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UNVEILING RESEARCH TREND ABOUT THE APPLICABILITY OF ION EXCHANGE MEMBRANES IN MICROBIAL FUEL CELLS-BASED WASTEWATER TREATMENT: A BIBLIOMETRIC AND CONTENT ANALYSIS (2014-2024)

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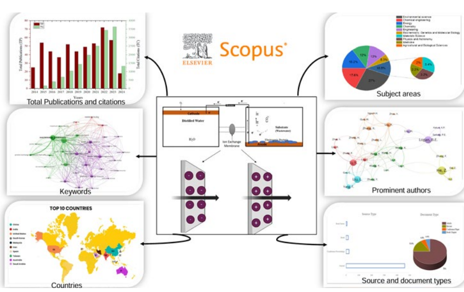
Graphical abstract



Abstract

Researchers are increasingly exploring sustainable bioresources and eco-friendly energy technologies for wastewater treatment. Microbial fuel cells (MFCs) are a promising green technology that generates energy while treating wastewater. A key component of MFCs is membrane technology, particularly ion exchange membranes (IEMs), which act as separators and facilitate ion transport to improve treatment efficiency and power output. Modifications to IEMs depend on their intended role in MFCs. This bibliometric study aims to quantitatively and qualitatively review research on IEM applications in MFCs from 2014 to 2024 using data from the Scopus database. The Scopus database yielded 501 applicable publications in the last decade, which was the most fruitful timeframe, with research articles accounting for 73.2% of the total. Several categories including total publications and citations history, distribution of subject categories, top journals, countries, and authors were analysed in this analysis. Environmental science leads the subject categories with a majority contribution of 27% for each. However, the energy fuel category has seen the greatest total expansion over the last ten years. Bioresource Technology also published a higher number of papers in MFCs research, with 26.8%. Ion exchange membrane reviews, nanocomposite membranes, developments in electrodes and membranes, ceramics operation, graphene electrodes and power enhancement are the most popular membrane topics discussed in MFCs research. MFC's separators are often made from perfluorinated ion-exchange membranes like Nafion, a widely used commercial option. However, composite biobased polymer membranes containing organic and inorganic additives are more cost-effective and biocompatible alternatives that can improve ionic conductivity.

Keywords: Microbial fuel cells, Wastewater, Ion exchange membranes, Bibliometric, Scopus

Abstrak

Penyelidik semakin meneroka sumber bio mampan dan teknologi tenaga mesra alam untuk rawatan air sisa. Sel bahan api mikrob (MFC) ialah teknologi hijau yang menjanjikan yang menjana tenaga sambil merawat air sisa. Komponen utama MFC ialah teknologi membran, terutamanya membran pertukaran ion (IEM), yang bertindak sebagai pemisah dan memudahkan pengangkutan ion untuk meningkatkan kecekapan rawatan dan output kuasa. Pengubahsuaian kepada IEM bergantung pada peranan yang dimaksudkan dalam MFC. Kajian bibliometrik ini bertujuan untuk mengkaji secara kuantitatif dan kualitatif penyelidikan mengenai aplikasi IEM dalam MFC dari 2014 hingga 2024 menggunakan data daripada pangkalan data Scopus. Pangkalan data Scopus menghasilkan 501 penerbitan yang dalam dekad yang lalu, merupakan jangka masa yang paling berkesan, dengan artikel penyelidikan menyumbang 73.2% daripada jumlah keseluruhan. Beberapa kategori termasuk jumlah penerbitan dan sejarah petikan, pengedaran kategori subjek, jurnal teratas, negara, dan pengarang telah dianalisis dalam analisis ini. Sains alam sekitar mendahului kategori mata pelajaran dengan sumbangan majoriti sebanyak 27%. Walau bagaimanapun, kategori bahan api tenaga telah menyaksikan jumlah pengembangan terbesar manakala Teknologi Biosumber juga menerbitkan lebih banyak kertas dalam penyelidikan MFC, dengan 26.8%. Ulasan membran pertukaran ion, membran nanokomposit, perkembangan dalam elektrod dan membran, operasi seramik, elektrod graphene dan peningkatan kuasa adalah topik membran paling popular yang dibincangkan dalam penyelidikan MFC. Pemisah MFC selalunya dibuat daripada membran pertukaran ion terfluorinasi seperti Nafion, pilihan komersial yang digunakan secara meluas. Walau bagaimanapun, membran polimer berasaskan bio komposit yang mengandungi bahan tambahan organik dan bukan organik adalah alternatif yang lebih kos efektif dan biokompatibel yang boleh meningkatkan kekonduksian ionik.

Kata kunci: Sel bahan api mikrob, Air Kumbahan, Membran pertukaran Ion, Bibliometrik, Scopus

1.0 INTRODUCTION

In recent years, microbial fuel cells (MFCs) have become a primary focus of study due to the desire to develop sustainable energy devices. The utilisation of synthetic polymer electrolyte membranes (PEMs), including commercially driven Nafion membranes, compromises the sustainability of this technology. A new environmentally friendly composite polymer electrolyte membrane has been created. An ion exchange membrane (IEM) is used to separate the anode and cathode electrodes to facilitate a full redox reaction in the cathode compartment. Electrogenic bacteria (EB) are usually found in the anode, where oxidation processes take place, whereas reduction reactions occur in the cathode compartment [1]. MFCs function by utilising electroactive bacteria to decompose the carbon compounds in wastewater and convert chemical energy into electrical energy. This bioremediation process will facilitate the movement of protons, specifically hydrogen ions, from the anodic compartment to the cathodic compartment. Single-chamber MFCs with an air-cathode electrode and dual-chamber MFCs using cation exchange membranes (CEMs) and anion exchange membranes (AEMs) as separators have been newly created.

Since the core of the MFCs is the ion exchange membrane (IEM), a robust electrolyte that permits protons or electrons to transport but prevents other electrical and chemical particles. Perfluorinated polymeric membrane, also known as Nafion, is frequently used as an IEM in fuel cell applications to transport proton ions because of its superior electrochemical, mechanical, and thermal properties [2]. Contrarily, commercial Nafion has many problems, including greater expenditure, switchover of oxygen, concentration losses, incomplete redox reaction and clogging pores of Nafion by other foreign particles known as fouling phenomenon [3]. An affordable price membrane with acceptable physio-chemical stability and moderately high proton conductivity is considered essential due to Nafion's well-known drawbacks, which include its subpar performance at elevated temperatures (above 80^{o}C) and humid conditions (below 30%) [4].Membrane science and technology are becoming increasingly popular as a result of the prospective applications of polymers and inorganic fillers for the removal of contaminants from wastewater. Nanoparticles improve separation performance by preventing unwanted species from entering and increasing thermal and mechanical properties by generating preferential permeation routes [5]. The incorporation of nanoparticles in polymeric membranes will upgrade the intensive properties of the overall membrane. Researchers are concentrating on a few aspects of membranes to improve their effectiveness. The majority of research projects seek to develop new membrane materials that could take the place of commercially available IEMs. The goal of the study was to create a polymer-based composite membrane with a minimal cost that would operate well with the MFCS system. Polymer-based membranes have been shown to outperform the widely used Nafion membrane. Although the majority of current research is focused on developing sustainable membranes using mixed matrix membranes and composite membranes composed of porous polymer and nanoparticles, composite ceramic materials have also received attention [6, 7]. In MFCs, proton exchange membranes with Nafion and SPEEK bases are commonly used [8, 9]. Non-solvent induced phase separation is commonly employed for casting thin film polymeric membranes. Furthermore, the membrane is critical in preventing crossover between the anode and cathode chambers, particularly by effluent, CO_2, and oxygen. Lower internal resistance, substrate loss, biofouling, and oxygen transport are all considered criteria during membrane selection [10].

The two most common solvents used in the solvent casting technique to manufacture PEM are N,N-dimethyl acetamide (DMAc) solutions and N-methyl-2-pyrrolidone solutions (NMP). Certain changes are made to membranes to improve their properties; these modified membranes are known as the incorporation of inorganic filler into the organic membranes [11]. These composite membranes are doped or incorporated with a particular filler material at the best concentration using the solvent casting method [12]. Additional methods of modification, including layer-by-layer assembly, surface modification, and cross-linking, have been tried and shown to enhance the membrane's characteristics [13]. The effectiveness and cost of polymers such as polyimide (PI), polybenzimidazole (PBI), polyetheretherketone (PEEK), and polyether sulfone were superior in MFCS. PEEK-based polymers are thought to be desirable candidates for membranes because of their outstanding physical and thermal durability, high electrochemical stability, and affordable price [14]. Furthermore, polymer membrane with sulfonation (SO_3H) is proven to improve the wettability of the membrane, the conductivity of positively charged ions and membrane stability [15].

The goal of this bibliometric analysis is to apprehend the history of major ion exchange membrane technology applications of MFCs in wastewater treatment research. Figure 1 displayed the schematic representations of the searching strategies ion exchange membrane functionality in microbial fuel cells and the steps of data extraction, processing as well as visualisation were executed from the Scopus database. The objective of bibliometric analysis as follows:

- To compile information that has been reported from the Scopus Database over the past ten years as well as to show the prominent authors and keyword analysis from VosViewer and Harzing's Publish and Perish software. This is because the researchers produced highly significant work about IEC in the MFC world in recent decades compared to the previous decade with limited and inadequate research interest.
- To depict the contributions of prolific authors, dominant countries, and productive affiliations.
- To identify the major research title that has received the most attention from researchers.
- To demonstrate the significance, limitations and future recommendations of bibliometric analysis about ion exchange membranes in MFCs.

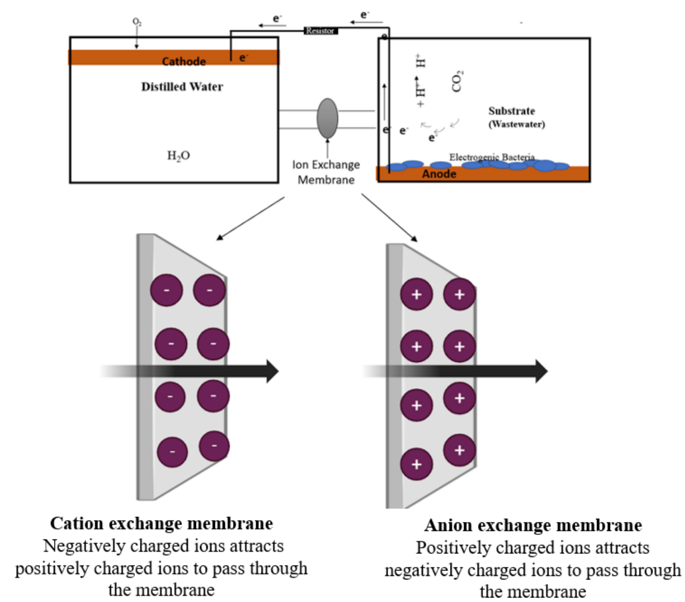


Figure 1a Schematic representations of types of ion exchange membrane functionality in microbial fuel cells

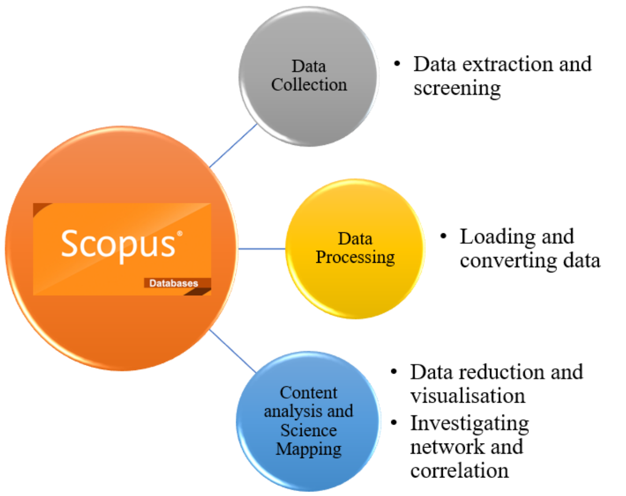


Figure 1b Searching strategies and steps of data extraction, processing as well as visualisation were executed from the Scopus database

2.0 METHODOLOGY

Microbial fuel cells show substantial industrial application potential across different wastewater treatment processes. More papers have been published to date on MFCs in treating wastewater such as municipal and industrial effluents. C. Santoro groundwork's showed that proton exchange membranes in MFCs can efficiently treat wastewater while aiding in producing electricity [16]. Examining search activity in a certain topic using both quantitative and qualitative methods is referred to as bibliometric and content analysis. This method is effective for quantitatively assessing the most frequently published material and mapping the evolution of the topic over time [18]. For bibliometric analysis, the Scopus Elsevier database was used over the Web of Science database because of its higher number of indexed data. The scope and emphasis of the Web of Science and the Scopus database are the main points of difference. The Elsevier-founded Scopus was established in 2004 and comprises over 76 million records from multiple disciplines. It emphasises modern sources and offers a wider range of metrics, including the h-index and g-index [19]. Clarivate Analytics founded Web of Science in 1960. It covers a vast amount of scientific citations and indexes over 20,000 articles. Author profiles, collaboration tools, and open-access material are just a few of the aspects that make Scopus a popular choice. Its wide content coverage is another. Scopus is known for being user-friendly and offering free access to specific information, which has made it a favoured option for scholars. Scopus is typically preferred over Web of Science because of its extensive coverage, easy-to-use interface, and contemporary research metrics methodology [20].

The method of "topic" was used for literature search. Topics are (*microbial fuel cell*) OR (*microbial fuel cells) OR (*membrane*) AND KEY(*membrane*) AND KEY(*wastewater*) AND KEY(*microbial fuel cell*). The deadline is April 12th , 2024. A total of 684 literatures were retrieved. Then the data was reduced into 501 literatures as the number of years of publications was limit from 2014 till 2024. This is to depict vividly that most of the research papers published and highly cited in the recent 10 years timeframe. After that, every piece of literary data (author, publication, year, citation frequency, etc.) is exported in text document format for use in bibliometric research. Among the popular research areas that were covered were improving IEM performance in MFCS [21], utilisation of nanomaterials for wastewater remediation [22], ceramics in MFCs [23], and development of a low-cost membrane made from sulfonated biochar for use in MFCs [24]. The VosViewer software is used to analyse several articles on the application of membrane MFCS and its relationships to the wastewater topic area. These networks, which can contain journals, researchers, or individual articles, can be produced through citation, bibliographic coupling, co-citation, or co-authorship relationships. Intending to discover the pivotal literature reviews and the main research area on MFCS in wastewater treatment, we executed a co-citation analysis to pinpoint and look into the major research area. The Scopus database was used to assemble the reported studies in that area over the preceding decade (2014-2024), and this study estimates notable MFCS recent developments and attractions in wastewater treatment.

Table 1 outlines the distinctions between prior research and this study regarding period, database formats, keywords, uniqueness of the study, methods of analysis, and software tools used. From the WOS database, the three researchers conducted their bibliometric analysis solely in the field of proton exchange membrane, membrane electrode, and microbial fuel cell research [25, 26, 27]. This was done consistently. Coherently, this demonstrates that they have conducted studies on more specific research themes. In contrast to that, our research is more comprehensive in the sense that it not only revealed a decade's worth of research trends regarding ion exchange membranes in MFCs, but it also demonstrated the relationship between each published paper over the years and a variety of critical components. These critical components include publishing countries, study areas, journals and author keywords, citation analysis, and also other important components that will be discussed in detail in this paper. Additionally, this study will describe a topic of research that requires further investigation. This is vital for directing future researchers toward finding research gaps and interesting research areas in membranes in MFCs, which is how this study will accomplish its goal. Apart from that, to the best of our knowledge, this is the first research that has brought attention to the wider application of IEM, which includes CEM and AEM in MFCs trends. This was accomplished through a detailed bibliometric analysis that was carried out with a variety of sophisticated software tools, including the most recent version of GraphPad Prism, Visme, VOSviewer, and Harzing's Publish or Perish in addition to others.

Table 1 Summary of previous research studies in comparison with current study

Author'n name	(Yonoff *et al.*, 2019) [25]	(Deng *et al.*, 2022) [26]	(Yan *et al.*, 2023) [27]	This study
Timeframe	2008-2018	1990-2022	2003-2023	2014-2024
Database formats	Web of Science	Web of Science	Web of Science	Scopus
Keywords	*Fuel*,*Cell*, *Membrane* and *Proton* as main title of the documents whereas *performance*, *Pemfc*, *Pem Fuel Cell* and *Fuel Cell*	*Proton exchange membrane fuel cell* and *Proton-exchange membrane fuel cell*, *PEM fuel cell*	*Proton exchange membrane fuel cell* and *PEM fuel cell* as main title whereas *membrane electrode assembly* and *membrane electrode* membrane material are the keywords	*Microbial fuel cell* and *membrane* as the main title whereas *wastewater*, *membrane*, and *microbial fuel cell* are the keywords
Novelty of study	To study the trend proton exchange membrane fuel cells	To study the trend proton exchange membrane fuel cells	To investigate application of membrane electrode assembly in proton exchange membrane fuel cells	To study the effectiveness of research trend of ion exchange membrane utilisation in microbial fuel cells especially in wastewater field.
Types of analysis	Bibliometric analysis	Bibliometric analysis	Bibliometric analysis	Bibliometric analysis and Content analysis
Software tools utilised	Histcite TM, CiteSpace, ArcGIS, Ucinet	VosViewer	VosViewer	VosViewer, Visme, GraphPhad Prism, Harzing's Publish&Perish

On April 12th, 2024, the Scopus database was accessed to retrieve and synthesise literature data concerning the utilisation of membranes in MFCs-based strategies for wastewater treatment. For the purpose of searching, the following terms were typed into the search bar: "Microbial fuel cell" and "Membrane" as the main title, whereas wastewater, membrane, and microbial fuel cell are the keywords." After narrowing the scope of the literature search to a specific year between 2014 and 2024, articles that were in the final stages of publishing, the type of source (journal, conference paper, book, book series), and the categories of documents (article, review, conference paper, and book chapter) were taken into consideration and included. The result was the discovery of a list of 501 unique documents out of 684 documents. The vast majority of publications were made available in the English language, in addition to the fact that only a negligible number of articles written in Chinese were excluded from the collection. Books, book series, conference proceedings, and scientific journals were the only types of sources that were deemed suitable for use in this study. As far as this collection is concerned, the only documents that are included are those that are currently being considered for publication. The process of extracting data from the Scopus Database is depicted in Figure 2, which represents the structure of the process.

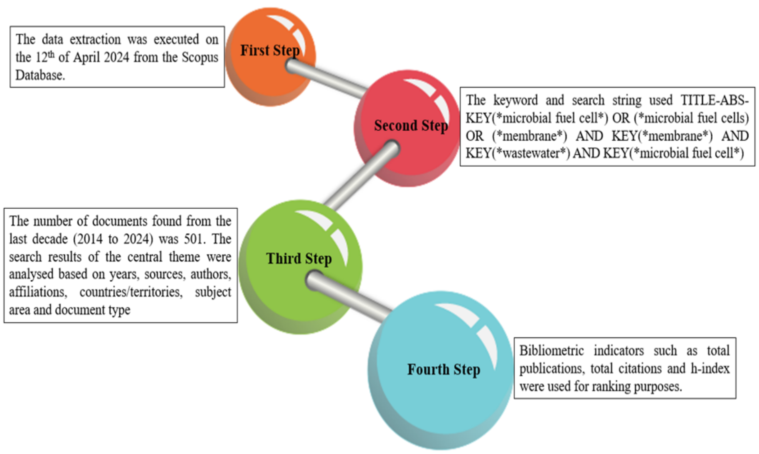


Figure 2 Searching strategy for Scopus database constructed in Visme

Information on citations, bibliographies, and author keywords was exported using VOSviewer (version 1.6.7, Leiden University, The Netherlands), a program for creating and viewing bibliometric maps [28]. Items are included in maps made with VOSviewer. Countries or author keywords are the elements of interest that are being investigated in this study. It is possible to connect or associate any one pair of objects with another pair of objects. The strength of each link can be stated as a positive value. Higher this value indicates that the connection is more robust. When analyzing co-authorship, the total link strength is a reflection of the overall strength of a country's co-authorship ties with other nations. On the other hand, the link strength between authors is a reflection of the number of publications that were co-authored by two countries associated with each other.

Table 2 displays the citation metrics that were obtained using Harzing's Publish and Perish tool. These metrics were taken from the tool. Information pertaining to publishing years, the number of patents and documents that have been published, total citations, citations per year, citations per paper, cumulative citations per author, cumulative papers per author, cumulative authors per paper, h-index, and g-index are all included in this table. The Scopus database contains the papers that have been cited the most and are generally accepted by the scientific community. These publications pertain to the research that has been conducted on microbial fuel cells over the course of the past 10 years. More than 129 researchers per paper, on the other hand, were responsible for publishing the documents, which got a total of 16977 citations. Through the utilisation of h-index and g-index, this section has made an effort to provide a concise review of the papers that have been published. Additionally, it has paid attention to the influence that researchers have had on citations. The h-index is a productivity and impact evaluation tool that was developed by J.E. Hirsch. It is used to determine how productive and influential a researcher is. Additionally, the amount of citations that each paper has received is taken into consideration by this technique [29].

This method takes into account the number of publications that the researcher has published. More specifically, a scientist has an h-index of 68 across all 501 of their papers. This is intended to be more particular. Using the number of publications that have been cited a considerable number of times, the h-index is able to determine the total impact of a researcher's work [30]. This is accomplished by focusing on the number of papers that have received references. In contrast, the g-index, which was established by Leo Egghe, is designed to give more weight to works that have earned a big number of citations. This is the intention of the g-index. The definition of this phrase is the highest number that the top g articles, which were ranked in decreasing order of citations, obtained [31]. These articles garnered around 105 citations. The g-index provides a larger emphasis on papers that have earned a significant number of citations. This is done in order to compensate for the inadequacies that are associated with the h-index. The fact that the g-index is higher than the h-index is converging evidence for the developing and widespread applicability of IEMs in MFCs in the present day. This evidence proves that IEMs are becoming increasingly applicable in MFCs.

Table 2 Citation metrics retrieved from Harzing's Publish and Perish

Publication years	2014-2024
Citation years	10
Papers	501
Patents	3845
Total citations	16977
Cites/year	1697.70
Cites/paper	33.68
Cites/author	4067.71
Papers/author	129.94
Authors/paper	4.77
h-index	68
g-index	105

3.0 RESULTS AND DISCUSSION

3.1 Publication Output Interpretation

In this part, a quantitative approach was utilised, and Figure 3 was used to explain the correlation that exists between the number of publications and the number of citations. Between the years 2014 and 2022, the annual publishing rate climbed in a manner that was both unsteady and exponential. The highest h index was approximately 27, which indicates that the majority of publications were referenced in that particular year (2022). After that, the number of publications had a minor decrease in 2023, but it is anticipated that it will increase again in 2024. The factors that caused the fluctuation in the number of papers are due to the scientific publishing process which takes a longer time to evaluate and publish a well written paper.

Moreover, it was shown that the number of publications increased between the years 2018 and 2022. The vast majority of these articles, on the other hand, demand money to access the information they contain; therefore, the user must be prepared to pay for access to the material. Inconsistent publication numbers throughout the 10 years may be attributed to underreporting of results, particularly in research utilising duplicate or triplicate reactors that fail to fully document cases where replicates yield inconsistent outcomes. Disseminating data with inconsistent duplicates is a crucial yet difficult task to gain a deeper comprehension of this essential matter. Various applications and methodologies are being researched for microbial fuel cells (MFCs), ranging from wastewater treatment to energy generation. Comparing results between research is challenging due to the variety of feedstocks, reactor designs, and microorganisms utilised. Although microbial fuel cells (MFCs) demonstrate potential in laboratory settings, there are substantial obstacles to overcome when transitioning to real-world applications. The discrepancies in performance between laboratory and pilot scales lead to the unpredictability in reported outcomes.

According to our projections, the number of citations that an article receives after it has been published in an open-access journal will have increased. Only 20.1% of papers had been made available to the public as open access by the years 2022 and 2023. An extensive variety of MFCS study fields are currently being actively pursued by a large number of research groups from all over the world. According to the findings of the topic area study, environmental concerns have been the primary focus of MFCS research during the course of the academic years. Selvasembiam *et al*. [32] published influential papers that received high citations. They focused on studying the significance of ion-exchange membranes (IEMs) in microbial fuel cells (MFCs) for optimal performance and membrane functions. Secondly, he talked about how the membrane prevents short circuits and mixing. Various separators such as CEM, AEM, ultrafiltration membrane, microfiltration membrane and salt bridge have been studied for their performance and efficiency in different MFC setups. Furthermore, the impact of the membrane on the MFC reactor's performance can represent a substantial amount of the overall investment cost. Lastly, he highlights the relevance of surface area and power generation of the membrane about the electrode's surface area, which significantly influences MFC performance. Power generation can be limited by internal resistance when the membrane's surface area is smaller than the electrode's surface area. The relevance of the ion exchange membrane in microbial fuel cells is underscored, emphasising the need to carefully choose the right membrane type and properties to enhance MFC performance and efficiency.

Other than that, noteworthy investigations about the different types of IEM have been reported by researchers [33]. These studies differentiate between AEM, BPM, and inorganic fillers. An example of this would be the utilisation of anion exchange membranes (AEMs), which have the ability to retain water, maintain stability, and conduct electric charge. An AEM and a Cation Exchange Membrane (CEM) are both components of a BPM, which is a unique type of membrane that is composed of two monopole membranes. This type of membrane allows for efficient transport of both $H+$ and $OH-$ ions as they pass over the water-splitting interface of the membranes. When utilising such membranes, however, the pH gradient is a significant concern that must be addressed. For the purpose of retaining water and improving conductivity in membranes that are used in MFCs, inorganic fillers such as titanium dioxide, silicone dioxide, bentonite, graphene, and other similar materials have been utilised. The importance of membranes in microbial fuel cells is brought to light by these considerations, as are the continuous efforts to improve the performance of membranes for use in environmentally responsible wastewater treatment applications.

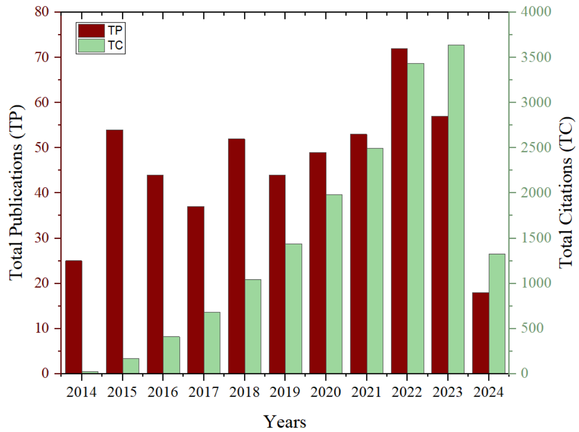


Figure 3 The representation of publications and citations on the use of membranes for wastewater treatment in MFCs from 2014 to 2023

3.2 Documents Profiles and Source Types Distribution

The Scopus database includes documents categorised by source types, which are classified as either serial (journals, book series, some conference series) with an ISSN or non-serial (books, one-off conferences) with an ISBN. Most of the information in Scopus consists of serial publications. The document type indicates the format for publication, such as article, conference paper, review, or book chapter. Scopus includes specific sorts of documents in its database, prioritising primary research outputs such as articles and review papers from both serial and non-serial sources. Figure 4 shows the distribution of source and document kinds, with articles making up approximately 75% of the published document types. The journal source type is categorised under articles and review documents. Thus, journal articles are the most often published sort of document among scholars, with conference proceedings papers, books, and book series being less common. Luo *et al.* [21] focused on the selectivity of ion exchange membranes in their journal article, while Anjum *et al.* [22] explored wastewater cleanup utilising nanomaterials and garnered the highest number of citations. The most productive journals in the last decade have been Journal of Membrane Science, Arabian Journal of Chemistry, and Journal of Industrial and Engineering Chemistry. Over the years, bibliometrics has gained popularity for its use in categorising academic output and creating comprehensive summaries that highlight key findings. The majority of documents in the Scopus database are predominantly in English because using English allows academics to effectively convey their findings to the global scientific community, fostering more collaboration among researchers worldwide. This demonstrates that having a universal language like English enables scholars worldwide to communicate in a shared language.

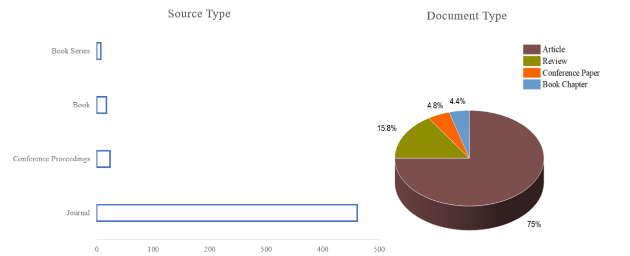


Figure 4 Source and document types related to MFCs field from 2014 to 2024

Chemical engineering encompasses an extensive variety of related topics to improve the efficacy of membranes in MFCs for wastewater treatment. In addition to energy, this category includes biological energies, where MFCS overlaps. The primary focus of chemistry subjects is membrane modifications because the essential phenomenon in MFCs is the generation of electricity, electrochemists have focused much of their research on looking for related chemical changes [34]. Engineering also includes research into human-caused environmental effects and solutions to those effects. Sludge management, policy formulation, and incineration are also covered. MFCS has become a hot topic for environmental researchers because it has emerged as a green source of energy with minimal anthropogenic environmental impact [35]. In the recent decade, the environmental science subject category has drawn a lot of attention because it produced the most journals.

One example is a highly cited journal article titled "Effective water/wastewater treatment methodologies for toxic pollutants removal: Processes and applications towards sustainable development" by Saravanan *et al.* which received about 417 citations from environmental science and chemistry subject categories [36]. Sarvanan outlines the key characteristics of membranes in wastewater treatment, including ion exchange membranes utilised in processes like reverse osmosis. Additionally, low-fouling antibacterial membranes are developed by surface grafting materials such as graphene oxide to improve water purification efficiency. Polymer-enhanced ultrafiltration and flocculation techniques use ion exchange membranes to effectively remove heavy metals from water, demonstrating the adaptability and efficiency of these membranes in water treatment. Furthermore, a prominent author submitted a work in the field of chemistry and chemical engineering that attracted significant interest from researchers [37]. The study offers significant information on how the use of ceramic membrane materials affects MFCs. In conclusion, each subject plays a crucial function in their research and academic literature.

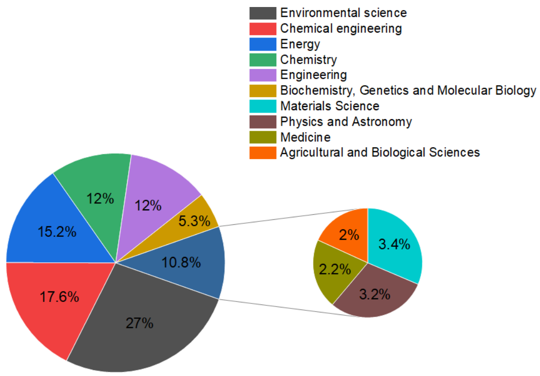


Figure 5 Works of literature retrieval from subject area categories

3.4 Leading Source Title

During the period that was given, ten leading source titles are currently prominent in the industry. Following the Chemical Engineering Journal (21), Chemosphere (21), International Journal of Hydrogen Energy (20), and Science of Total Environment (18) as the most productive journals, Bioresource Technology was the most productive journal, accounting for all publications with a total of 46 articles. In addition to having the highest number of citations, the paper that was published in the year 2022 in the Bioresource Technology journal published by Elsevier also received the highest number of references (136896 citations) and had a Cite Score of 19.1. However, according to the Cite Score 2023 report, the remaining five top journals all had Cite Scores of 10 or greater, which indicates that these papers had a significant number of citations during their publication. Furthermore, the title of the source is strongly connected to the subject areas. For instance, the title of the bioresource is categorised as belonging to the subject areas of environmental science and chemical engineering.

Table 3. Total publication and citation for leading source titles

Source Title	Summation of Publication	Summation of Citations
Bioresource Technology	46	2345
Chemical Engineering Journal	21	870
Chemosphere	21	870
International Journal Of Hydrogen Energy	20	622
Science Of Total Environment	18	599
Water Research	13	731
Journal of Environmental Chemical Engineering	13	372
Journal of Environmental Management	12	230
Membranes	11	108
Journal of Power Sources	10	326

3.5 Leading Countries and Institutions

Figure 6 charts the top ten most resourceful nations that have made significant contributions to the expansion of research activity about MFCs on a global scale. The fact that China and India were responsible for almost fifty percent of all publications across the globe is evidence of the significance of these two countries in the advancement of membrane-based MFC research. China came in first place with 123 publications out of a total of 501 publications, which is equivalent to 24.5% of the total number of publications worldwide. Because China is the country that receives the most citations on an annual basis, the majority of scholars likely cite articles that have been published in China. In terms of publishing output, India was listed as the second-most productive nation, with 118 publications. The United States of America, South Korea, Malaysia, Spain, Iran, Taiwan, Australia, and Saudi Arabia were among the countries that were allowed to receive. A negative trend has been observed in the number of papers published in this topic since the year 2014. However, beginning in 2016, the number of papers published began to steadily increase, and it is expected to reach its highest point in the year 2022.

Figure 6 Top 10 countries and number of publications displayed on the map

Table 4 Prominent countries that published most number of papers

Countries	Number of published papers
China	123
India	118
United States	53
South Korea	39
Malaysia	37
Iran	35
Spain	27
Taiwan	22
Australia	21
Saudi Arabia	18
Canada	16

From 2014 to 2024, the MFC study conducted by IEM included participation from ten research centres located in eight different nations, as shown in Figure 7. The performance analysis for institutions and countries revealed this information. This topic has been the subject of at least ten publications published by ten of these institutions throughout the course of the past ten years. In general, the most prolific institution was Dalian University Technology, which provided 25 documents. Harbin University, which is located in China, also contributed approximately 13 publications. There are sixteen documents from the India Institute of Technology Kharagpur and Anna University, both located in India. According to the number of publications that come from the United States of America, the Virginia Polytechnic Institute and State University as well as the Virginia Tech College of Engineering are among the most active institutions in the field of publications. In addition, equal number of publications were published by the Universiti Teknologi Malaysia, the Universiti Kebangsaan Malaysia, the Universidad de Murcia, and the Universidad Politecnica de Cartagena. As was indicated earlier, countries in the Asian region such as China, India, and Malaysia have made a substantial contribution to research. This is demonstrated by the fact that research is sponsored by the six universities that were mentioned earlier. The benefits of international collaboration are not limited to the expansion of one's network, the sharing of one's experience and the exchange of information; additional advantages include the development of an efficient plan for climbing the ranks.

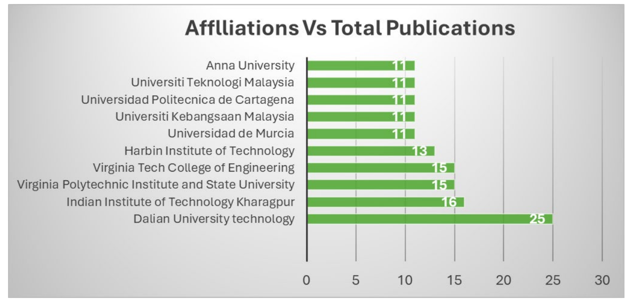


Figure 7 Institutions with the highest productivity. Among the ten institutions, only China (75.5%) and India (82.4%) have more than two-thirds of the single-country publications (SCP). This suggests that intra-country cooperation is highly developed in these nations. The lowest SCP rate, however, was in England (26.3%)

3.7 Dominant Authors in Past Decade

There were seven distinct nations represented among the top 10 authors in MFCs, and their connections were as follows: China, the United States of America, India, the United Kingdom, Spain, Saudi Arabia, and Malaysia. Based on the links that the authors had, the study that was done on MFCs was carried out in fields that were associated with the environment, energy, science, and engineering. The Chinese researcher Liu.L was at the top of the list, having published 19 works since 2014, having a 14-h index, and having 375 citations. He. Z and Ghangrekar.M are the second and third renowned authors associated with Washington University in the United States and India Institute of Technology Kharagpur in India, respectively. Both of these institutions are located in India. According to the VosViewer map that can be found in Figure 7, the top four writers are responsible for 50.66 percent of the publications and 65.46 percent of the citations. These authors are Logan E. Bruce, He. Z, Ghangrekar.M, Liu.L, and Feng.Y. With a record of 146 publications since 2004, 146 h-index, and 84,337 times citations, B. E. Logan, who is from the United States of America, was at the top of the list. The Dalian University of Technology and the Indian Institute of Technology Kharagpur are the institutions that are associated with the second and third best authors, respectively, Feng.Y and Ghangrekar.M. It is also essential to take note of the fact that forty-five countries succeeded in meeting the threshold criteria, as demonstrated in Figure 8. Collaboration among authors is shown by the connecting lines, and the size of the circle indicates the amount of contribution made by a country.

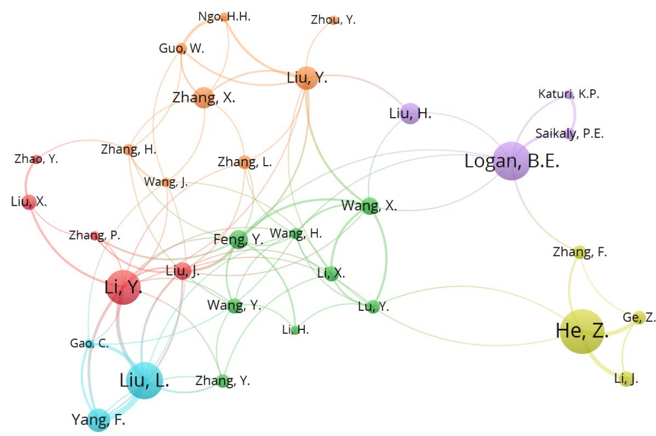


Figure 8 Visualisation of co-authorship network generated from VosViewer, each colours represent the relationship and collaboration among researchers, the size of the circle denotes the weightage and contribution of authors

The distinct contributions made by each author are presented in Table 5, along with the journal that received the most citations and interpretations. China has the most authors on the list of the top ten leading authors, according to a study that was conducted on the nation's most accomplished authors in the field [37]. According to the findings of the nation study, the fact that six of the ten authors are from either China or India lends credibility to the findings. Investigating the ways in which researchers work together within a specific topic is the focus of co-authorship analysis. Due to the fact that co-authorship is a formal form of intellectual collaboration among academics from China, the United States of America, and India (including linked author qualities such as affiliated institutions and nations), it is essential to have a solid understanding of how scholars engage with one another. As the theoretical and methodological complexity of research has increased, there has been an increase in the number of scholarly collaborations and partnerships. In addition, in order to publish articles on MFCS, researchers from Saudi Arabia, India, and the United Kingdom were the only ones who were not linked with any other nation. Guo [45] have stated that there are a few unanticipated factors that could potentially influence the dynamics of international collaboration. These factors include the existence of a large number of postgraduate students studying abroad, as well as viewing intellectuals and very considerable research funds.

Table 5 Contribution of authors by representatives their instutions and highly cited paper with the relevance to IEM in MFCs

Author	Affiliation	Total Publication	Total Citations	H-index	High-cited and relevant paper
[38]	Pennsylvania State University, University Park, United States	647	84337	146	Microbial fuel cells: Methodology and technology. (TC: 5151)
[39]	Washington University in St. Louis	261	19201	77	Towards sustainable wastewater treatment by using microbial fuel cells-centered technologies. (TC: 747)
[40]	Dalian University of Technology	524	21427	78	Recent advances in membrane bioreactors (MBRs): Membrane fouling and membrane material. (TC: 1647)
[41]	Indian Institute of Technology Kharagpur	312	10343	58	Performance of microbial fuel cell subjected to variation in pH, temperature, external load and substrate concentration (TC:482)
[42]	Dalian University of Technology	248	7474	46	Current progress of Pt and Pt-based electrocatalysts used for fuel cells. (TC: 348)
[43]	Department of Environmental Science and Engineering, Tsinghua University	132	6743	47	Separator characteristics for increasing performance of microbial fuel cells (TC: 297)
[44]	Universidad de Murcia,Spain	120	3663	36	Recent advances in supported ionic liquid membrane technology (TC: 351)

3.9 Highly Cited Insightful Articles

In the past 10 years, there have been a significant number of citations from five different studies that discuss the utilisation of membranes in the MFCs. A comprehensive grasp of the essential aspects of the topic can be obtained from the articles that are cited the most frequently. The top five MFCS articles are listed in Table 6, which includes a number of citations for each article. In the first place, Luo.T [21] focused on IEMs that were capable of fine-tuning ion selectivity. This included both perm selectivity between counter- and co-ions as well as selectivity between counter-ions of different valences. This is an essential component for the success of a wide range of technical processes, such as MFCS, ion exchange membrane bioreactors, and redox flow batteries. It is necessary to have a greater understanding of ion transport selectivity and economical membrane preparation processes in order to make use of IEMs in MFCs for sustainable development. The generalised selectivity order for common cations that are transported via regular CEMs with fixed sulfonic acid groups is as follows: Ba2+ > Sr2+ > Ca2+ > Mg2+ > H+ > (Cu2+ ~ Zn2+ ~ Ni2+) > K+ > Na+ > Li+ > Fe3+. It can be established that this arrangement is correct because the over-limiting current density of the system is significantly lower than the current density [46]. On the other hand, Anjum *et al*. [22] explain the potential developments associated with nanotechnology in the field of wastewater treatment. The article explained the utilization several nanomaterial classes in wastewater treatment techniques. This is divided into four main categories; the first category includes nano-adsorbents, which are frequently used to remove heavy metals from wastewater. Second, nano-catalysts with the capacity to eliminate both organic and inorganic pollutants include photocatalysts, electrocatalysts, Heterogeneous catalytic catalysts, and chemical oxidants.

The use of nanotechnology as a wastewater treatment technique has been mentioned in a number of publications as being among the most inventive technologies. Nanomaterials can be classified into three distinct categories, namely nano-adsorbents, nano-catalysts, and nano-membranes, according to the characteristics of the nanomaterials themselves. The removal of heavy metals from wastewater is made possible by the utilisation of nano-adsorbents. These heavy metals include Cr, As, Hg, Zn, Cu, Ni, Pb, and Vd. When it comes to improving membrane performance, nanoparticles are absolutely necessary [47]. According to Palanisamy *et al*., [48], numerous kinds of polymeric membranes have been developed for the purpose of being utilised in operating systems in MFCS that have variable degrees of power generation and proton mobility. Hydrocarbon polymer membranes, perfluorinated polymer membranes, and composite membranes are the three forms of membranes that are typically utilised in various membrane applications. The findings of Singha *et al*. [49], indicate that Nafion membranes are among the most successful membranes for MFCS, despite the fact that they are expensive and do not have any biocompatible properties. In order to address the issue of cost, the Nafion ionomer has been coupled with a number of other polymers and inorganic additives (including SiO2, TiO2, ZnO2, and others) to generate an effective Nafion-based polyethylene methylene (PEM) [50].

Another method involved the synthesis of a novel semi-fluorinated sulfonated poly triazole and its cross-linking with polyvinyl alcohol (PVA) for MFCs use. In this system, crosslinking increased MFCs oxidative stability, dimensional change, and water intake control. The Nafion membrane in MFCs has been replaced with various alternative materials, particularly sulfonated polymers, as membranes or separators. Membranes with various levels of sulfonation (DS) in sulfonated PEEK (SPEEK), such as DS-20.8%, 41%, 63.6%, and 76%, were developed to evaluate MFCS performance. The DS membrane with a 63.6% opacity performed the best during MFCS operation. Power density, CE, and COD removal percentage can all be increased with enhanced DS in SPEEK polymers, but other performance indicators occur due to membrane structural changes and the formation of useless cations during MFCS cell operation. Additionally, phenol and acetone have been extracted from wastewater while also producing energy using MFCS with a SPEEK membrane. This green technology, MFCS, was applied to eliminate phenol and acetone from wastewater.

Lastly, but certainly not least, researcher Do M.H *et al*., [51] presented a complete overview of microbial fuel cells (MFCs) and the prospective applications of these cells in the treatment of wastewater and the production of energy. Within the scope of this study, the obstacles and opportunities that are related with MFC technology are discussed. These challenges and opportunities include concerns such as membrane fouling, high internal resistance, electrode materials, and scalability for large-scale applications. In addition, a number of other elements concerning microbial fuel cells (MFCs) were reviewed, including the many kinds of membranes that are utilised in these systems. Several important points related membrane types in MFCs are highlighted in the research, including the following: (PEM) stands for proton exchange membrane. When it comes to MFCs, PEMs are an essential component in the process of separating the anode and cathode compartments.The creation of electrical current is made possible by these membranes, which make it easier for protons to go from the anode to the cathode along the electrochemical chain.

When it comes to optimising the performance and efficiency of MFCs, the selection of an appropriate PEM is a crucial component. In the second place, we will discuss conductive membranes, which are a new technique that involves the utilisation of conductive membranes that have been modified using materials such as polypyrrole in order to improve electron transmission and decrease membrane fouling. It is possible to increase the overall performance of the system by combining membrane bioreactors with bio-electrochemical cells equipped with conductive membranes [52]. This can be accomplished by preserving the electrical potential and minimising fouling. Thirdly, membrane fouling is a significant problem that can have an effect on the efficiency of MFCs by obstructing the movement of ions and electrons through the membrane [53]. It is vital to implement strategies to decrease membrane fouling in order to improve system efficiency. Some examples of these strategies include the use of new membrane materials and the integration of membrane bioreactors with MFCs. In conclusion, the discussion on the different types of membranes used in MFCs highlights the significance of selecting appropriate membranes in order to improve the overall performance of microbial fuel cell systems, as well as the transport of electrons and the transfer of protons. Strategies to combat membrane fouling and increase conductivity through the usage of innovative membrane materials are necessary for optimising the efficiency of IEM MFCs in wastewater treatment and energy generating applications. A condition known as membrane fouling can reduce a membrane's effectiveness and lifespan when unwanted components accumulate on its surface or within its holes.

Table 6 Top 5 Highly Cited Relevant Articles of IEM in MFCs

No.	Authors	Title	Year	Cites	Cites per Year
1	Luo T., Abdu S., Wessling M.	Selectivity of ion exchange membranes: A review	2018	713	122.50
2	Anjum M., Miandad R., Waqas M., Gehany F., Barakat M.A.	Remediation of wastewater using various nano-materials	2019	490	99.80
3	Saravanan A., Senthil Kumar P., Jeevanantham S., Karishma S., Tajsabreen B., Yaashikaa P.R., Reshma B.	Effective water/wastewater treatment methodologies for toxic pollutants removal: Processes and applications towards sustainable development	2021	397	138.67
4	Palanisamy G., Jung H.-Y., Sadhasivam T., Kurkuri M.D., Kim S.C., Roh S.-H.	A comprehensive review on microbial fuel cell technologies: Processes, utilization, and advanced developments in electrodes and membranes	2019	357	72.00
5	Do M.H. , Ngo H.H. Guo W.S., Liu Y. Chang S.W., Nguyen D.D. Nghiem L.D. Ni B.J.	Challenges in the application of microbial fuel cells to wastewater treatment and energy production: A mini review	2018	220	45.43

3.10 Keywords

Specifically, the author mined the keyword that was declared in MFC documents by using the same record that was utilised earlier. The majority of the document is comprised of between five and ten separate keywords. (1) An Author Keyword and (2) an Index Keyword are the two categories of keywords that are available. Authors make the decision to use the 'Index keyword' as the primary priority, while the 'Author Keyword' is used in situations where there is no accessible 'Index keyword'. Two of the keywords are missing from a certain document. It would appear that this document is only contributing less than thirty percent of the entire data, hence the author has decided to remove it off the list. The total keywords have been completed for the study after numerous stages of filtration of thesaurus words have been applied, including sorting, text to the column, arrangement in a single column, and trimming. Following the utilisation of the ' remove duplicate' function and the 'search and replace' function, the writers were able to finalise a total of one hundred distinct keywords that have been utilised in MFC-based papers during the course of the past ten years. Subsequently, the author arranged the keywords in descending order and discovered that they were classified into three distinct subject groups. Appears to have been a manual procedure; the author decided to take into consideration the top 100 terms in the list, which encompasses 501 records (nearly 73.2%).

Keywords for a research study contain important information about the task. Keyword co-occurrence analysis is a prominent research approach that helps readers identify research differences and developing patterns in a specific field shown in Figure 9 and 10. It depicts the intrinsic relationship between terms in a certain topic and the discipline's study horizons. The data collection, which included 501 research publications and reviews articles, was analysed for key terms using the VOSviewer software, as described in Section 2.1. VOSviewer detected 1150 keywords, 100 of which passed the threshold criterion of at least ten repetitions of the terms. After filtering the keywords, a final map was created with 105 relevant keywords. Figure 10 shows three clusters. The majority of widely read publications focused on MFCS's application in wastewater treatment. The key hot research field right now is MFCS performance improvement. As indicated in the keyword analysis section of Figure 8, a few more keywords that have recently gained attention and are currently under development include proton exchange membrane, ion exchange membrane, maximum power density, cost-effectiveness, and coulombic efficiency. As a result, the keywords mentioned above represent current hot themes in the field. In contrast, the probability of co-occurrence increases with the thickness of the connecting line [54]. According to research, "microbial fuel cell" is the most commonly used abraxas, followed by "wastewater". According to Figure 8, which elaborates on this issue, 2015 and 2016 were pivotal years for microbial fuel cells. Furthermore, since 2016, MFCS research has shifted towards graphene, air cathodes, catalysts, nitrogen removal, and nanoparticles. The word "waste" was used 16 times in total, including allusions to activated sludge, anaerobic sludge, excess sludge, food waste, municipal solid waste, and organic waste. According to our findings, the total number of keywords connected to liquid-phase wastes amounted for approximately 30% of all semi-solid/solid-phase wastes. The goal is to increase Coulombic efficiency while simultaneously improving the bioelectrochemical process. Microbial community research in "Cluster 1 materials" focused mostly on microbial diversity, growth, structure, electrodes, biodegradation activity, and so on.

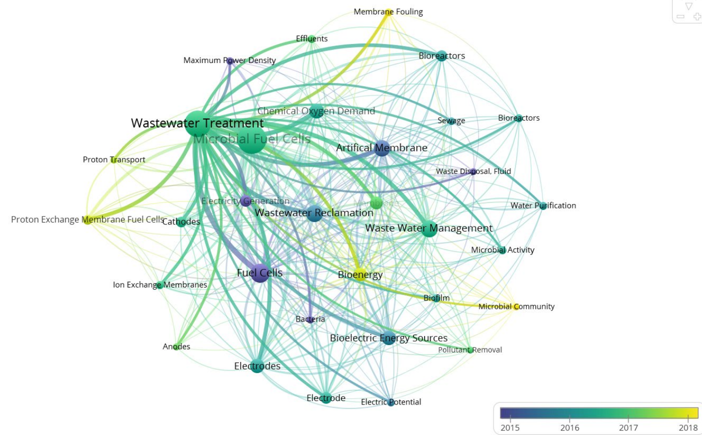


Figure 9 A snippet of the keywords based bibliometric map produced using network density based on active years of publications

The "Cluster 1 materials" category mostly consists of eleven high-frequency phrases. One way to summarise the research that has been done on IEM MFCs is that it involves the preparation, modification, and performance improvement of materials that are used in the internal components. These materials include novel membrane materials and electrodes. There is a connection between the keywords "proton exchange membranes," "proton transport," "ion exchange membranes," and so on, and the fabrications of synthetic materials. Traditional materials have been replaced by new crucial materials in the field of IEM, while keywords that include "artificial membrane" and "bioenergy" provide more information about the properties of the materials. "Cluster 2 design" is comprised of 21 hot picks, including "wastewater treatment," "wastewater reclamation," and "pollutant removal." These hot items are involved in wastewater desalination and management, specifically about the removal of harmful pollutants and bioremediation [55,56,57]. These hot items can be classed as application research. The use of model simulation is essential to the verification of the structure design in IEM experiments. From the design stage through to the implementation stage, there are a few challenges that need to be addressed and resolved. One example is the efforts that researchers have been making to find answers to problems with the production of bioenergy and the management of wastewater. Using the terms "membrane fouling," "effluents," and "bioreactor" as the keywords in the investigation, it was discovered that "Cluster 3 mechanisms" are responsible for the phenomenon. This is due to the fact that the permeability of the membrane has an effect on the transport of protons and the durability of the battery. Additionally, the catalysts present in the oxygen reduction reaction under various operating circumstances also affect the stability of the battery. Additionally, several researchers attempted to provide an outline of the mechanisms that may be responsible for membrane fouling [58]. These mechanisms include the durability of the material and the stability of ion transfer.

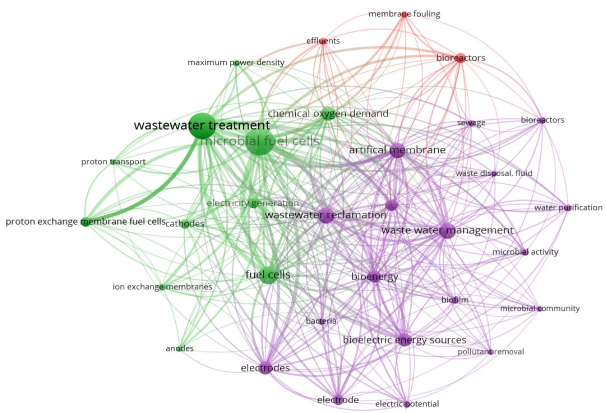


Figure 10 A snippet of the keywords based bibliometric map produced using network visualisation in overlay mode

4.0 IMPORTANCE, LIMITATIONS AND RECOMMENDATIONS

Membranes that exchange ions are utilised in a variety of processes, each of which is distinct from the others in terms of their fundamental notion, their practical application, and their technical significance. On the other hand, membranes that carry electrical charges are utilised in each of these processes in order to govern the movement of ionic species and to selectively separate them from a mixture that contains neutral components. The coupling of the transport of electrical charges, such as an electrical current, with the transport of mass, i.e. cations or anions, through a perm-selective membrane as a result of an electrical potential gradient that is either applied from the outside or generated from the inside is the fundamental principle that underpins all IEM separation processes [59]. This principle is the basis for all IEM separation processes. Membranes are incredibly significant components of microbial fuel cells (MFCs) because they make it possible for a wide range of activities to take place and they enhance the efficiency of the energy storage device as a whole. The following is a list of the significant roles that membranes in microbial fuel cells are responsible for performing:

- Ion transfer: Microbial Fuel Cells (MFCs) is facilitated by membranes, enabling the movement of ions between the anode and cathode compartments to support the electrochemical reactions [60,61].
- Preventing Crossover: Membranes restrict reactants from crossing between the anode and cathode compartments, such as substrate loss from anode to cathode and dissolved oxygen penetration from cathode to anode.
- Control of Oxygen Diffusion: Ion exchange membranes regulate the transport of oxygen between the cathode and anode compartments. High levels of oxygen diffusion to the anode might hinder microbial activity and electron transfer activities, impacting the MFC's overall effectiveness [62].
- Maintaining Reaction Condition: Membranes play a crucial role in maintaining optimal conditions for the anode and cathode electrodes to ensure efficient energy production in MFCs by separating them.
- Antifouling Mitigation: Membranes can reduce biofouling by altering the microbial makeup of the biofilm and encouraging the growth of particular microorganisms [63].
- Microbial Diversity: Membranes can influence the microbial diversity of anodic and membrane-surface biofilms in MFCs, which can affect the composition of microbial communities and potentially affect system stability and performance.
- Enhancing Power Production: Some membrane materials, including poly [2,5-benzimidazole] impregnated non-woven fabric filters, have been proven to increase power generation in microbial fuel cells (MFCs) by enhancing the effectiveness of electron transfer mechanisms [64,65].
- Structural Properties: Membranes can affect the structural characteristics of biofouling layers, including extracellular polymeric material concentration, thickness, and heterogeneity, which can subsequently affect the overall efficiency of MFCs [66].

In a nutshell, membranes in microbial fuel cells have various important functions such as aiding ion transfer, preventing crossover, maintaining reaction conditions, reducing biofouling, impacting microbial diversity, and boosting power production. These roles are crucial for the effective functioning of MFCs as shown in Figure 11. Progress in membrane technology remains crucial for improving the efficiency and economic feasibility of microbial fuel cells in converting bioenergy.

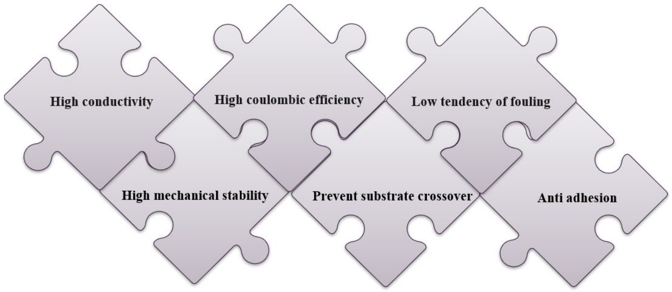


Figure 11 Crucial elements for ion exchange membrane

Example based on current research:

For many reasons, including their beneficial effects on the environment and their high efficiency in energy conversion, solid polymer fuel cells are anticipated to become the fuel source for automobiles of the next generation. Electromotive force is a property that is influenced by the electrolyte film [68]. Because of the significant im

pact it has on protonic conductivity, this microstructure is well-known. We can get knowledge regarding the development of high-performance elements if we make use of this microstructure in order to comprehend the dynamics of the ion transport process and the consequences of the interactions between polymer and water. A sulfonated polymeric membrane, such as sulfonated polysulfone, is frequently utilised in the dewatered sludge that is based on MFCs. Figure 12 depicts the before and after picture of the system that is utilised throughout the process.

Figure 12 Example illustration of application of the ion exchange membrane in microbial fuel cell-based dewatered sludge

PEM based on polysulfone, more precisely sulfonated polysulfone (SPSf), was the subject of the current investigation, which concerned both the physical and chemical characterization of the mixture as well as its formulation. For the purpose of fabricating high-performance blended proton exchange membranes, the wet phase inversion method was utilised, and three distinct solvent compositions were utilised in the synthesis of SPSf [67]. An examination into the use of SPSf membranes in MFCs has been carried out in order to investigate their potential as PEM. This was done to enable the simultaneous production of electrical energy and the treatment of wastewater.

Figure 12. Example illustration of application of the ion exchange membrane in microbial fuel cell-based dewaThe bibliometric study that is presented in this paper has a few inherent limitations to a certain degree. On the one hand, the data source is relatively peculiar, both in terms of the data and the techniques, because it is exclusively taken from Scopus. This implies that the data source is a particularly peculiar source. There are other databases that are not taken into consideration, such as Web of Science and Lens [68]. Furthermore, the maps that are generated by the VOSviewer software only display a single style, and the algorithm is rather subpar when the amount of data information is considerable. However, the software does make maps. When it comes to the conclusions of study, on the other hand, the number of publications that writers have produced does not adequately reflect the extent of their influence in the field of IEM research. Additionally, due to the fact that they have less connections with other writers, certain authors are more likely to be overlooked in the map. This may lead to the exclusion of some sample literature on IEM that was published by such authors. In addition, the research that is carried out in the field of MFCs covers a wide range of topics, but the keywords that are derived from bibliometric approaches are considered to be rather basic. This has the effect of making it more difficult to form an all-encompassing opinion regarding the trends that will emerge in the decades to come. Through the use of titles and abstracts to narrow the search for "microbial fuel cell," it is possible that the search result will not include all of the studies that are associated with MFC that are available on Scopus. This is because some researchers did not refer to their systems as MFC; rather, they used various terminology (such as bioelectrochemical systems and photovoltaics). Additionally, due to the absence of author keyword information from certain publications, such as RSC Advances, Scientific Report, PLOSOne, and others, the cooccurrence analysis of author keywords only covered sixty percent of the 501 articles. It is advised that future research be conducted to compare the results obtained from a number of different databases, such as Scopus and Web of Sciences [69,70]. For example, the search results from Web of Science indicate automatically the articles that are the most popular in the field. This is accomplished using a feature known as "hot paper", which is a feature that is still absent from Scopus research databases. This hot document feature highlights important works that are recognised extremely quickly after they have been published, as evidenced by a considerable number of citations that occur relatively short after

publication. An investigation that is more extensive will benefit from the utilisation of bibliometric analysis that is carried out using a variety of data sources.

5.0 CONCLUSIONS

The special focus of this study is on the construction of a membrane that functions well during the MFCS era. The material for this study is retrieved from the Scopus database through the use of bibliometric analysis. Within a span of ten years, from December 2014 to 2024, the publications were made available to the public. A comprehensive review of membrane harnessing and its development in the context of the current MFCS research trends has been provided by this study, which is based on 501 publications. Over the past ten years, there has been a significant increase in the quantity of publications, and it is anticipated that this pattern will continue. We were able to identify countries and academic institutions such as China and India that have a substantial archive of works and strong ties with other countries around the world. Researchers from other countries may be able to broaden the scope of their research cooperation by utilising these organisations. In this article, we have discussed some issues that are now receiving a lot of attention from researchers. These topics include the application of nanotechnology to polymer membranes (using nanomaterials) and the manufacture of membranes, both of which have been the subject of research in the past and may become popular research topics in the future. To add insult to injury, there are ongoing efforts to find less expensive membrane materials that have reliable qualities, may already be widely available, and can perform with superior properties and running efficiently in MFCS facilities. For the purpose of determining sustainable development, future research must take into consideration the scaling up of MFCS by utilising this modified membrane in addition to life cycle evaluation.

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Data Availability Statement: The data that support this study are available in the article.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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