per document, Barole's work is cited eight times per document, a marginally lower rate. In contrast, Liu's research is cited an average of 17 times per document, and Angelidaki's contributions are cited an astounding 113 times per document, making her one of the most frequently cited authors in this group. P. Sharma, S. Dharmalingam, O. Konur, and W.S. Verwoerd have 6 documents each. The citation rates for Sharma and Dharmalingam's works are respectable, with nine and twelve citations per document, respectively.

The significance of Konur's contributions is demonstrated by the above-average citation rate of 32 per document attributable to his research. The 14 citations per document indicate that W.S. Verwoerd's work is gaining significant attention. The Figure S2 highlights the varying degrees to which authors' research impacts the scientific community. The number of citations garnered can be considerably impacted by aspects such as research quality, field of study, and relevance. Figure S2 also highpoint the significance of conducting high-quality, influential research that advances knowledge and influences future scientific investigations. Contributing to the advancement of their respective disciplines, the authors with the highest rates of citation likely have insights that resonate with and influence their peers.

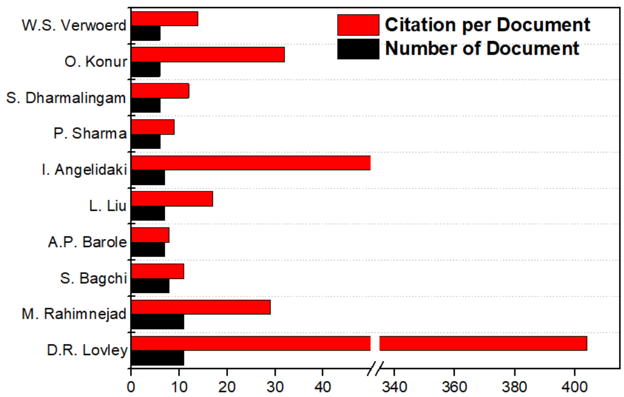

Figure 7. The top 10 core researchers with threshold 5 publications in number of documents

Biofilm MFCs have emerged as a prospective research area in the field of bioelectrochemical systems, and the authors shown in the Figure 8 have made substantial contributions to this field. One notable researcher, D.R. Lovley, has amassed an impressive number of citations for his work in biofilm MFCs: 4,442 citations. The average of 404 citations per document by Lovley demonstrates the significant impact of his research in this field. His findings most likely include biofilm formation, mechanisms of electron transfer, and performance optimization.

B.E. Logan is another influential scientist in the field of biofilm MFCs; his work has received 4264 citations at an impressive rate of 851 per document. Exploring novel electrode materials, reactor configurations, and system scalability, Logan's research may have focused on the development and application of MFCs including biofilm development (Sun et al., 2015; Rossi et al., 2015). His contributions have likely increased knowledge of biofilm MFCs and their potential for renewable energy production. I. Angelidaki and B.E. Rittmann, who have 790 and 787 citations, respectively, are also notable contributors (Zhang, I. Angelidaki, 2011; Kato Marcus et al., 2007). These researchers may have investigated the biofilm community dynamics, substrate utilization, and process optimization of MFCs. Their citation rates of 113 and 131 per document indicate that their research findings have had a significant impact and advanced the field significantly. According to their citation counts and citation rates, the remaining authors, including M. Rahimnejad, I. Ieropoulos, W. Li, T.K. Sajana, O. Konur, and L. Liu, have all made significant contributions to biofilm MFCs research (Mashkour et al., 2020; Ledezma et al., 2012; Zhang et al., 2008; Sajana et al., 2017; Lu et al., 2021; Konur, 2017). Their work probably involves biofilm characterization, bioelectrode design, and performance enhancement techniques, or in the biofilm development itself.

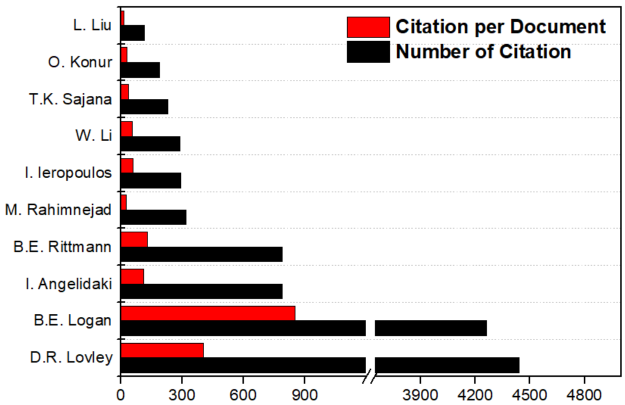

Figure 8. The top 10 core researchers with threshold 5 publications in number of citations

The numerous citations received by these researchers demonstrate the significance of biofilm MFCs as a field of study, emphasizing the significance and applicability of their findings. Their combined efforts have contributed to the comprehension, development, and potential applications of biofilm MFCs, paving the way for sustainable energy generation, effluent treatment, and bioremediation. As biofilm MFCs research continues to evolve, the knowledge and insights provided by these scientists will unquestionably influence the future of this fascinating field.

3.4. Bibliometric analysis on journals and highly cited papers

Table 2 lists many leading scientific publications in (Bio) electrochemistry, including Biofilm MFCs. These publications spread research results, develop knowledge, and shape scientific inquiry. Bioresource Technology is a notable journal with an impact factor of 11.4. The 1198 articles have gotten 61,474 citations. Bioresource Technology study receives an average of 51 citations per document, indicating scientific recognition. Science of the Total Environment, another famous environmental research journal, with an impact value of 9.8. Its 522 publications have 11,358 citations. The journal's 22 citations per article demonstrate its environmental scientific impact. Due to its 15.1 impact factor, Chemical Engineering Journal is esteemed in the field. With 431 papers and 15,236 citations, it is a leading platform for cutting-edge research. Academics and industry specialists are drawn to this journal's study since each article averages 35 citations. Chemosphere's 8.8 impact factor helps understand environmental chemistry and toxicity. It contains 420 works mentioned 9,818 times. With 23 citations per article, the journal helps environmental managers and policymakers understand chemical-environment interactions. The 7.2-impact International Journal of Hydrogen Energy covers hydrogen generation, storage, and use. Its 405 publications have 15,179 citations.

Table 2. Top 10 journals in the number of published articles

Journal Name	Impact Factor (2022)	Document	Citation	Citation per Document
Bioresource Technology	11.4	1198	61474	51
Science of The Total Technology	9.8	522	11358	22
Chemical Engineering Journal	15.1	431	15236	35
Chemosphere	8.8	420	9818	23
International Journal of Hydrogen Energy	7.2	405	15179	37
Water Research	12.8	313	20540	66
Journal of Power Sources	9.2	278	14914	54
Bioelectrochemistry	5	278	8647	31
Environmental Science and Technology	11.4	249	31873	128
Electrochimica Acta	6.6	235	8953	38

The International Journal of Hydrogen Energy helps improve hydrogen-based energy technologies and integrate them into sustainable energy systems with 37 citations per article. Water Research is a top water science and technology journal with a 12.8% impact factor. Its 313 publications have 20,540 citations. Water Research, with an average of 66 citations per publication, allows academics to communicate novel methods for sustainable use and protection of this vital resource. The 9.2-impact Journal of Power Sources studies

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electrochemical power sources such batteries, fuel cells, and supercapacitors. The energy storage and conversion technology progress rely on this journal's 278 articles and 14,914 citations. This journal's 54 citations per article reflect its importance and impact, driving the development of efficient and sustainable energy sources. Bioelectrochemistry, which blends biology, electrochemistry, and materials science, has a 5-impact factor. The 278 publications and 8,647 citations cover bioelectrochemical systems, biosensors, bioelectronics, and biofuel cells. Each publication averages 31 citations.

Environmental Science and Technology, with an impact factor of 11.4, is a top environmental science journal. With 249 papers and 31,873 citations, it supports environmental pollution, fate and transit, monitoring, and sustainable practices research. The journal's 128 citations per article show its significance and worldwide awareness among researchers and politicians. Electrochimica Acta covers electrochemistry, energy storage, corrosion, sensors, and electroanalytical methods. Its Impact factor is 6.6. This journal helps study electrochemical processes and develop new electrochemical technologies with 235 articles and 8,953 citations. The document's average of 38 citations shows its importance to the area and gives insight into electrochemical processes and applications.

Generally speaking, the correlation between impact factor and citations per document is positive, indicating a connection between the two metrics (López-Illescas et al., 2008; Tahamtan et al., 2016). Journals with greater impact factors typically have a greater average number of citations per article. This indicates that scientific journals with greater influence and visibility receive more citations for each article they publish. In order to increase the likelihood that their work will be cited by peers, researchers frequently prioritize publication in journals with a high impact factor (Roldan-Valadez et al., 2019). It is crucial to note, however, that the impact factor alone does not provide a complete picture of a journal's quality; thus, other factors must also be considered when determining the significance of research findings.

3.5. Analysis of keywords co-occurrence

Using keyword co-occurrence analysis, the research areas in this discipline can be comprehended based on keywords with high frequency. The extracted literature for this investigation contained a total of 25,450 keywords, with 1,975 keywords appearing in at least five-keyword publications. Figure 9 depicts a map of co-occurring keywords in biofilm research on MFCs (Microbial Fuel Cells). The size of the box indicates the occurrence frequency, while the lines connecting the nodes represent the relationships between co-occurring keywords, forming three main clusters.

Cluster 1 contains approximately 78 keywords, such as microbial fuel cell, graphene, halophilic, dyes, textile, alginate, metabolic modelling, renewable energy, nanoparticle, biofuel cells, polymers, enzymatic fuel cell, carbon, MEMS, *thiobacillus*, anaerobic methane oxidation, separator, biocorrosion, EIS, lactate, electrogenicity, *geobacter*, sewage, and polyaniline, as shown in the red box in Figure 9. MFCs and its application to the development of renewable energy sources are the focus of the covered research topics, as indicated by the keywords. Terms such as microbial fuel cell, enzymatic fuel cell, and biofuel cell indicate an emphasis on using microorganisms or enzymes to leverage natural resources for the production of energy. This is consistent with the trend in research toward identifying sustainable and environmentally favorable energy alternatives (Kumar et al., 2019). Moreover, terms such as graphene, nanoparticle, polymers, and electrode modification indicate the application of sophisticated materials and technologies in MFCs.

Graphene, a two-dimensional carbon material, enhances biofilm formation as an electrode material. The use of graphene and nanoparticles in electrode construction hopes to improve the performance of microbial fuel cells, whereas electrode modification seeks to enhance electron transfer and reaction efficiency (Chen et al., 2020; Mashkour et al., 2021). The application of microbial fuel cells in specific fields, such as effluent treatment and anaerobic methane oxidation, is a second topic that is gaining attention, where biofilms in MFCs treat sewage and wastewater. This demonstrates that research in MFCs includes the application of this technology in environmental and sustainability contexts. In addition, the presence of terms such as dyes, textile, and biocorrosion suggests an emphasis on the application of MFCs in the textile industry and dye waste management. In order to comprehend reaction mechanisms and system efficacy, biofilm research in MFCs also incorporates metabolic modelling and electrochemical impedance spectroscopy (EIS) analysis where EIS analyzes biofilm-electrode interfaces (He & Mansfeld, 2009). This suggests an interdisciplinary approach, integrating bioelectrochemistry with disciplines such as bioinformatics and electrochemical engineering.

Cluster 2 contains approximately 39 keywords, including bioenergy, nutrient removal, biomass, biofuel, biophotolysis, bioenergy generation, anaerobic process, current density, cattle manure, wetland, stormwater, pollution, food waste, biological processes, wastewater treatment, and mass transport, as shown in the blue box in the Figure 9. Based on the cluster of keywords supplied, it can be deduced that the research topics covered involve bioenergy and the use of biological processes for waste treatment and environmental protection. Bioenergy, biomass, biofuel, and bioelectricity generation are terms that signify an emphasis on biological resource utilization for sustainable energy production (Obileke et al., 2021). This aligns with global efforts to find environmentally favorable alternatives and reduce reliance on fossil fuels. MFCs offer a unique platform for biofilm research to enhance bioenergy production through the conversion of various organic sources (Ouyang et al., 2022). In addition, terms such as nutrient removal, effluent treatment, and pollution suggest a focus on refuse treatment processes and environmental protection (Christwardana et al., 2020). In this context, research focuses on the development of technologies to remove excessive nutrient levels from waste and maintain water quality. This is crucial for reducing negative impacts on water ecosystems and the environment in general. Biofilms facilitate nutrient removal, including nitrogen and phosphorus, from wastewater, making MFCs an attractive option for sustainable and efficient biological processes in wastewater treatment (Stöckl et al., 2019; Wang et al., 2020). Efficient management of agricultural waste can generate renewable energy sources and reduce the environmental impact of such refuse. Biofilm research in MFCs explores mass transport phenomena, current density optimization, and the integration of MFCs in wetland and stormwater systems to mitigate pollution and enhance bioenergy generation through biophotolysis or anaerobic processes (Song et al., 2020; Gonzalez-Nava et al., 2022). Research on biofilm of MFCs can contribute to the development of more effective bioenergy processes by incorporating electrochemical technology.

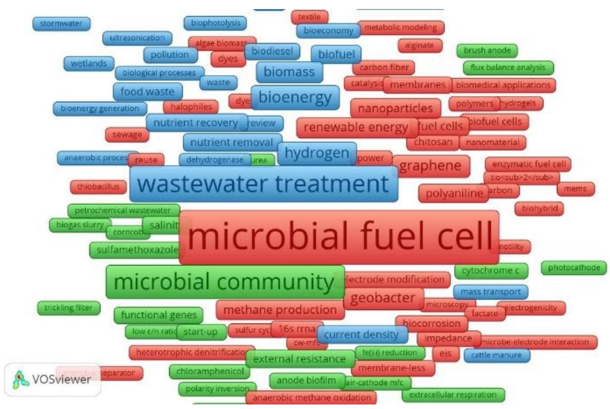

Figure 9. Keyword co-occurrence map

Cluster 3 contains approximately 20 keywords, such as microbial community, cytochrome C, biogas slurry, salinity, functional genes, trickling filter, external resistance, anode biofilm, extracellular respiration, polarity inversion, photocathode, brush anode, flux balance analysis, corncob, and low C/N ratio, as shown in the green box in Figure 9. The keywords in this cluster are associated with numerous bioelectrochemistry and microbial community-related concepts. This data indicates that this cluster concentrates on the study of microbial interactions in the context of bioelectrochemistry. Biofilm research in MFCs explores the formation and composition of the anode biofilm, focusing on the role of cytochrome C and extracellular respiration for efficient electron transfer (Li et al., 2021). The biochemical processes involved in the production of electricity from biogas sediment rely heavily on the participation of microbial communities (Wang et al., 2019). This research could entail functional gene analysis aimed at elucidating the role of microorganisms in the transformation of organic matter into electricity and biogas. The keyword salinity indicates that this cluster is also interested in environmental aspects. The composition and activity of microorganisms in MFC systems can be altered by a high salinity level (Yang et al., 2020). This research may focus on optimizing the efficacy of MFCs under varied salinity conditions. In addition, terms such as cascading filter, external resistance, and anode biofilm indicate that this cluster also incorporates aspects of MFCs pertaining to the design and development of microbial electrochemical systems (Godain et al., 2022; Prabowo et al., 2016). By optimizing factors such as anode material usage, biofilm structure, and external resistance modulation, this research may seek to improve the efficiency and productivity of MFCs. Additional keywords such as photocathode, brush anode, and polarity inversion indicate research in the field of bioelectrochemistry involving renewable energy. This cluster illustrates the expanding research field in MFCs. These studies may employ various analytical methods, such as flux balance analysis, to model and predict the response of bioelectrochemical systems to modifications in environmental conditions or operational parameters.

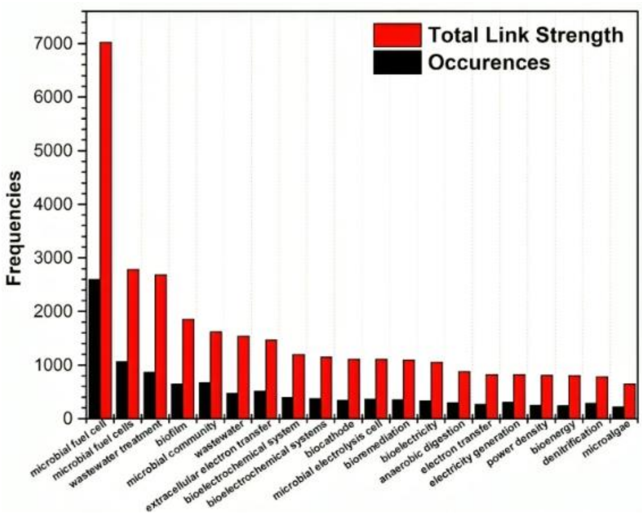

Figure 10. The top 20 keywords in occurrence frequency

The information as in Figure 10 pertains to keywords associated with microbial fuel cells (MFCs), wastewater remediation, and bioelectrochemical systems. The occurrences column indicates the frequency with which each keyword appears, whereas the total link strength column indicates the cumulative strength of connections to other concepts or research related to each keyword. Microbial fuel cells (MFCs) are prominently featured in the table, with the term "microbial fuel cell" occurring 2,599 times. This indicates that MFCs are an extensively investigated and well-recognized area of bioelectrochemical system research. The occurrence of "microbial fuel cells" at position 1064 indicates that this subject remains of interest. The occurrences of "wastewater treatment" at 861 and "wastewater" at 468 indicate that waste water treatment is another significant subject. This emphasizes the significance of devising sustainable and effective microbial-based wastewater treatment methods. The high total link strength values associated with these keywords indicate that wastewater treatment is the subject of a substantial quantity

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of research and knowledge. Other notable keywords with moderate occurrences and link strengths include "biofilm", "microbial community", and "extracellular electron transfer". Biofilm, a community of microorganisms embedded in a substrate, serves a vital role in numerous biological processes, such as effluent treatment and MFCs.

The microbial community comprises the diverse collection of microorganisms utilized in biotechnology. Extracellular electron transfer is a fundamental bioelectrochemical process in which microorganisms transfer electrons to or from solid conductive surfaces. In addition to "biocathode", "microbial electrolysis cells", and "bioelectrochemical systems", the Figure 10 contains additional keywords pertaining to particular aspects of biofilm research on MFCs. These terms refer to research areas aimed at improving the efficacy and efficiency of MFCs and related technologies. The presence of terms such as "bioremediation", "anaerobic digestion", "denitrification", and "microalgae" demonstrates the breadth of applications within the field of microbiological technologies. These keywords emphasize the potential of using microorganisms to resolve environmental challenges, such as pollution mitigation, the production of renewable energy, and nutrient removal.

3.6. Analysis of research trend

Biofilm research in MFCs has made significant strides between the years 2012 and 2021, focusing on MFC performance, biofilm behaviour, and sustainable energy production and wastewater treatment applications, as shown in Figure 11. In the years 2012-2017, anaerobic processes were the focus of research as scientists sought to comprehend the biofilm formation and function in anaerobic MFCs. Optimizing the composition and structure of biofilms to enhance electron transfer efficiency and overall MFC performance was the subject of research (Yuan et al., 2012). In addition, the incorporation of MEMS technology yielded important insights into the mechanical and physical properties of biofilms, which aided in the design and optimization of MFC systems (Malvankar et al., 2012). Utilizing the metabolic activities of biofilms formed in MFCs, researchers also emphasized the eradication of biochemical oxygen demand (BOD), a crucial parameter in wastewater treatment, by exploiting the metabolic activities of biofilms (Abrevaya et al., 2015).

During the years 2017 to 2019, biofilm research in MFCs shifted toward investigating specific applications and enhancing power density. The eradication of ammonium became a focal point, with researchers investigating the potential for biofilms to convert ammonium into nitrogen gas via microbial processes (Park et al., 2017). The objective of power density optimization was to maximize the electrical output of MFCs by increasing the electrogenic activity of biofilms. Utilizing diverse waste streams, such as urine and dairy wastewater, demonstrated the adaptability of biofilms in cleansing and producing bioenergy from a variety of wastewater types (Barbosa et al., 2017; Faria et al., 2017). In addition, fouling, a prevalent problem in MFCs, was addressed by means of research aiming at comprehending and mitigating biofilm-related fouling phenomena.

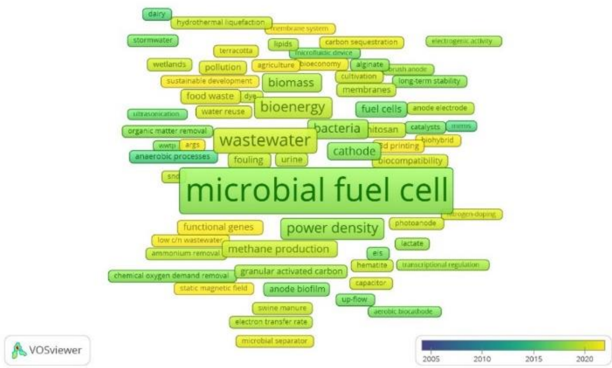

Figure 11. Trend map of keyword co-occurrence with time from 2005 to 2021

Biofilm research in MFCs aligned with the global emphasis on sustainable development and the bioeconomy in the 2019s and 2021s. Membrane systems played an essential role in biofilm research by facilitating selective ion transport, enhancing mass transport within the biofilm, and enhancing the performance and stability of MFCs (Sun et al., 2019). Carbon sequestration was investigated by integrating carbon capture and utilization with MFC systems, offering the possibility of concurrent bioenergy production and carbon mitigation (Noori et al., 2019; Elmaadawy et al., 2020). The objective of the research on microbial separators was to develop novel techniques for controlling and manipulating biofilm growth, thereby facilitating efficient bioelectrochemical processes. In addition, the role of functional genes, particularly nitrogen supplementation, was investigated in order to increase the biofilm's catalytic activity and nitrogen removal efficacy in low carbon-to-nitrogen (C/N) effluent treatment (Yang et al., 2021).

Throughout these time periods, biofilm research in MFCs concentrated on the formation, structure, and activity of biofilms in an effort to optimize their efficacy and application in sustainable energy generation and effluent treatment. These studies' findings have contributed to the advancement of electrode materials, reactor designs, and operational strategies, thereby augmenting the scalability and practical application of MFCs. In addition, the knowledge garnered from biofilm research has paved the way for novel approaches, such as biofilm engineering, biofilm-modified electrodes, and advanced analytical techniques, thereby facilitating the development of MFC technology and expanding its potential for use in the real world.

The provided keywords from the previous three years of biofilm research in microbial fuel cells (MFCs) illustrate key areas of concentration and emergent trends. The focus in 2020-2021 was on comprehending microbial fuel cells and their use in bioenergy production, as shown in Figure S5. Bacteria played a central role in biofilm formation, while chitosan, a natural polymer, was investigated for its potential to immobilize biofilms. A focus was placed on cathode design and optimization in an effort to increase the efficiency of electron transfer in MFCs. Wetlands and dairy wastewater have emerged as particular applications of MFCs, demonstrating the adaptability of biofilms in various environments (Liu et al., 2020; Tajdid Khajeh et al., 2020). Traditional terracotta was evaluated for its potential in MFC construction, and long-term stability studies focused on maintaining biofilm activity over extended time periods (Me et al., 2020). To enhance biofilm efficacy and overall MFC efficiency, catalysts such as nitrogen-doped hematite were investigated (Guo et al., 2020). EIS still proved to be a useful method for analysing biofilm-electrode interfaces and gaining an understanding of system behaviour.

In 2021 and 2022, the focus broadened to include low carbon-to-nitrogen (C/N) effluent remediation, functional genes, sustainable development, and the bioeconomy. The study of biofilm investigated the use of functional genes to enhance biofilm activity and optimize MFCs processes (Leung et al., 2021). The incorporation of MFC technology into sustainable development and the bioeconomy revealed the potential of biofilms as essential components of environmentally benign and economically viable energy production systems. Agriculture also emerged as an area of particular interest, highlighting the use of MFCs in agricultural waste remediation and resource recovery (Pandit et al., 2021).

The most recent time period, 2023, demonstrates a significant emphasis on membrane systems. Low-cost membrane is popular membrane to be developed (Palanisamy et al., 2023; Sarma & Mohanty, 2023). The popularity of membrane systems in biofilm research for MFCs can be attributed to their capacity to improve mass transport, enable selective ion transport, control biofilm growth, prevent cross-contamination, ensure long-term stability, facilitate system control and monitoring, and provide scalability (Li et al., 2023; Tian et al., 2023; Pal et al., 2023; Munoz-Cupa & Bassi, 2023; Terbish & Popuri, 2023). Low-cost membranes comprised of materials such as chitosan, cellulose, or polymers derived from agricultural waste provide cost-effective alternatives to Nafion, thereby facilitating the practical implementation of MFCs on a larger scale. The substitution of inexpensive membrane for pricey Nafion in biofilm research for MFCs has the potential to surmount the economic barriers associated with MFC technology. Innovative membrane designs and modifications, such as surface modifications, composite structures, and functionalization, further improve their performance. Utilizing low-cost membranes in MFCs can considerably reduce costs, making bioenergy systems more accessible for decentralized effluent treatment, resource recovery, and off-grid power generation, thereby encouraging the development of economically and sustainably viable solutions (Sun et al., 2023; Suransh & Mungray, 2022).

4. Conclusion

Biofilm research on MFCs has increased significantly since 1994. Environmental awareness, renewable energy projects, and international legislation shaped the research. The 2016 Paris Agreement focused the globe on renewable energy and sustainable technologies, including hydrogen fuel cells. In 2014, biofilm research on MFCs increased somewhat due to hydrogen energy's role in carbon neutrality. MFC research and technology have advanced due to hydrogen energy's growing importance in carbon neutrality. Since 2017, publications and citations on biofilm growth in MFCs have increased, demonstrating the scientific community's interest. China, the United States, India, South Korea, Japan, Malaysia, Indonesia, Nigeria, Oman, the United Arab Emirates, and Pakistan are actively researching innovative biofilm performance and MFC system optimization methods. China and the US rule these nations. South Korea, Australia, and the UK have the highest average frequency of citations, suggesting their articles are influential. Germany and Malaysia stand out owing to their high article counts and citation rates while China has a large number of published papers and total citations. Further study of their scientific contributions might illuminate MFC research advancement.

Biofilm MFCs are a promising bioelectrochemical system study topic with many citations and publications. Biofilm MFC research by D.R. Lovley, B.E. Logan, I. Angelidaki, and B.E. Rittmann has focused on biofilm generation, electron transfer processes, and performance improvement. I. Ieropoulos, M. Rahimnejad, W. Li, T.K. Sajana, O. Konur, and L. Liu are some important researchers who have advanced biofilm MFC knowledge, development, and applications, enabling sustainable energy production, effluent treatment, and bioremediation. Biofilm research in Microbial Fuel Cells (MFCs) reveals three prominent clusters of high-frequency keywords. Cluster 1 encompasses topics such as graphene, halophilic microorganisms, textile dyes, metabolic modelling, renewable energy, and biofuel cells. Cluster 2 focuses on bioenergy production, nutrient removal, biomass utilization, anaerobic processes, and wastewater treatment. Cluster 3 investigates microbial communities, functional genes, extracellular respiration, polarity inversion, and flux balance analysis. These clusters demonstrate the diverse aspects of biofilm research in MFCs, encompassing areas such as renewable energy generation, biogas production, and the study of microbial communities in various environmental conditions. Microbial separator research tries to limit biofilm formation using membrane technologies. Electrode materials, reactor designs, and operating tactics have improved MFC scalability and practicality due to the discoveries. Functional genes, sustainable development, low carbon-to-nitrogen wastewater treatment, and the bioeconomy were prioritized in last two years. MFC technology's economic obstacles may be solved using low-cost membrane systems like chitosan, cellulose, or agricultural waste.

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