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The Scientometric Evaluation of The Research on Yeast Microbial Fuel Cells as A Promising Sustainable Energy Source

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Abstract- The yeast microbial fuel cells (MFCs) are promising energy conversion devices that use yeast as a biocatalyst to convert chemical energy to electrical energy. Yeast MFCs have garnered considerable interest due to their ability to create electrons, low cost, moderate functioning at ambient temperature, ease of growth, and specificity for substrates. The scientometric analysis of the Web of Science database was carried out to identify the historical research trend related to yeast MFC of 148 high-quality publications from 2005 to mid-2022. The detailed analysis starting with the notion of energy generation during fermentation. Noteworthy breakthroughs in the creation of electrode materials, mediator addition, and in-situ application of yeast MFCs are highlighted. The analysis results revealed that Asian researcher dominated the on yeast MFCs topic, with India and South Korea leading the way. Diponegoro University researcher has the most publications on yeast MFCs, while a researcher from Pennsylvania State University has the most citations. This article may help the yeast MFCs researchers to navigate the overview of this research area and identify the most significant articles, countries, researchers, potential transdisciplinary collaboration and prolific contribution by researcher on this topic. These findings also reveal the future of yeast MFC research trend.

Keywords- Bioenergy; *Saccharomyces cerevisiae*; Web of Science; Scopus; Impacted author; International collaboration

1. INTRODUCTION

The depletion of non-renewable energy sources such as oil, natural gas, and coal, combined with the growth in human population and impacted by climate change, has forced many people to compete to find alternative energy sources, both new and/or renewable energy sources [1]. Microbial Fuel Cells are (MFCs) one of the new and renewable energy sources. MFCs are devices that can transform chemical energy inside organic materials into electrical energy by using microorganisms as biocatalysts [2]. MFCs offer several benefits, including the ability to function at low temperatures, in-situ energy conversion, fairly easy system operation, and the ability to be applied to areas with limited electrical infrastructure [3,4]. However, other flaws remain, such as the modest output of electrical energy (mW/m^2), which poses a challenge for researchers [5,6]. Several efforts have been undertaken to increase the performance of MFCs, including modifying the electrodes [7], recombining microbes as biocatalysts [8], modifying the separating membrane [9], and redesigning the MFCs system or reactor [10].

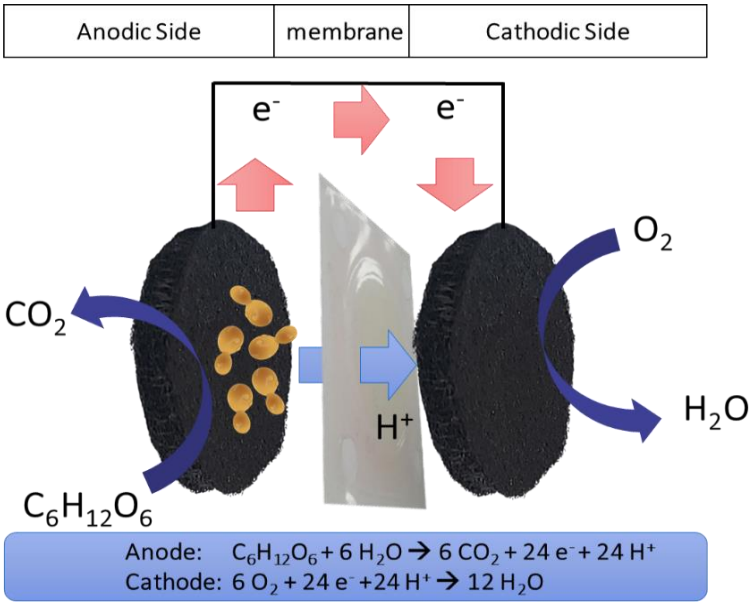

Figure 1. Schematic of yeast microbial fuel cells

Yeast MFCs are one type of MFC in which yeast of various species are utilized as biocatalysts to generate electrical energy from organic materials [11]. Some of the benefits of yeast MFCs include their ease of operation, the availability of yeast as a biocatalyst, the low cost of yeast, and the ease with which yeast may be cultured to ensure long-term sustainability [12-14]. Yeast MFCs generate electrical energy by using glucose-based materials or the like as substrates [15,16]. Yeast consumes glucose, which subsequently undergoes glycolysis and the

Krebs cycle, which initiates the redox processes NAD/NADH and FAD/$FADH_2$ to produce electrons [17,18]. The electrons then move via the electron transfer chain before departing the yeast cell's surface. The concentration of the yeast cells, anaerobic and aerobic states, substrate concentration, temperature and agitation rate will affect to performance of yeast MFCs. Figure 1 depicts the yeast metabolic pathway from glucose consumption to electron production. In general, the reactions of yeast metabolism are completely described in equation (1):

$$C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 24e^- + 24H^+ \quad (1)$$

MFC technology, notably yeast MFCs, has advanced at a breakneck pace. Davis and Yarbrough [19] were the first to publish a paper on MFCs, which discussed the use of hydrocarbons as food for microbes in their efforts to produce electrical energy. Obviously, numerous hurdles have been addressed by researchers over the last 59 years, thus they have been innovative in overcoming the problems that exist in MFC. The study of scientometric and bibliometrics are two methods for identifying the trend and advancement of MFCs technology. Wang et al., [20] served the bibliometric review on bioelectrochemical systems in general, without focusing on MFCs in particular, with a database from 1991 to 2014 and stated that China was the most productive country conducting research related to bioelectrochemistry, including MFCs, and bio-cathodes are frequently discussed. Mercuri et al., [21], on the other hand, studied MFCs associated with the database from 1985 to 2015, but with an emphasis on marine fresh water and microbiology. While Khudzari et al., [22] analyze the research trends of MFCs in diverse applications from 1962 to 2017, the study is concerned with publication output, co-authorship, associated countries, and author keywords. Databases from several sources, including Web of Science (WoS) and Scopus, were utilized to review the available literatures.

The two main indexes of scientific publications, WoS and Scopus, are frequently employed as data mining sources in the literature review processes [23]. Both index separate journals, albeit the majority of their indexing overlaps [24,25]. WoS is a Thomson Reuters Institute of Scientific Information (ISI) product founded in the 1960s by Eugene Garfield. The WoS database has 12 million articles from over 5000 journals [26], which is less than Scopus' 78 million articles from 5500 journals [27]. WoS, on the other hand, stated that the journals included are of high quality and comprehensive, which demonstrates that WoS can only index journals of extremely high quality [24,28,29]. WoS offers numerous features that Scopus does not have, including Cited Reference Search (CRS) to identify previously published and cited papers and "Related Records" to determine which writers are referring the same record [30]. Simply told, WoS includes functionality and an easy-to-use user interface. Because of additional indexing, the WOS database is a more academic source than the Scopus database [31]. WoS offers extensive coverage dating back to 1990, with the majority of its publications written in English [32].

Science mapping, also known as a bibliometric network visualization tool, is frequently used to generate representations of the various intellectual contributions of various yeast MFC researchers, as well as to graphically depict unimaginable trends regarding research collaboration networks, countries, research outlets, keywords, and so on [33,34]. Bibliometric data extracted from bibliographic databases may be utilized to quantitatively map networks and patterns using the quantitative science mapping technique [35]. Scientometric analysis is a subtype of science mapping, and it will be actively employed in this research because it may be used to achieve the objective of unraveling the network connecting entities of interest, hence offering insight into trends in a specific area of interest [36]. IN-SPIRE, CiteSpace, BibExcel, CoPalRed, SciMAT, CitNetExplorer, Gephi, VOSviewer, Network Workbench Tool, and VantagePoint are some of the available science mapping tools [37-43]. They all have their own unique features, limitations, and benefits.

Based on the studies above, yeast MFC research topics have the potential to be investigated further. This subject is only discussed in a few articles. The database is taken from WoS and processed using VOSviewer. The objectives of this paper are as follows: (i) to analyze the distribution pattern of journal articles on the topic of yeast MFCs, (ii) to highlight research focus and common terminology in the yeast MFCs topic, (iii) to see the contributions of the authors, the leading and most productive countries publish journal articles on yeast MFCs, and (iv) to provide insight into potential collaboration and future research directions on yeast MFCs. Several of the above-mentioned scholars have conducted scientometrics research, although the scope of MFC is expansive in general. The scope of this study was confined to yeast MFCs; hence this is an academic novelty. We hope that this paper will become a cornerstone for research on the topic of yeast MFCs, and that it will be helpful to researchers, policymakers, communities, and stakeholders in developing technology and future potential research and applications of MFCs, particularly yeast MFCs as an environmentally friendly new and renewable energy source.

2. METHODOLOGY

To obtain the outcomes of scientometrics, various processes must be completed, including data searching and data mining to develop a database of the topics that will be examined, followed by the data extraction and data mapping to determine the trend of the topic from year to year. The advantages stated in the previous sections guided the selection of database source and science mapping tool. In this study, the process of data searching, mining, extracting, and mapping is summarized in Figure 2.

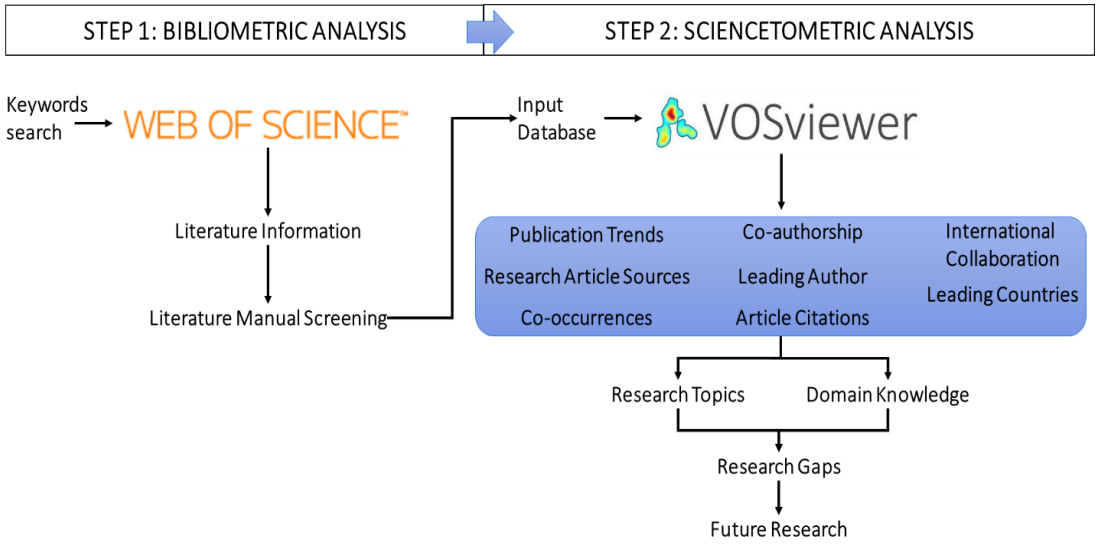

Figure 2. Outline of research design

2.1. Data searching and mining

The online search within WoS database that used for data mining was completed in July 2022. The search of the published scientific literature was performed after the selection of the online version of WoS as the database. For the selection of search strings in all fields, the publications found for this study contained of ***yeast "microbial fuel cell"*** as keyword. This due to (i) articles with the words ***yeast microbial fuel cell*** in the title to appear, as well as (ii) publications with the words ***yeast*** in the title and the term ***microbial fuel cell*** in the abstract and/or keywords to appear in the list. This query yielded around 148 documents, including journals and proceedings related to yeast microbial fuel cell, with the oldest paper launched in 2005. This scientometric analysis is based only on the WoS database and only the keyword of ***yeast "microbial fuel cell"*** were used as search terms to find the sample documents for the analysis. The list of search results also covered WoS categories, authors, affiliations, journal titles, publishers, funding agencies, research areas, countries/regions, and the WoS index from all geographical regions. The data mining results are then exported via EndNote online, EndNote desktop, add to my Publons profile, plain text file, RIS, BibTex, Excel, tab delimited file, printable HTML file, and InCites. Further, the obtained bibliometric data in ***.txt*** format was uploaded into VOSviewer for scientometric analysis. Similarly, database publications containing the term ***"microbial fuel cell"*** were extracted for comparison. Therefore, all data mining results presented in this work should be interpreted in the context of these limitations.

2.2. Data mapping

VOSviewer (version 1.6.17), created by the Centre for Science and Technology Studies at Leiden University in the Netherlands, was applied in this study since it is open-source and has attributes appropriate for this investigation, as evidenced by prior published publications [44-

46]. The scientific documents found in the online search were analyzed in detail to provide a firm base for a better understanding of the research panorama, which could help to identify current and future strategies within this field. Prior to scientometric analysis, the format of the database file to be imported into VOSviewer must be validated. The function "create maps based on bibliometric data" in VOSviewer was then selected, followed by "read data from bibliographic database files." The database file (in the form of a .txt file) is then imported in order to proceed to the main options. VOSviewer offers main option analysis types such as co-authorship, co-occurrence, citation, bibliographic coupling, and co-citation. The mapping resulted in a link—connection or relation between two items, where each link has a strength, expressed by a positive integer number. The greater this number, the stronger the link.

3. RESULTS AND DISCUSSION

3.1. MFC and yeast MFC annual publication trend

From WoS database, 7497 MFC research papers were published from 1985 to mid of 2022. Unfortunately, the first publication in 1962 by Davis and Yarbrough [19], was not found in the WoS database. Several MFC studies began in the late 1980s (1985-1988) and mid 1990s (1994-1996), although the number was small. As demonstrated in Figure 3a, interest in MFC research began to increase in 1999, climbed dramatically in 2003, and more than doubled in 2007/2008. Since then, the number of yearly papers on MFCs has increased, and the topic of MFCs has begun to be preferred by researchers as a response to the depletion of fossil fuels and the issue of climate change. The increase in paper on MFCs occurred until 2021 and then fell by 57% in mid-2022, which is attributed to the COVID-19 pandemic. There are various distinct explanations causing the paper's drop in MFCs. First, research fundings are mostly focused on COVID-19-related research, therefore MFC research is not a priority. Second, research on MFCs is typically conducted over a lengthy period of time (weeks or months), making it difficult for researchers to monitor the incubation process for MFCs, or even to do so at all owing to workplace closures in some countries.

Meanwhile, research on yeast MFCs began in 2006 and since then has fluctuated [47]. In comparison to MFCs in general, research themes linked to yeast MFCs do not dominate, as seen in Figure 3a, where articles on the topic of yeast MFCs accounted for just 2.5 % of all papers on the topic of MFCs. This demonstrates that researchers are unfamiliar with the issue of yeast MFCs. The MFCs system, which has not yet been established, also participates. There are no more than 20 papers about yeast MFCs published each year. The researchers favor the use of other bacteria that produce more electrons, such as *Aeromonas hydrophila*, *Geothrix fermentans*, *Shewanella putrefaciens*, *Geobacter sulfurreducens*, *Geobacter metallireducens*, and *Clostridium butyricum* [48-51]. It is due to yeast is expected to be sluggish in creating and transporting electrons to the electrode, necessitating the use of an external mediator.

Nevertheless, the trend of papers linked to yeast MFC continued to climb until 2020, when it declined again owing to issues associated to COVID-19 (Figure 3b).

The field of study on yeast MFCs has not been well investigated, therefore this has the potential to be explored. In contrast to MFCs that normally focus on the environment, analysis in the field of study suggests that the potential of yeast MFCs as energy sources is the major emphasis in the study of yeast MFCs. This is evidenced by the number of publications in the category of energy fuels (47 articles), which is followed by biotechnology applied microbiology (36 articles), electrochemistry (33 articles), engineering (34 articles), and chemistry (32 articles). This demonstrates that yeast MFCs are part of an interdisciplinary field with diverse educational backgrounds. It is intended that this type of multidisciplinary study would boost acceptability of yeast MFCs technology, which is being researched to be eventually developed on a large scale as a form of application of the waste-to-energy (WtE) paradigm. The findings also demonstrate that the publications employed in this study were only published in English. The growth of research on yeast MFCs is also influenced by article accessibility, with 34 publications published in all open access journals, 20 articles in gold journals, 11 articles in green published journals, and 11 articles in green submitted journals. This demonstrates that many researchers use all open access journals as a way of faster distributing the topic of yeast MFCs, despite the fact that the field has not been extensively researched, indicating that more cost-effective introduction procedures are essential.

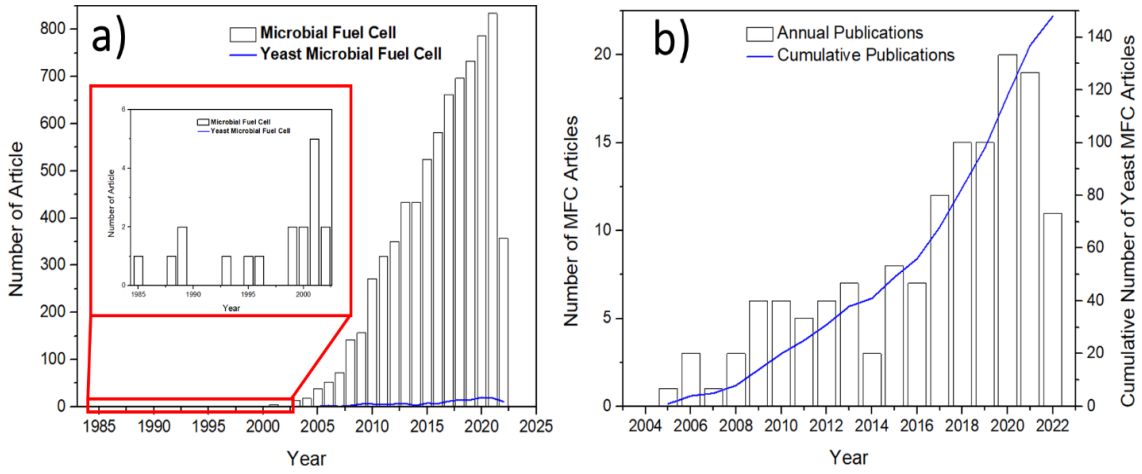

Figure 3. a) Number of published articles on MFCs and yeast MFCs, while b) the annual and cumulative numbers of research articles on yeast MFCs. All published articles are indexed in Web of Science

3.2. Preferred Journal

A journal is one of the research media sources where research results are presented to the research community, particularly scholars with study interests in the same field, for development and commercial purposes. Each journal has a specific scope that is determined by

the intended readers' field or study area. As a result, it is critical to analyze the trend mapping of research subject articles in journals. Table 1 shows the preference for journals as MFCs research sources. Bioelectrochemistry is the most productive journal, accounting for 6.87% of all publications, with 9 articles, followed by Bioresource Technology (5.34%), Journal of Power Sources (4.58%), International Journal of Hydrogen Energy (3.05%), and Journal of Bioscience and Bioengineering (3.05%). According to our findings, three publishers with reasonably good reputations, including Elsevier, Taylor & Francis, and Wiley, dominate the top 15 most productive journals.

Table 1. The top 15 most productive journals on yeast MFCs research

Journal Name	Number of Articles
Bioelectrochemistry	9
Bioresource Technology	7
Journal of Power Sources	6
International Journal of Hydrogen Energy	4
Journal of Bioscience and Bioengineering	4
Applied Energy	3
Biosensors and Bioelectronics	3
Chemosphere	3
Energy	3
Energy Sources Part A	3
Advanced Micro-Device Engineering	2
Biochemical Engineering Journal	2
Bioengineered	2
Biomass and Bioenergy	2

Figure 4 shows a network of scientific journals that publish publications on yeast MFCs. The number of papers from each research outlet is shown by the different node sizes. Figure 3 shows that Bioelectrochemistry and Bioresource Technology has a very large node size when compared to the others, followed by the Journal of Power Sources and the International Journal of Hydrogen Energy. This confirms that their contribution to the advancement of knowledge in yeast MFCs is very high, and that the cross-quotation or strength of the links between the four is also very strong. Figure 4 also demonstrates the pattern of the years in which the writers published their works on yeast MFC. In the early years of MFC yeast research, publications were published in the Journal of Chemical Society, Applied and Environmental Microbiology, Fuel Cells, and Yeast. This topic was further investigated and widely published by Bioelectrochemistry and Bioresource Technology, a journal whose coverage is strongly linked to yeast MFC, between 2012 and 2016. Yeast MFC articles, on the other hand, are progressively being published in the Journal of Hydrogen Energy and the Journal of Power Sources between 2017 and mid-2022. This implies that the two publications' confidence in the

development of yeast MFC has grown. This is quite useful in presenting the topic of MFC yeast, as both journals have high Impact Factors and strong reputations. The yeast MFC research topics are currently unable to compete with similar topics in Bioresource Technology and Bioelectrochemistry, such as Plant Microbial Fuel Cells, Microbial Electrochemical Technology, Microbial Electrolysis Cells, or Microbial Desalination Cell Technology, resulting in no articles on yeast MFC being published in either journal in the last 5 years.

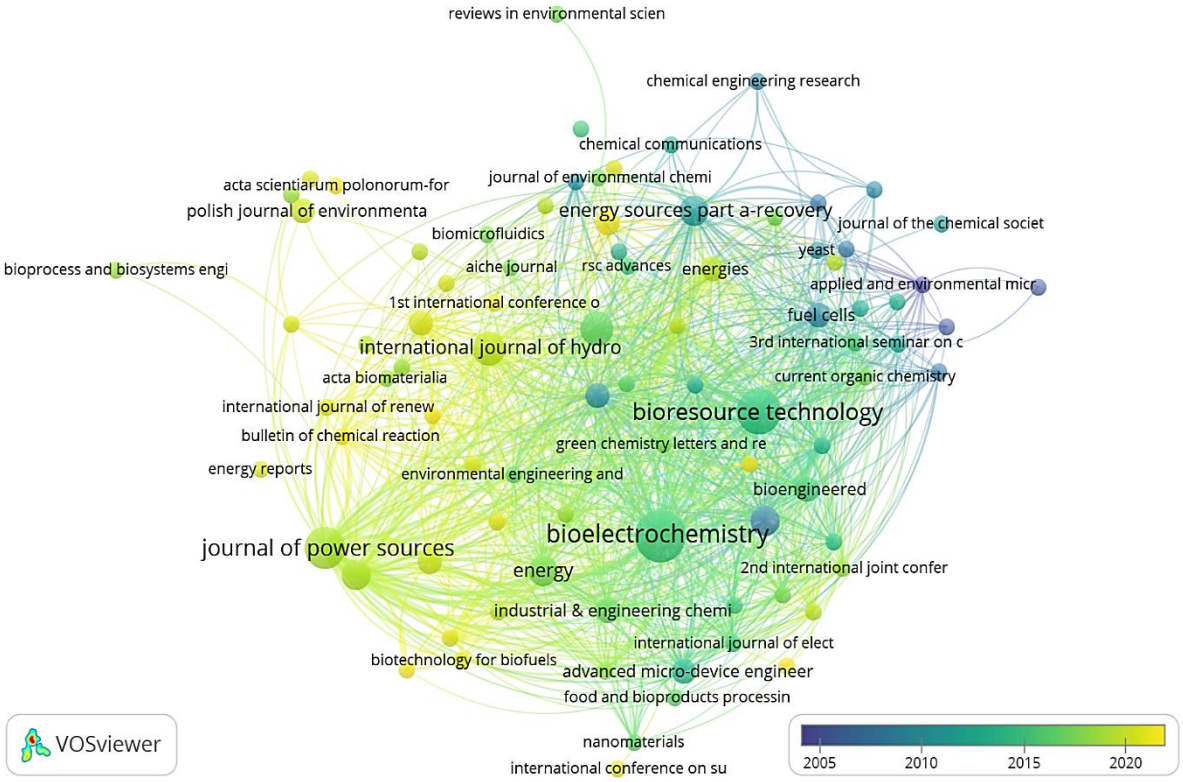

Figure 4. Overlay visualization of the time range articles were published in different research journal

It's interesting to observe the relationship between the number of articles and the number of citations and the Journal Impact Factor (JIF) or Total Link Strength as shown Table 2. There is just one paper about yeast MFCs in Nature Reviews Microbiology, although it has been cited 407 times. This is proportionate to the journal's relatively high JIF [52,53]. However, as compared to other publications, the Total Link Strength in this journal is quite low, indicating that the content of the yeast MFCs article concentrates on microbiology rather than electrochemistry. This is also demonstrated in an article on yeast MFCs published in Applied and Environmental Microbiology. Bioresources Technology has 40 citations per paper for yeast MFCs, but Biosensors and Bioelectronics has 87 citations per article, which is impacted indirectly by JIF. The total connection strength in the two journals is rather strong, indicating that yeast MFCs papers published in both journals cover subjects that intersect with other

electrochemistry journals. Bioelectrochemistry, Journal of Power Sources, and Applied Energy are top three journals with a high Total Link Strength rating, indicating that publications relevant to yeast MFCs published in these three journals have a focus on electrochemistry and are thus connected to other journals with the same scope.

Table 2. Popular sources for research articles citation in yeast MFCs

Journal Name	Number of Articles	Citation	Citation Per Article	JIF*	Total Link Strength	Publisher
Nature Reviews Microbiology	1	407	407	60.63	3	Springer Nature
Bioresources Technology	7	282	40	9.64	53	Elsevier
Biosensors and Bioelectronics	3	261	87	10.62	41	Elsevier
Applied and Environmental Microbiology	1	222	222	4.79	5	American Society for Microbiology
Bioelectrochemistry	9	207	23	5.37	62	Elsevier
Journal of The American Chemical Society	2	189	95	15.42	11	American Chemical Society
Fuel Cells	2	151	76	2.25	19	Wiley
Journal of Mechanics and Microengineering	1	124	124	1.88	2	IOP Publishing
Journal of Power Sources	6	126	21	9.12	43	Elsevier
Journal of Bioscience and Bioengineering	4	110	28	2.89	10	Elsevier
Applied Energy	3	91	30	9.75	40	Elsevier
Biotechnology and Bioengineering	1	71	71	4.53	2	Wiley
International Journal of Molecular Sciences	1	68	68	5.92	26	MDPI
Energy Sources Part A	3	70	23	3.45	11	Taylor & Francis
Journal of Microbiology	1	61	61	3.42	13	Springer Nature

***** Based on IF year 2021

3.3. Co-occurrence

Keywords play an important role in indexing and arranging relevant research findings. Keywords make it easier to determine the relevance of research effort to one's area of interest. Table 3 shows the network analysis of term co-occurrence in the 131 extracted research articles related to yeast MFC. According to our findings, the most often discovered keyword is 'microbial fuel cell,' with 64 occurrences and 762 Total Link Strength. We also discovered the usage of other frequent phrases such as ‘electricity generation’ (45 occurrences, 497 links), 'yeast' (39 occurrences, 452 links), '*Saccharomyces cerevisiae*' (15 occurrences, 167 links), and

'performance' (36 occurrences, 384 links). This is also seen in Figure 5, where these keywords have a bigger node size than the others, indicating that they are popular and frequently used. Yeast MFCs are also seen, as a major conceptual uses of yeast MFCs such as 'wastewater treatment,' 'biosensors,' and 'electricity production'. The frequency of occurrence of these keywords is tremendously important for researchers who aim to focus about MFC research, particularly yeast MFCs, because it will aid them in determining their research roadmap over the next several years.

Table 3. Top commonly used keywords in the research of yeast MFCs

Keywords	Occurrences	Total Link Strength
microbial fuel cell	64	762
electricity-generation	45	497
yeast	39	452
performance	36	384
electron-transfer	34	378
waste-water treatment	21	258
generation	20	225
microbial fuel-cell	18	223
saccharomyces-cerevisiae	19	215
energy	16	173
saccharomyces cerevisiae	15	167
power-generation	14	165
microbial fuel-cells	14	163
microorganism	14	157
biofuel cells	15	141

Furthermore, the common terms used from year to year are worth investigating since they are connected to the emphasis of MFC yeast research conducted by researchers. Words like 'algae,' 'ethanol,' 'bioethanol,' or 'mediator' were used in yeast MFC publications published between 2006 and 2010, or nodes with a blue purple color. This demonstrates that yeast MFC research is integrated with the ethanol or bioethanol production process by microorganisms, in this instance yeast. Because of the low electron transfer in yeast MFC, researchers added mediators to their research that year in order to boost electron transfer. While algae are utilized as an oxide agent on the cathode side to create oxygen. While in 2011 – 2015 or blue-green nodes, terms such as 'neutral red,' 'electron transfer,' 'cathode,' or 'biosensor' occur. In that year, researchers were still concerned about electron transfer in yeast MFC, and neutral red was one of the choices for exogenous mediators to promote electron transfer. Meanwhile, the use of yeast MFC as a biosensor is being tested and investigated. Popular terms in yellowish green nodes or around 2016 - 2019 include 'microbial fuel cell,' 'yeast,' *'Saccharomyces cerevisiae*,'

and 'bioelectricity'. These common terms do not appear in 2020 to mid-2022 since numerous journals writing techniques courses recommend not writing significant words that occur in the title. In other words, key words should not be generated from the terms in the article title. Since the terms 'boron doped diamond anode,' 'carbon paper,' and 'carbon nanotube' originally appeared, anodes for yeast MFCs have also begun to be created in order to increase electron transport. The words 'BOD,' 'electricity production,' 'wastewater treatment,' 'urea,' and 'power density' appear in the yellow nodes in 2020 and 2021, indicating the use of yeast MFC in the wastewater treatment area in reducing BOD and converting it into electricity, as well as the promotion of the Waste-to-Energy (WtE) concept as an alternative energy solution.

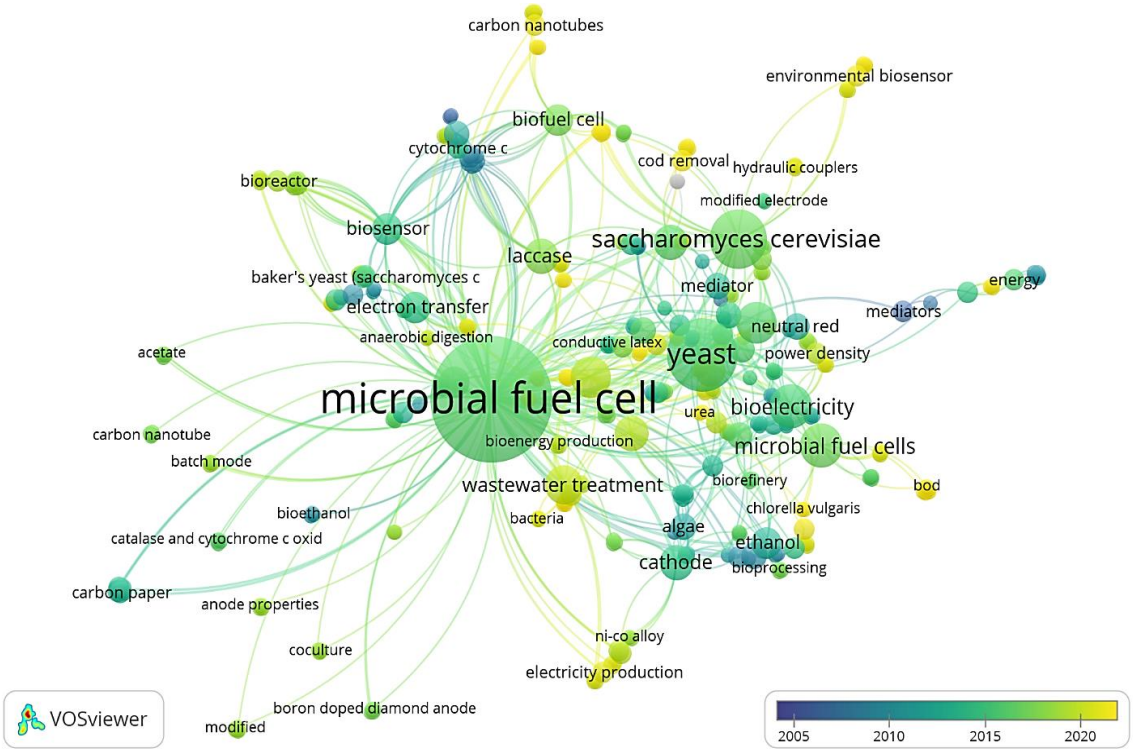

Figure 5. Co-occurrence network of keywords commonly used in articles focused on yeast MFCs

3.4. Co-authorship network, leading author, and article citations analysis

Figure 6 depicts the network of the most influential researchers in yeast MFC. There are several diverse clusters in the network of collaborating researchers represented in Figure 6, each identified by a different color, however there are around 14 clusters with sufficient strong connections. The red cluster comprises of three researchers, E.T. Sayed, N. Nakagawa, and T. Tsujiguchi, who all have quite large nodes. Each researcher in the red cluster group has a strong connection and began researching yeast MFCs quite early, making them the most significant research group based on the attention they have earned in the field of yeast MFCs. Among the

other study groups are the blue and dark grey clusters. In the blue cluster, the M. Christwardana and Y. Kwon groups collaborated extensively in the past, before establishing a connection with other cluster groups in this study field, such as the Hadiyanto group, in the present. While, M. Mitov and Y. Hubenova are the most collaborative members of the dark grey cluster group. They conducted research on yeast MFC earlier than M. Christwardana, although their study focus has shifted somewhat in recent years.

Table 4. List of the 15 most prolific authors in yeast MFC research area

Author Name	Documents	Citation	Citation per Document	Scopus H-Index	Current Institution	Country of Current Institution
Marcelinus Christwardana	14	215	15	17	Diponegoro University	Indonesia
Yongchai Kwon	8	206	26	33	Seoul National University of Science and Technology	South Korea
Domenico Frattini	5	159	32	17	Basque Research and Technology Alliance	Spain
Enas Taha Sayed	6	130	22	25	Minia University	Egypt
Arunas Ramanavicius	5	17	3	54	Vilniaus Universitetas	Lithuania
Nobuyoshi Nakagawa	5	122	24	29	Gunma University	Japan
Yolina Hubenova	5	83	17	12	Plovdiv University Paisii Hiledarski	Bulgaria
Mario Mitov	5	83	17	15	South-West University Neofit Rilski	Bulgaria
Grazia Accardo	4	139	35	18	Basque Research and Technology Alliance	Spain
Fabian Fischer	4	43	11	16	Haute Ecole Spécialisée de Suisse Occidentale	Switzerland
Pimprapa Chaijak	5	28	6	3	Thaksin University	Thailand
Lital Alfonta	4	166	42	22	Ben-Gurion University of the Negev	Israel
H. Hadiyanto	4	33	8	20	Diponegoro University	Indonesia
Gordon A. Hill	4	97	24	27	University of Saskatchewan	Canada
Ruggero Rossi	4	442	111	13	Pennsylvania State University	USA

Table 4 highlights the 15 most prolific writers in yeast MFC, who are linked with 11 countries: Canada, USA, Bulgaria, and Spain each have two productive authors. South Korea, Indonesia, Egypt, Japan, Switzerland, Thailand, and Israel, on the other hand, each have one prolific author. There are no set restrictions about authorship order, however the last place is

often connected with seniority and supervisory responsibilities. According to the authors' affiliation, yeast MFC research was conducted in domains such as material science, environmental science, energy, and engineering. M. Christwardana of Indonesia topped the list with 14 papers linked to yeast MFC during 2017, and currently has an h-index of 17 and 215 citations. The second is Y. Kwon of Seoul National University of Science and Technology, who has 8 publications, 206 citations, and an h-index of 33. While D. Frattini is in third place with 5 publications, 127 citations, and a 17 h-index. D. Frattini's publishing record is comparable to that of E.T. Sayed, N. Nakagawa, Y. Hubenova, and M. Mitov, although his works get more citations. M. Christwardana, Y. Kwon, and D. Frattini previously collaborated on yeast MFC research in the same research group in South Korean before pursuing careers elsewhere. Additionally, we discovered that R. Rossi is ranked 15th with four papers relevant to yeast MFC, 294 citations, and a 13 h-index. According to the article document, R. Rossi is ranked last with 4 papers, comparable to the other 7 prolific authors. However, when citation counts are considered, R. Rossi is the most cited author. The findings of Table 4 may also be seen in Figure 7a, where M. Christwardana and Y. Kwon's heatmap is colored red, while the heatmaps of other prolific writers are colored orange, yellow, green, sky blue, purple, or dark blue.

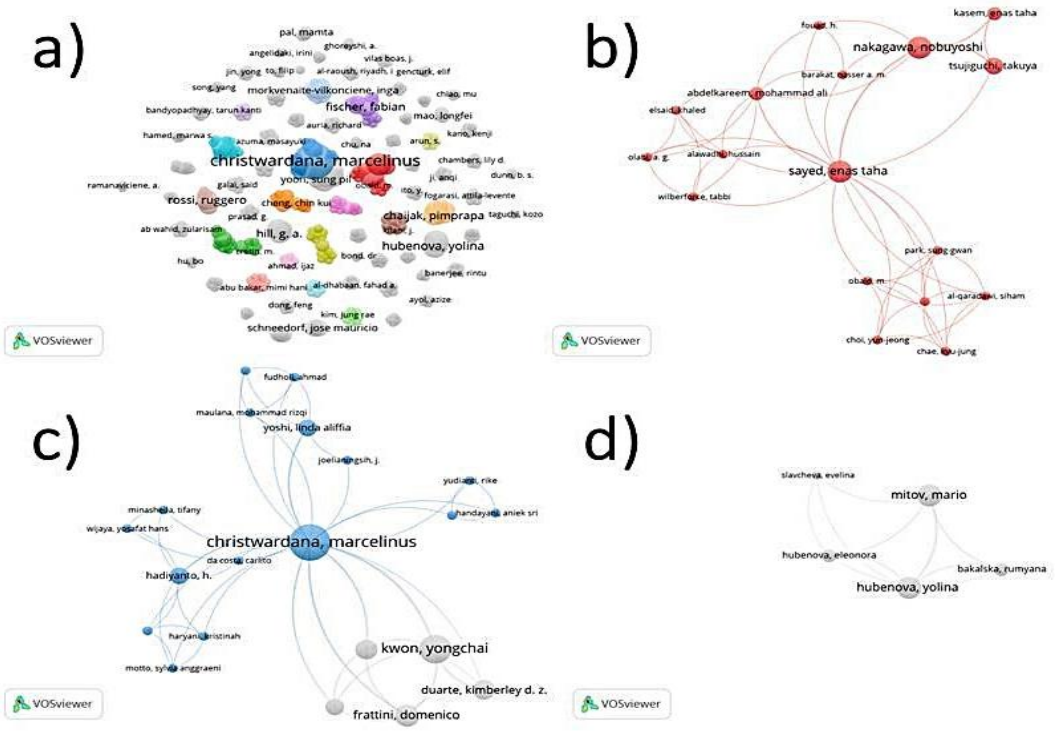

Figure 6. a) Co-authorship clusters of most impactful researchers in yeast MFCs, and some examples of network from b) E.T. Sayed group, c) M. Christwardana group, and d) Y. Hubenova group

The number of citations obtained by research articles is an essential indicator for determining the quality of such publications. As a result, articles with a high number of citations are often seen as highly insightful, even though this is not always the case. Additionally, a density map was built to correct for older articles that have a citation advantage due to their publication date, giving them an edge over their younger counterparts. Divide the total number of citations for a particular year by the average number of citations for all articles published that year to get a more precise count. The density of the articles that satisfied the aforementioned criteria is shown in Figure 7b. As seen in Figure 7b, the most influential researchers, as measured by normalized citations, are R. Rossi and B.E. Logan of Pennsylvania State University, who conduct the greatest group research in microbial electrochemical technology (MET), as indicated by the red and dark orange color heatmaps. These researchers have made major contributions to the improvement of MFC in general, not only yeast MFC. Several of their major articles have been published in Nature Publishers journals and other journals with a higher JIF.

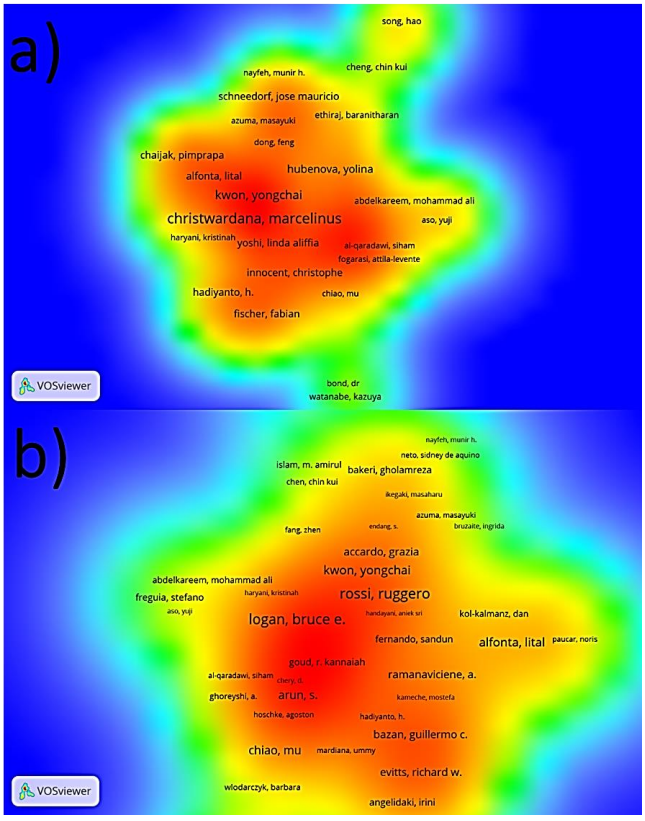

Figure 7. Cluster density visualization of the a) top article documents and b) top-cited articles focused on yeast MFCs research area

3.5. International Collaboration and Leading Countries

The distribution of countries/territories per region is shown in Figure 8a. The closer two countries are located to each other in VOSviewer, the stronger their relatedness and the stronger

the link between two countries, the thicker the line. The list was followed by South Korea (14 articles, 13 total link strength), India (18 articles, 12 total link strength), Malaysia (8 articles, 11 total link strength), USA (17 articles, 11 total link strength), and others. It was also shown that most of the listed countries had international collaborative publications with less than 10 countries for publishing articles on yeast MFC. The diversity of research collaborators, the vast number of foreign postgraduates/visiting scholars, and the substantial funding for research all contribute to the international collaboration dynamic. A flexible and steady research approach is also essential to ensure the long-term success of international collaboration.

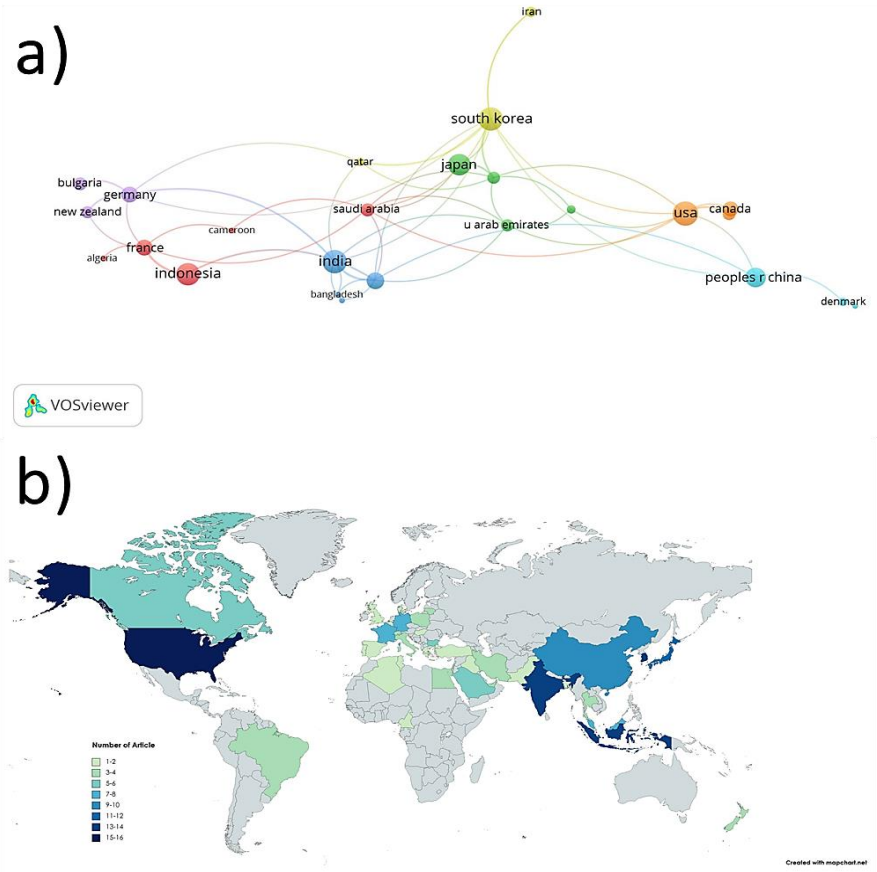

Figure 8. a) Most vibrant countries and b) geographical distribution of contributing countries to yeast MFCs research

The geographical distribution of all nations involved in yeast MFCs research is shown in Figure 8b. Asia, America, Europe, Africa, and Oceania all had the most nations per region. Asia produced over 70% of worldwide articles on yeast MFCs, with Saudi Arabia, India and South Korea leading the way, while the United States contributed greatly with 17 publications receiving 1093 citations. This demonstrates that these three nations are significant contributors to the advancement of yeast MFC research. Additionally, we can notice that Indonesia, China, and Japan contain more than 10 publications relating to yeast MFCs, although their links are quite weak. This demonstrates that the three nations have not engaged in significant

international collaboration. Malaysia, on the other side, has just 8 publications but the second-highest link strength, indicating that they participate in extensive international collaboration in the field of yeast MFCs research. Along with expanding one's network, international collaboration provides opportunities for information exchange and expertise sharing.

3.6. Research trend and knowledge gap

As with exoelectrogenic bacteria-based MFCs, the primary limitation of yeast-based MFCs is their inability to generate sufficient electricity. The inability of the yeast cell to transport electrons to the anode is the primary cause of unstable power production. As a result, several researchers have deployed yeast MFCs with or without exogenous mediators throughout the past decade [54-56], in which mediators were supplied externally to the anode chamber to enhance electron transfer from the yeast cell. Exogenous mediators are the most often used method for increasing extracellular electron transport in yeast cells. Apart from introducing the mediator, there are numerous strategies to improve electron transfer in yeast MFCs, including anode surface modification [57], yeast cell immobilization [14], yeast surface display [58], and genetically modified yeast cells [59]. Another impediment is the microorganisms used for the MFC, i.e., choosing yeast over electrogenic bacteria leads in less electron transfer (in the absence of mediator) than electrogenic bacteria [60]. The majority of research on yeast based MFCs has focused on *S. cerevisiae* and has proposed studying other strains of yeast that are more effective at generating electricity. Additionally, researchers are working to improve the electrode material. The usage of conductive carbon-based materials, such as graphite or graphene oxide, is still being investigated and developed. Commercially available carbon-based electrodes, such as carbon felt, may be modified with conductive materials to improve electron transmission, which is still a part of the desired sub-topic for the foreseeable future. Numerous studies have been conducted to determine the applicability of mixed consortia of yeast and electrogenic bacteria at the anode chamber for enhancing complex substrate degradation and MFC performance when compared to yeast alone [61-63]. If the substrate to be degraded is glucose-based, using yeast in conjunction with enzymes such as glucose oxidase or glucose dehydrogenase as a co-biocatalyst is a novel concept that might be researched further.

4. CONCLUSIONS

This work completes a scientometric overview on the yeast MFC based on the WoS database with 7497 research publications were published during the 1985 to mid-2022 period. A small number of MFC studies were begun in the late 1980s (1985-1988) and early 1990s (1994–1996). The very significant contribution on MFCs grew until 2021, when it reduced by 57% in mid-2022. The reduction in MFC articles for the publication might be due to a multitude of events. The same thing happened with papers on yeast MFCs. Bioelectrochemistry

contributes to the majority of output, more than any other publication source. Access to articles is critical for the development of research on yeast MFCs. The yeast MFC research was first published in journals such as the *Journal of the Chemical Society*, *Applied Microbiology*, *Fuel Cells*, and *Yeast*. The *Bioelectrochemistry and Bioresource Technology* did substantial study and published a flood of articles on the issue during the 2012–2016 period. During 2017 to mid-2022 period, however, papers on yeast MFC were identified in *International Journal of Hydrogen Energy* and the *Journal of Power Sources*. While yeast MFC publications get an average of 87 citations per article in *Biosensors and Bioelectronics*, they receive an average of 40 citations per article in *Bioresources Technology*, where the JIF number has also such influence. Total Link Strength scores for *Applied Energy*, *Bioelectrochemistry*, and *Journal of Power Sources* are all outstanding. All of these periodicals place a premium on electrochemistry, which is why their papers are connected to those published in other journals with a similar concentration.

M. Christwardana of Indonesia topped the list in 2017 with 13 publications on yeast MFC. He currently has an h-index of 17 and over 215 citations. When compared to the other prolific authors based on the number of documents, R. Rossi ranks last. However, R. Rossi together with B.E. Logan of Pennsylvania State University have the greatest number of citations of all researchers. Numerous outstanding key works have been published in Nature Publishers' journals, as well as in other prestigious journals. Asia, led by India and South Korea, represented for more than 70% of all yeast MFC articles published worldwide. The 16 papers from the United States received a total of 880 citations. Researchers in Indonesia, China, and Japan have published more than 10 articles on yeast MFC research. Most academics have advised that more yeast strains with higher energy production efficiency be investigated further. As a co-biocatalyst for the degradation of glucose-based substrates, yeast in combination with enzymes such as glucose oxidase or glucose dehydrogenase may be an intriguing concept worth exploring. This text includes an advanced Web of Science code that may be used to search for all relevant publications within this area. From these scientometric data, it can be concluded that yeast MFC is a highly fascinating and promising topic that deserves to be researched as a future alternative energy source.

Declaration of competing interest

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

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CRediT authors contributions

Conceptualization, D.S.K.; data curation, M.C.; formal analysis, M.C. and D.S.K.; funding acquisition, M.C.; investigation, M.C.; methodology, M.C. and D.S.K.; validation, D.S.K.; visualization, M.C.; writing-original draft, M.C.; writing-review and editing, D.S.K. All authors have read and agreed to be published version of the manuscript.

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