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Bibliometric analysis of global research trends on microbial fuel cells using Scopus database

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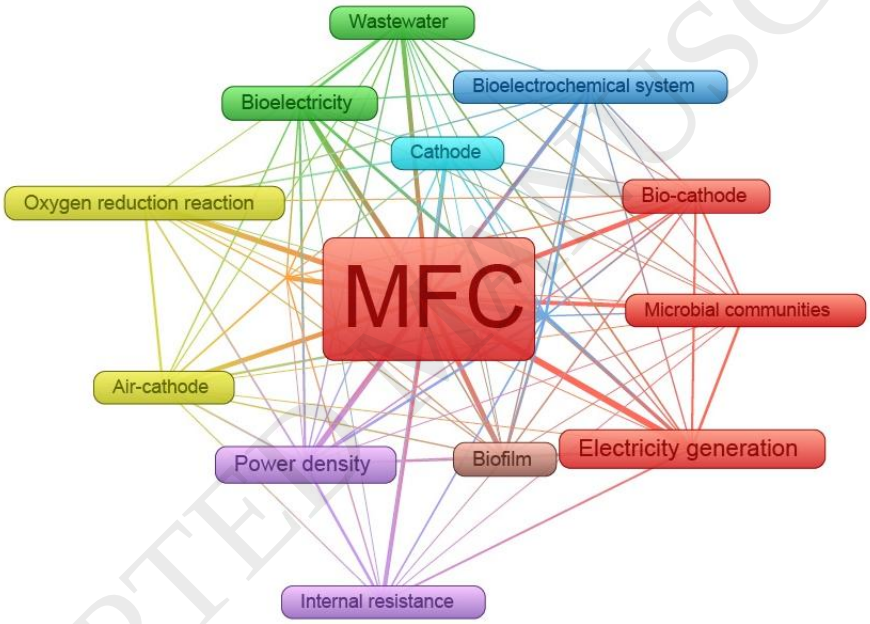
Graphical abstract



Highlights

- We studied MFC research trends and discovered opportunities for future direction and collaboration areas.

- We retrieved 4162 MFC journal research articles in Scopus, published between 1962–2017.
- The annual publication increased about 100 articles for every two years since 2008.
- Sixty percent of the total publications were from China and USA, leading 70 other countries.
- Recent progress included low-cost electrodes, neural network, and economic assessment.

Abstract

The rising demand for sustainable energy and the availability of abundant wastes have stimulated research efforts around the world. As a newly emerging energy-based technology, microbial fuel cell (MFC) has received a significant attention due to its broad range of applications. Therefore, understanding the topics of interest and broadening collaboration network are necessary to advance the research development towards integrated efforts. In this bibliometric study, our aim was to evaluate the global research trends in MFC area based on publication outputs, co-authorships among authors and affiliated countries, and co-occurrences of author keywords. Using the Scopus database, a total of 4126 journal articles published between 1962–2017 were retrieved. Results have shown that since 2008, the number of publications increased by 100 articles for every two years, resulting in the steady increase in the cumulative total publications until present. About 60% of the global publications was contributed by researchers from China and USA, leading the other 70 countries/territories. Also, among the most productive university from each of the 15 leading countries, four were amongst the world's top 100 universities. In conclusion, recent progress in MFC research includes the following (but not limited to) (i) electrode materials incorporated

nanotechnology, ceramic, and biochar; (ii) mathematical modeling (e.g. artificial neural network); and (iii) economic assessment and life cycle analysis.

Keywords: bibliometric analysis; author keyword co-occurrences; co-authorship; microbial fuel cell; VOSviewer; Scopus database

Abbreviations:

MFC = Microbial fuel cell

AGR = Annual growth rate

SCP = Single-country publication

MCP = Multi-country publication

TP = Total publications

TC = Total citations

TPc = Total publication of a given country

TPi = Total publication of a given academic institution

1. Introduction

Depletion of fossil fuels, abundance of wastes, impacts of climate change, and exponential growth of human populations are among of the factors that lead the global community to search for alternatives to fulfill the global energy demand [1]. Microbial fuel cell (MFC) technology has been identified as one of the promising solutions for a sustainable energy [2], with a bright prospect for future implementation [3]. MFC is a device that exploits microbial catabolic activities to generate electricity from carbon source under anaerobic conditions. Several advantages, which MFC offers over other

energy technologies using organic matter, include the flexible operating temperatures, *in-situ* energy conversion, and potential application in remote locations lacking electrical infrastructures [4]. Previous studies suggested that applications of MFC included but not limited to electricity generation, wastewater treatment, bioremediation/biodegradation, and biosensor [2, 5].

Although there has been a growing interest in MFC technology, very few studies were dedicated to measuring and analyzing scientific publications from a global perspective. Juan et al. [5] presented research trends on bioelectrochemical systems (BES) for a period of 24 years since 1991, where MFC was a part of discussion besides enzymatic fuel cell, microbial electrolysis cell, microbial desalination cell, and microbial solar cell. On the other hand, Mercuri et al. [1] had focused specifically on MFC, however, it was limited to microbiology and marine freshwater biology areas. Additionally, both studies used Web of Science (WoS) as a source of data mining.

Despite the fact that WoS and Scopus databases have a high association i.e. overlap in journal indexing, they also index different journals [6, 7]. Scopus is recognized as the largest abstract and citation database of peer-reviewed literature covering a wide range of subjects. Thus, using Scopus is an attempt to cover more topics which may not be available in WoS and may not have discussed by Juan et al. [5] and Mercuri et al. [1].

In this paper, our objectives were as follows: i) to analyze temporal distribution patterns of MFC journal articles; ii) to show contributions of prolific authors, leading countries and the most productive academic institutions; (iii) to highlight common terminology and research topics; (iv) to determine domination of countries based on major applications; and (v) to provide insight into potential collaboration and future directions. This paper will be beneficial for researchers, policy makers, and individuals to understand the research trends in MFC and to discover the potential and opportunities for future research.

2. Methods

Bibliometric analysis study is a mechanistic approach to understand the global research trends in a specific area based on the outputs of the academic literature database. This kind of approach distinguishes a bibliometric analysis paper from a review paper which primarily intended to discuss the latest progress, challenges, and future directions of a certain topic.

2.1 Data source and search strategy

Data mining was conducted within February 9 and 15, 2018 using Scopus database. The central theme in this study was research articles containing "microbial* fuel* cell*" in the title and abstract. The oldest publication dates to 1962 and the more recent ones are from 2017. The query string used for the search was: (TITLE-ABS ("microbial* fuel* cell*")) AND DOCTYPE (ar) AND PUBYEAR > 1959 AND PUBYEAR < 2018 AND (LIMIT-TO (SRCTYPE, "j ")). This query string resulted in 4246 documents. To ensure no review articles in our analysis, additional phrases were added in the query string which resulted in 148 articles potentially irrelevant to our study. These articles contained terms such as review, recent, progress, critical, revisit, advance, highlight, in the title and abstract. After screening them by reading abstracts and full-texts, we identified 84 of them were review articles. EID, a Scopus unique article identifier, of these review articles were noted and added in the next search string (so that they would not appear in the next search results).

It is noteworthy that the best method to obtain the most accurate data on an author's output is to use its author ID (Scopus field code: AU-ID). An author profile is a collection of all the name variants placed in one single profile, e.g., our exported data had the last name Ieropoulos twice, however, with different initials which were Ieropoulos, I. (68 articles) and Ieropoulos, I.A. (17 articles).

Information for single-country publication (SCP) were retrieved by limiting the search result to a specific country using a field code AFFILCOUNTRY.

The search results of the central theme were analyzed based on year, source, author, affiliation, country/territory, subject area, and document type. Bibliometric indicators such as total publications, total citations, CiteScore, and h-index were used for ranking purposes.

In addition, we also created a sub-theme to explore the output trends in MFC major uses. The MFC major applications included in this study were i) electricity generation; ii) wastewater treatment; iii) biodegradation/bioremediation; and iv) biosensor. The search string for each application was run separately. By using previous search string, specific terms were added to it depending on the type of applications, for e.g. (*electricity OR "power generation") or ("waste*water treatment") or (*remediat* OR *degradat*) or (*sensor). The search results by sub-theme were analyzed based on publication output per year.

There are chances that one application overlapping with other application(s). For example, an article on biosensor application is likely related as well to the electricity generation. However, to minimize the overlap between wastewater treatment and biodegradation/bioremediation, we excluded "wastewater treatment" from the biodegradation/bioremediation search. By excluding "wastewater treatment", the search on biodegradation/bioremediation was made to focus on contaminated soil, sediment, solid waste, etc.

The process of record collection and study elimination is summarized in **Figure 1.** The details on search strings used in Scopus are provided in **Table S1** (Supplementary Material).

2.2 Bibliometric maps

Citation, bibliographical, and author keywords information of 4126 articles were exported to VOSviewer (version 1.6.7, Centre for Science and Technology Studies, Leiden University, The Netherlands), a software tool for constructing and visualizing bibliometric maps. Maps created using VOSviewer include items. In this study, the items are the objects of interest, namely the countries or author keywords. Between any pair of items there can be a link—connection or relation between two

items. Each link has a strength, represented by a positive numerical value. The higher this value, the stronger the link.

In the case of co-authorship analysis, the link strength between countries indicates the number of publications that two affiliated countries have co-authored, whereas the total link strength indicates the total strength of the co-authorship links of a given country with other countries. Similarly, in the case of co-occurrence analysis, the link strength between author keywords indicates the number of publications in which two keywords occur together. Details on the features of VOSviewer can be found in the user manual [8].

2.2.1 Analysis of co-authorship

In the analysis of co-authorship, we included all 72 countries affiliated with 6783 authors. The affiliated countries/territories were clustered into 5 continents: Africa, America, Asia, Europe and Oceania.

2.2.2 Analysis of co-occurrence

Analysis of co-occurrence of author keywords (not Scopus indexed keyword) involved 6059 keywords from 3464 articles. The remaining 698 articles were excluded due to the lack of author keywords information available from 142 journals. Prior to importing the list of author keywords to VOSviewer, synonymic single words and congeneric phrases were analyzed. For example, plant microbial fuel cell, plant microbial fuel cell (PMFC), plant-microbial fuel cell, PMFCs and PMFC were counted as one and re-labeled as plant MFC.

In VOSviewer, minimum occurrences of a keyword to be analyzed was set to 5. Overlay visualization mode was selected to view the average publication year, number of occurrences and link strength of the keywords. The color of a keyword indicates the average publication year of the documents in which a keyword occurs.

2.3 MFC applications

The trends of search outputs between central theme (keyword co-occurrences) and sub-theme (total publication) were compared. For example, if biosensor is the application, thus in VOSviewer software, keywords occurrences for 'sensor', 'biosensor' and 'BOD sensor' were all counted. We also analyzed the five countries with the highest number of publications for each MFC application.

3. Results and discussion

3.1 Publication output and growth of research interest

For a period of 56 years, a total of 4162 research articles had been published **(Figure 2).** The oldest publication dates to 1962 [9], and there was no other publication record until 1983. It is suggested that strong interest in MFC research started from 1999. In 2003, the annual growth rate (AGR) increased by 600% and it was doubled in 2006 and 2008. Since then, annual publications have increased steadily, resulting in a rapid increase in the cumulative total publications. It was also found that the number of publications increased by 100 for every two years. Therefore, it is anticipated that the annual publication will continue to rise. However, most of these articles are not freely available and the user has to pay to access the information in them. We suggest that an article will likely receive more citations if it is published through an open access journal. As of 2017, only 2.3% (94 articles) were published as an open access type.

MFC research areas are extensive and many research groups worldwide are working actively in these areas. Analysis on subject area showed that environmental concerns are the primary focus in MFC studies. This is evidenced by the total publications classified under the following subject areas: Environmental Science (1652 articles), Chemistry (1447 articles), Chemical Engineering (1423 articles), and Energy (1118 articles). Indeed, MFC is a multidisciplinary area and one of the publications was categorized under Arts and Humanities subject area. MFC experiments was once given an artistic approach in sculptural projects at the Künstlerdorf Schöppingen, North Rhine-

Westphalia, Germany by an artist named Lorusso [10]. This kind of approach can be used to increase social acceptance of a developing technology through fresh narratives around functional research.

Results also showed that the articles used in this study were published in 12 different languages. English (3792; 91%) was the most commonly used language followed by Chinese (338; 8.1%), and Spanish (12, 0.3%). Other languages (23; 0.6%) such as Korean, Russian, German, Polish, Italian, Japanese, Malay, Persian, and Turkish were used in less than 8 articles. When a publisher submits an article in a foreign language to be indexed in Scopus, the article should have a title and abstract in English.

3.2 Preferred journals

Our results showed that the top 10 most productive journals are owned by four different publishers **(Table 1).** The top three journals were published by Elsevier with seven in total. The rest three journals were published by the American Chemical Society (ACS), Royal Society of Chemistry (RSC) and Science Press.

The most productive journal was Bioresource Technology with 458 articles covering 11.1% of the total publications, followed by Journal of Power Sources (260, 6.3%), International Journal of Hydrogen Energy (161, 3.9%) and Environmental Science and Technology (139, 3.4%). Environmental Science and Technology, an ACS journal, had not only received the highest number of citations with a total of 20056, but one of their articles published in 2004 was also the most cited article, with 1170 citations.

According to the CiteScore 2016 report, five journals had a CiteScore of 5 and above. Journals of the highest and lowest CiteScore belonged to Biosensors and Bioelectronics (7.22), and Chinese Journal of Environmental Engineering (0.31), respectively. Although ranked 8th with 64 articles in Scopus, the total citation and CiteScore of Chinese Journal of Environmental Engineering was significantly

lower compared to other journals. This was likely due to the primary language of publication which is in Chinese, making it less accessible to English readers.

Furthermore, we also understand that CiteScore can influence the decision of some authors in selecting journals that fit their most novel and significant work. CiteScore, the Elsevier-Scopus alternative to the Clarivate Analytics Impact Factor, is a metric for measuring journal impact based on citation data from the Scopus database. In our opinion, however, CiteScore should not be taken as the only measure. Beside CiteScore, authors should also consider whether the journal can deliver the work to the right audience and contributes to the progress of the field. To support our fellow researchers to find the possible journals to submit their MFC-related work, we have listed the top 37 CiteScore journals in **Table S2** (Supplementary Material).

3.3 Leading countries, top institutions, and international collaboration

Figure 3 shows the top 15 most productive countries contributing to the growth of MFC research activity worldwide. About 60% of the global publications was contributed by China and USA indicating these two countries are key players in the MFC research progress. China was the leading country with 1632 publications in a total of 238 journals, covering 39% of the global total publications. With one-half of China's total publication, USA was ranked the second most productive country. Although the total publications (TPi) from Pennsylvania State University was slightly lower than that of Chinese Academy of Sciences, it should be noted that Chinese Academy of Sciences has 124 branches, thus a direct comparison might be a bias. Otherwise, Harbin Institute of Technology can be considered as the most productive academic institution in China with 171 publications.

In addition to **Figure 3**, we have also listed the 50 most productive institutions based on the number of MFC articles these institutions have published which can be found in **Table S3** (Supplementary Material). This supplementary information includes academic as well as non-academic institutions (e.g. National Research Center or National Research Laboratory).

Among the 15 countries, only India (82.4%), China (75.5%), and Japan (71.7%) had more than 2/3 single-country publications (SCP). This suggests that these countries have a strong intra-country collaboration. On the other hand, Australia was the country of the least SCP with 26.3%, where 56 out of 76 publications were linked to multiple affiliations from 20 different countries. The advantages of an international collaboration are not limited to the broadening network, exchanging knowledge and sharing expertise, but also an effective strategy for ranking up. Singapore, for example, despite being a small country, 72.3% (68 articles) of its publications were international collaborative papers which affiliated to 17 countries, ranking it the 12th most productive country.

Furthermore, there were also four universities listed in the top 100 best universities based on the World University Rankings 2018 [11]—Pennsylvania State University (ranking 10th), The University of Tokyo (46th), Nanyang Technological University (52nd) and University of Queensland (65th). This demonstrates that MFC field has received attention at the top universities in the world.

The distribution of countries/territories per region is shown in **Figure 4.** 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 highest number of countries per region came from Asia (26), followed by Europe (22), America (12), Africa (10), and Oceania (2). Results of co-authorship showed that the UK was the most affiliated country, linked to 35 countries/territories with 154 times of co-authorship. The list was followed by USA (33 links, 417 co-authorships), China (32 links, 461 co-authorships), South Korea (28 links, 224 co-authorships), Malaysia (25 links, 105 co-authorships), and others. It was also shown that 2/3 of the listed countries had international collaborative publications with less than 10 countries. In addition, only the researchers in Colombia and Slovenia were not affiliated with any other country for publishing articles on MFC.

Several possible factors contributing to the dynamic of international collaboration can be attributed to the diversity of research partners, high percentage of foreign postgraduates/ visiting scholars, and

strong research funding. It is also important to have a flexible and stable research policy to ensure the sustainability of the international collaboration.

3.4 Leading authors

Table 2 lists the 15 most prolific authors in MFC, affiliated to six countries as follows; China (7 authors), USA (3 authors), UK (1 author), South Korea (1 author), India (1 author) and Malaysia (1 author). The first publications ranged between year 1999–2009 in which 6 authors had a role as the first author, 5 as a co-author, and 4 as the last author. While there are no specific rules in the sequence of authorship, the last position is normally associated with seniority and the supervisory role. The affiliations of the authors showed that MFC research was within fields related to environmental, energy, science and engineering.

B. E. Logan from the USA led the list with a record of 175 publications since 2004, 71 h-index, and 20205 times citations. The 2nd and 3rd top authors, I. Ieropoulos and J. Greenman are both affiliated with the University of the West of England. Authors from Tsinghua University, China ranked 7th (X. Huang) and 10th (P. Liang). Another pair from China are N. Ren (11th) and Y. Feng (14th), are both affiliated to Harbin Institute of Technology. We also found that the publication dates back to 1999 in **Table 2** refers to the same article [12], written by two prolific authors, I. S. Chang and B. H. Kim. Even though these authors are both from S. Korea, the latter author is shown to be affiliated with Universiti Kebangsaan Malaysia, the authors' current affiliation.

It should be noted that the authors for the most cited articles listed in **Table 1** does not necessarily to appear in **Table 2**. Their names would only be found in both tables if they had published prolifically such as authors Logan E. Bruce, Zhen He and Byung Hong Kim.

3.5 Author keywords

A total of 6059 author keywords was recorded, among which 4466 (73.7%) were used only once, 732 keywords (12.1%) were used twice, and 261 (4.3%) were used thrice. After re-labeling synonymic

single words and congeneric phrases, 401 keywords met the threshold of minimum 5 occurrences for the mapping in VOSviewer.

3.5.1 Terminology and concept

Our results showed that 'MFC' was the most frequently encountered keyword with 2682 occurrences and 397 links to other keywords **(Figure 5).** We also came across the use of general terms such as 'bioelectrochemical systems' (97 occurrences, 106 links), 'fuel cells' (52 occurrences, 70 links) and 'biofuel cells' (21 occurrences, 38 links). MFC was also seen co-occurred with conceptual keywords including 'bioenergy', 'renewable energy', 'sustainable energy', and 'green energy'.

In addition, we noticed several attributes—substrate, mechanism, and configuration, were used in naming the MFC. Examples of MFCs associating with substrate/mechanism were 'sediment MFC' (59 occurrences), 'plant MFC' (23), 'soil MFC' (9), 'photosynthetic MFC' (9), 'benthic MFC' (8), and 'osmotic MFC' (6). Examples of MFCs associating with reactor configuration were 'single-chamber MFC' (30 occurrences), 'double-chamber MFC' (17), 'membrane-less MFC' (7), 'air-cathode MFC' (14), and 'stacked MFC' (12).

It is also interesting to see how a particular term is established. For instance, the term plant MFC was first introduced by Strik et al. in 2008 [13] and it has been popularized by European research groups consistently. Consequently, the term is widely used in many publications related to the MFC incorporating living plants.

Similarly, several terms were used to refer to the microorganisms capable of producing electricity, which included 'exoelectrogens' (42 occurrences) [14], 'electrochemically active bacteria' (29 occurrences) [15], 'electrogens' (22 occurrences) [16], and 'electricigens' (10 occurrences) [17].

3.5.2 Topics of interest

As an evolving technology, MFC performance is often evaluated. Keywords containing 'performance' were repeated 39 times. In MFC research, selection of substrates, reactor components, and operational conditions are among the keys parameters.

In comparison to many carbon sources (substrates), 'wastewater' appeared the most by 185 occurrences. The wastewater originated from multiple sources, including winery, dairy, distillery, domestic, molasses, swine, and urine. 'Leachate' was less used (24 occurrences) as a substrate of MFC and was mainly associated with landfill related studies.

Furthermore, while most MFCs use liquid-phase substrates i.e. dissolved carbon source, studies using solid or semi solid-phase substrates are also valuable because these substrates are normally rich in organic matter [18]. Keywords associated with 'sludge' and 'waste' were repeated 42 and 16 times, respectively, among which were activated sludge, anaerobic sludge, excess sludge, food waste, municipal solid waste, and organic waste. Our results found that the total keywords referring to semi/solid-phase wastes accounted for approximately 30% of the total keywords of liquid-phase wastes.

Since the carbon source can be so complex, the use of catalysts and the addition of bacteria have been widely practiced. It is to enhance bioelectrochemical process as well as to increase Coulombic efficiency. Keywords containing 'catalyst' were encountered by 99 times, and this consisted of several related processes such as 'bioelectrocatalysis' 'catalytic activity', 'electrocatalysis' and 'photocatalysis'. Research on microbial communities was primarily on microbial diversity, growth, structure, activity, etc. Among microbial communities, we found several gram-negative bacteria such as (i) *'shewanella', 's. oneidensis'* and *'s. putrefaciens'* (90 occurrences); (ii) *'geobacter'* and '*geobacter sulfurreducens'* (48 occurrences); (iii) *'escherichia coli'* (32 occurrences); (iv) *'pseudomonas aereuginosa'* (22 occurrences); and (v) *'klebsiella pneumoniae'* (6 occurrences). An example of gram-positive bacteria found in MFC was *'bacilus subtilis'* (5 occurrences).

In MFC, a fully developed electroactive biofilm is essential to produce high electrical power. The keywords 'biofilm' and 'electroactive biofilm' were used 131 and 21 times, respectively. 'Anodic biofilm' appeared three times more than the 'cathodic biofilm'. This is because in a single-chamber MFC, it is the anode compartment that receives carbon source, while the cathode side is exposed to the air.

Although biofilm formation is important, excessive growth of microbial biomass can cause a problem and it is biofouling whenever the biofilm affects performance parameters negatively [19]. Keywords 'membrane fouling', 'biofouling' and 'fouling' were used 19, 10, 8 times, respectively.

For MFC reactor components, 'bio-cathode', 'air-cathode, and 'cathodes' were the top three keywords and summed to a total of 279 occurrences. The total occurrences of 'cathode' was 2.5 times more than that of 'anodes'. We also found that 'air-cathode' was used by 91 times in author keywords, showing that the use of air-cathode has become more common nowadays due to its operational simplicity and cost-effectiveness of oxygen diffusion systems [20].

In addition to regular electrodes, research on electrode modification was also noticed as evidenced by the keywords 'modified anodes' and 'modified electrodes'. Progress on electrode materials incorporated nanotechnology in MFC research can be seen by certain keywords such as 'carbon nanotubes' and 'multi-wall carbon nanotubes' (occurrences: 70, avg. publication year: 2013.8). This was followed by 'graphene', 'graphene oxide' and 'reduced graphene oxide' (63 occurrences; 2014.7–2016). Other related keywords including 'carbon nanofibers' (13 occurrences; 2015.1), as well as 'nanoparticles' and 'nanocomposite' (13 occurrences; 2014.9–2015.4). Reduced graphene oxide has been reported to be superior to graphene oxide and graphene due to its unique combination of excellent conductivity, large surface area, high electrochemical activity and ease of functionalization [21].

Expensive maintenance requirement of ionic exchange membranes has led to the discovery of membrane-less MFCs. The strong need for membrane-less MFC can be linked to the number of citations received by the most cited article presented earlier in **Table 1**. However, removing membranes from MFC design has several drawbacks, including oxygen diffusion towards the anode. This kind of circumstances has motivated researchers to find alternative for the conventional membranes which are relatively cheap. Research has found that ceramic membrane is a promising material, and it can provide a natural, stable environment for bacteria, while offering a better system for energy harvesting [22]. With an average publication year of 2016.4, our results show that ceramic membrane was the one latest advancement in MFC studies. The keyword 'ceramic membrane' appeared 5 times, and co-occurred with 'electroosmotic drag', 'urine', 'bioenergy', 'microalgae', and 'catholyte'.

In addition to the search for low-cost materials, biochar has also been tested (7 occurrences; 2015.3) as electrodes and electrocatalyst. The biochars used in MFC studies were derived from different kinds of biomass/wastes, for instance, wood-based biochar (forestry and milling residue) [23], fruit-based biochar [24], and plant-based biochar such as from coconut shells [25] and cotton stalk [26].

Among electrical unit parameters (e.g. voltage, resistance, current, capacitance), 'power density' was heavily used (196 occurrences) for reporting electricity generation. Unless the actual power was also reported, comparison between studies can be very challenging due to the use of different normalization factor (e.g. surface area of anode, cathode, membrane), which consequently resulting in different normalized outputs [27]. Therefore, He [28] encourages researchers to create an "energy picture" for MFC technology, and not just limited to "power picture" since power density does not comprehensively reflect energy production from an MFC.

Keywords addressing problems within MFC systems by internal or external factors were also found. For instance, 'voltage reversal' was repeated 23 times, and co-occurred frequently with 'stacked MFC', 'stack' and 'series connection'. 'Power overshoot' was repeated 14 times, often co-occurred

with ‘polarization’, ‘internal resistance’, and ‘external resistance’. Results also showed that ‘internal resistance’ appeared 3 times more in author keywords compared to the ‘external resistance’. This suggests that the internal resistance, the MFC’s internal property has a greater impact to the MFC performance in comparison to the external resistance that serves as an operational parameter. Similarly, keywords like ‘start-up time’ and ‘start-up’ can be associated with the time required to stabilize an MFC. These keywords were both linked to other keywords involving microorganisms such as ‘microbial communities’ and ‘biofilm’, respectively.

Following that, several strategies were employed to control the affecting factors. Keywords such as ‘power management system’, ‘maximum power point tracking’, and ‘supercapacitors’ were among the strategies to optimize ‘energy harvesting’. Techniques such as ‘inoculation’ can be applied to enrich the microbial community populations in the MFC. This technique includes the cutting of little pieces of old electrode and placing them on the new anode or adding microorganisms from another well-working MFC into the new MFC. To overcome the slow microbial ‘acclimation’ process in conventional inoculation, Vogl et al. [29] came up with a technique called surface-to-surface biofilm transfer (BFT). They found this biofilm transfer technique was able to provide a quick and reliable start-up strategy.

Since the biological nature of MFC research could lead to lengthy experiments (months or even longer), prediction-based studies will be useful towards the ‘scaling-up’ and practical implementation of this technology, including real-time process control [30]. The recent small efforts towards using this approach can be seen from keywords ‘mathematical modeling’ (10 occurrences), ‘modeling’ (10 occurrences), and ‘artificial neural network’ (5 occurrences). Future applications would also be fascinating if many more studies include economic and life cycle assessment in the reports as demonstrated in these references [3, 31].

3.6 Distribution of MFC publications based on major applications

Based on the number of articles and author keyword occurrences, there were positive correlations found between the outputs of sub-theme search and the central theme search. **Figure 6** shows that electricity generation (search phrase: *electricity OR "power generation") was the most popular application with 2039 articles in Scopus and 672 occurrences in VOSviewer. This was followed by wastewater treatment (531 articles and 281 occurrences), bioremediation/biodegradation (173 articles and 175 occurrences) and biosensor (162 articles and 68 occurrences).

MFC was not associated with purposes other than electricity generation and biodegradation prior to 1999. Articles attributed to biosensor and wastewater treatment were published in 1999 and 2004, respectively. This suggests that researchers are realizing that power production cannot be the sole goal, rather using the energy and benefits of MFCs for some sort of environmental remediation purposes, i.e. wastewater treatment, contaminant removal/recovery, etc.

Furthermore, research interest in certain areas can also be analyzed by the link strength of two keywords. For example, 'biosensor' had 39 links (i.e. connected to 39 other keywords), namely, 'toxicity', 'sensitivity', and 'seawater'. It is suggested that research interest on biosensor–toxicity was stronger compared to biosensor–seawater as shown by the link strength which were 7 and 2, respectively.

We found that most publications related to the electricity generation, wastewater treatment, and biodegradation/bioremediation came from China, with the USA being the second except on the biosensor application **(Figure 7).** Also, in general, India, Korea and UK were among the top 5 countries publishing articles on each MFC application. Other countries such as Taiwan, Australia and Japan were listed in different applications of MFC and only once.

3.7 Limitation of study

By restricting the search of "*microbial* fuel* cell*" within titles and abstracts, the search result might not cover all MFC-related studies available on Scopus. This is because some researchers did

not refer their systems as MFC, but instead using different terms (e.g. bioelectrochemical systems, biophotovoltaics). Also, co-occurrence analysis of author keywords covered only 83% of 4126 articles due to missing author keywords information from certain journals, namely, RSC Advances, Scientific Report, PLOSOne and others.

Future studies to compare the outputs from multiple databases such as Scopus and Web of Sciences are recommended. The search results from Web of Science, for instance, display automatically the most popular articles in the field by a feature known as 'hot paper', a feature that is still lacking in Scopus. This hot paper feature displays key papers that are recognized very soon after publications, reflected by a rapid and significant number of citations. Conducting bibliometric analysis using multiple data sources will be useful for a more comprehensive study.

4. Conclusion

This study has provided an overview of MFC research trends based on 4126 publications retrieved from the Scopus database. Publication growth has been rapid since the last 10 years, and it is anticipated to continue to rise. We have discovered countries/academic institutions (e.g. China and USA) that have a massive number of publications and strong international collaborations. These entities can be an opportunity for researchers from other countries (e.g. Slovenia and Colombia) to broaden their research collaborations. We have discussed several areas that are currently well-explored such as material sciences incorporating nanotechnology and we have also presented some areas newly investigated with MFC such as artificial neural network and economic assessments which can be potential hot topics for future studies. Not to mention, the continuous efforts to search for low-cost materials which are non-toxic and available abundantly.

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Figures

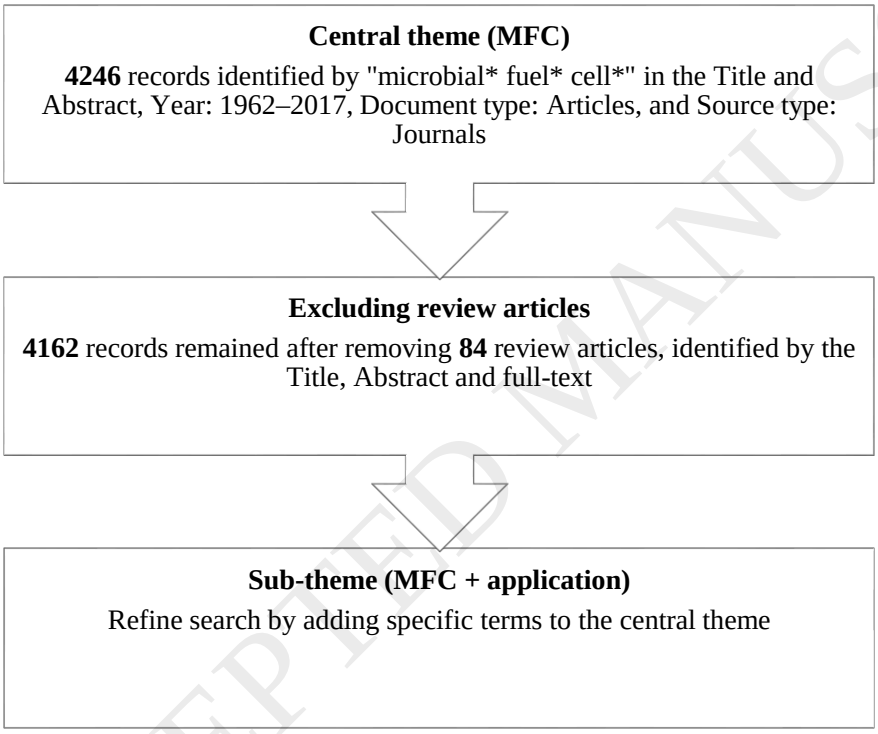

Figure 1: Flowchart of gathering data of publications for central and sub-themes.

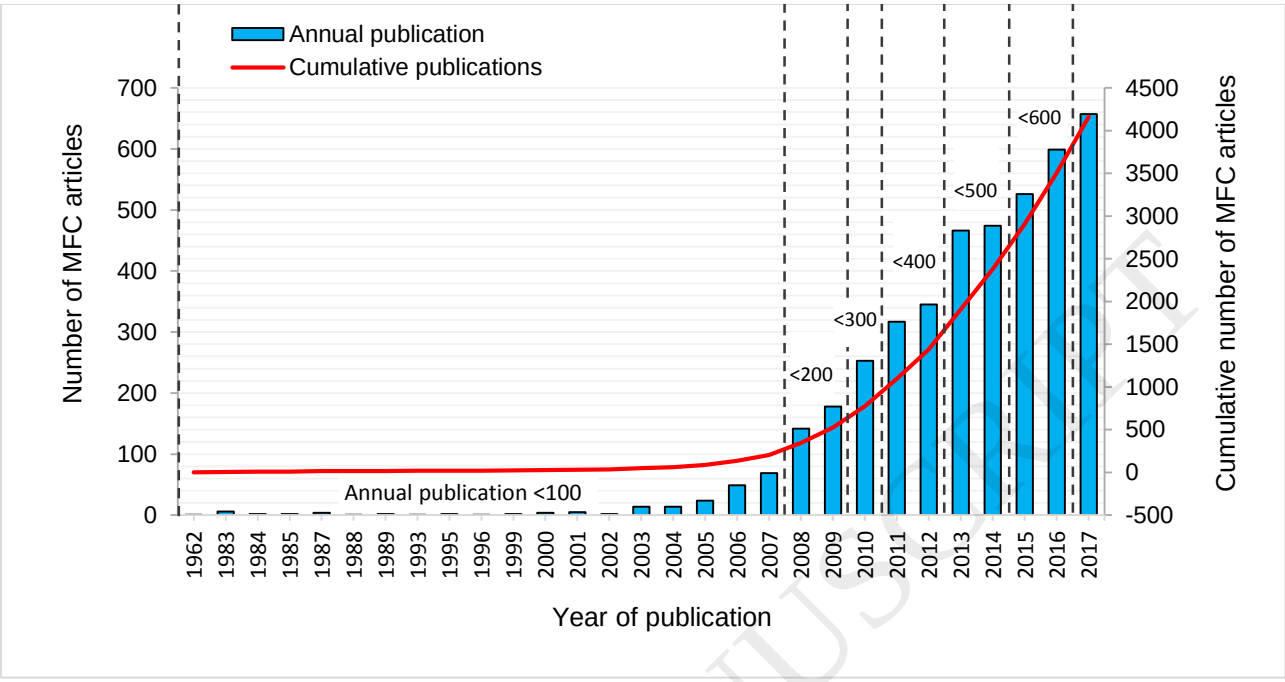

Figure 2: The annual and cumulative numbers of research articles on microbial fuel cells indexed in Scopus from 1962 until 2017.

Rank	Country	TPc	SCP (%)	The most productive academic institution	TPi
1	China	1632	75.5	Chinese Academy of Sciences	217
2	USA	855	57.7	Pennsylvania State University	199
3	S. Korea	370	55.1	Gwangju Inst. of Science and Technology	60
4	India	341	82.4	Indian Inst. of Technology, Kharagpur	68
5	UK	243	49.0	University of the West of England	79
6	Japan	127	71.7	University of Tokyo	29
7	Taiwan	125	52.0	National Ilan University Taiwan	40

Rank	Country	TPc	SCP (%)	The most productive academic institution	TPi
8	Spain	119	55.5	Universidad de Castilla-La Mancha	30
9	Iran	104	66.3	Babol Noshirvani University of Technology	38
10	Italy	101	47.5	Universita degli Studi di Milano	22
11	Malaysia	98	40.8	Universiti Kebangsaan Malaysia	42
12	Singapore	94	27.7	Nanyang Technological University	56
13	Canada	88	64.8	Ecole Polytechnique de Montreal	15
14	Germany	81	49.4	Technische Universitat Braunschweig	17
15	Australia	76	26.3	University of Queensland	31

Figure 3: The top 15 most productive countries and academic institutions in MFC publications.

TPc: total publications of a given country; TPi: total publications of a given academic institution; SCP: single-country publications.

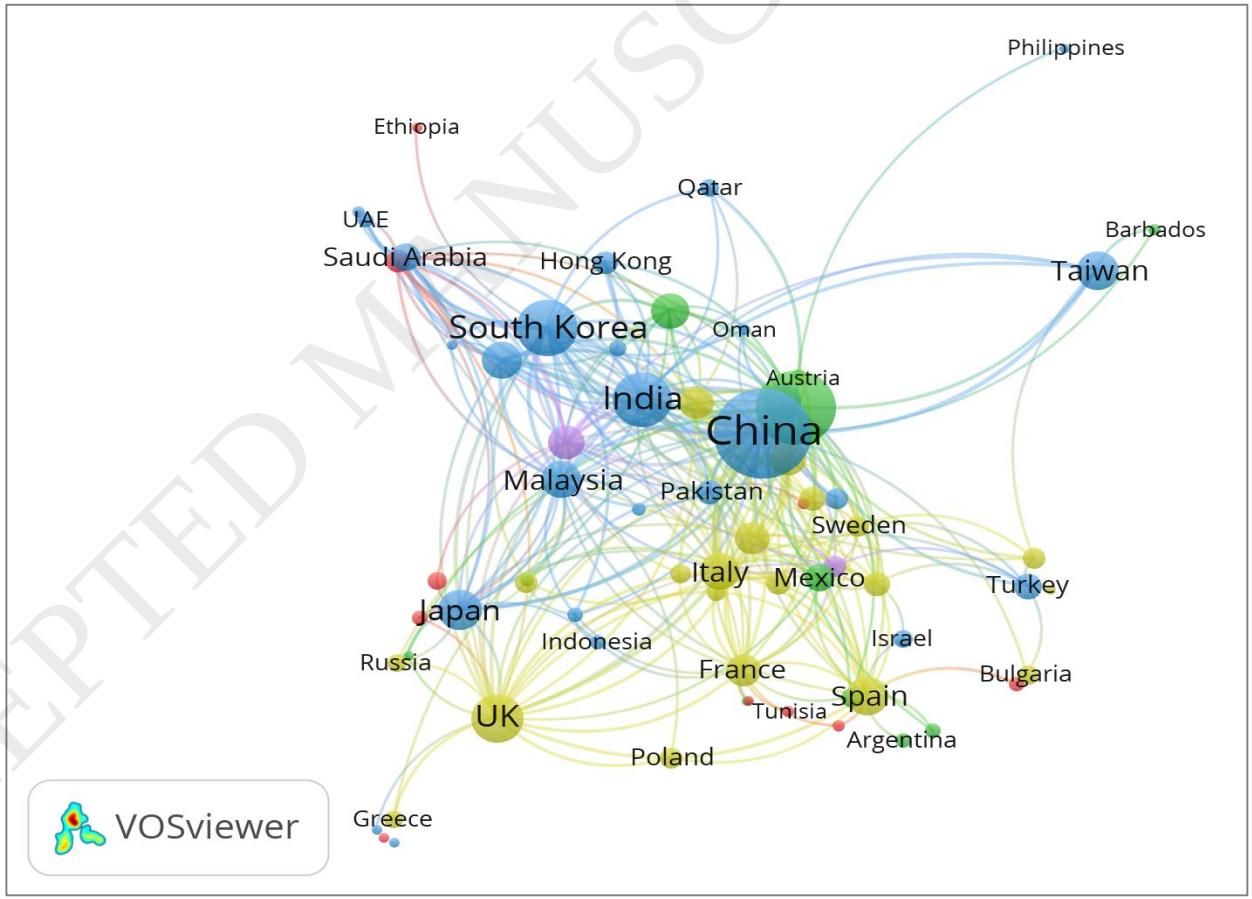

Figure 4: A screenshot of bibliometric map created based on co-authorships with network visualization mode. The following URL can be used to open Figure 4 in VOSviewer: http://bit.ly/2qUlf9O

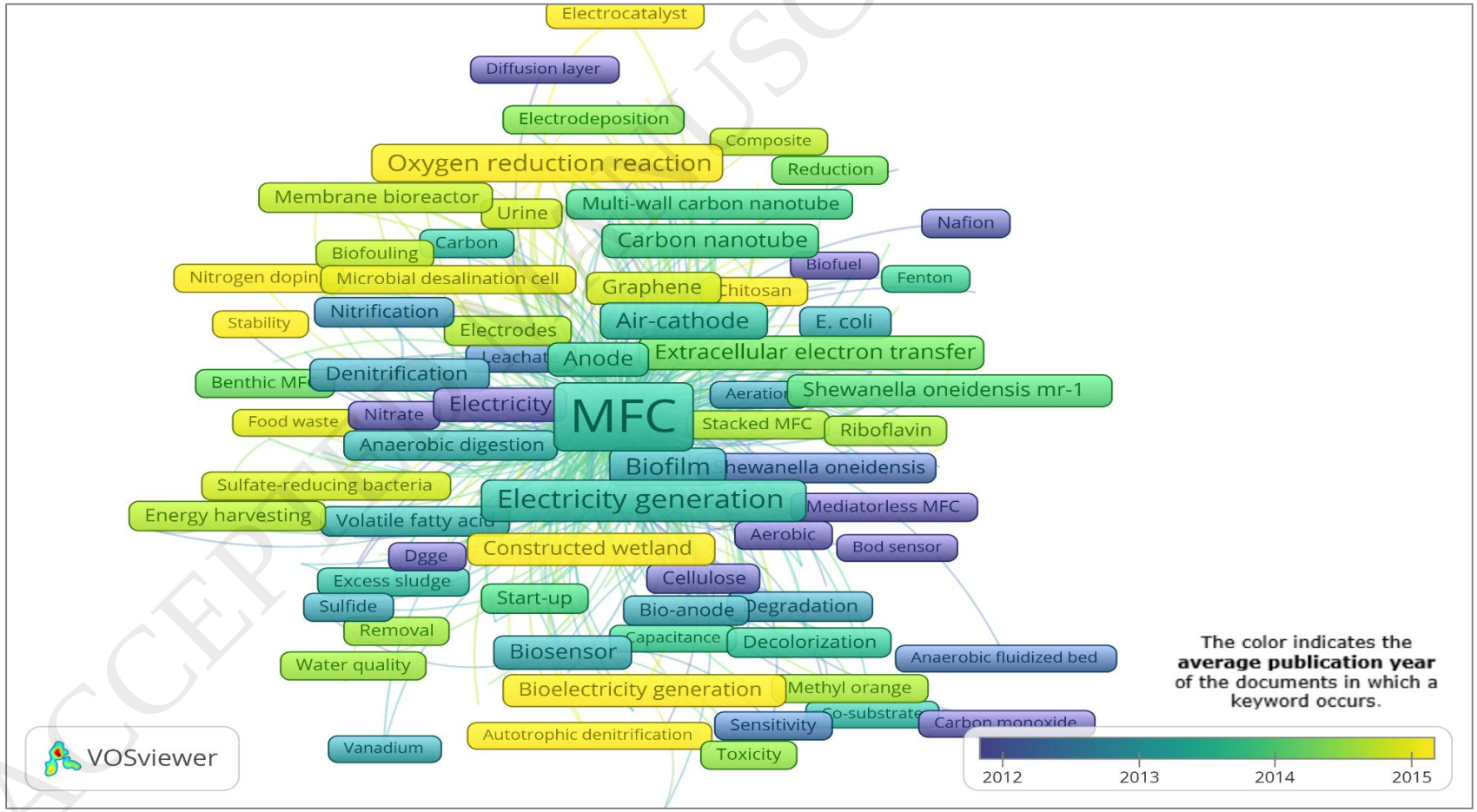

Figure 5: A screenshot of the bibliometric map created based on author keywords co-occurrence with overlay visualization mode. Minimum occurrences of a keyword are set to five. The following URL can be used to open Figure 5 in VOSviewer:

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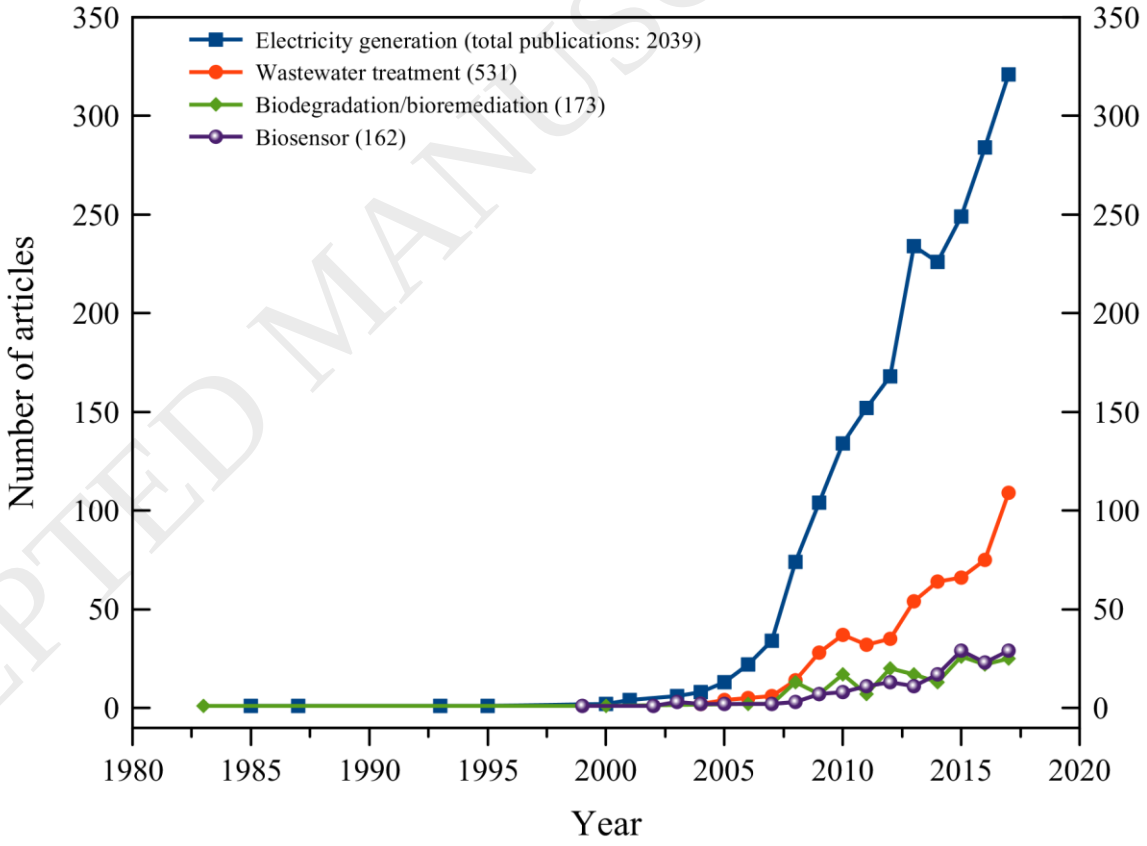

Figure 6: Research trends of the selected major applications in MFC.

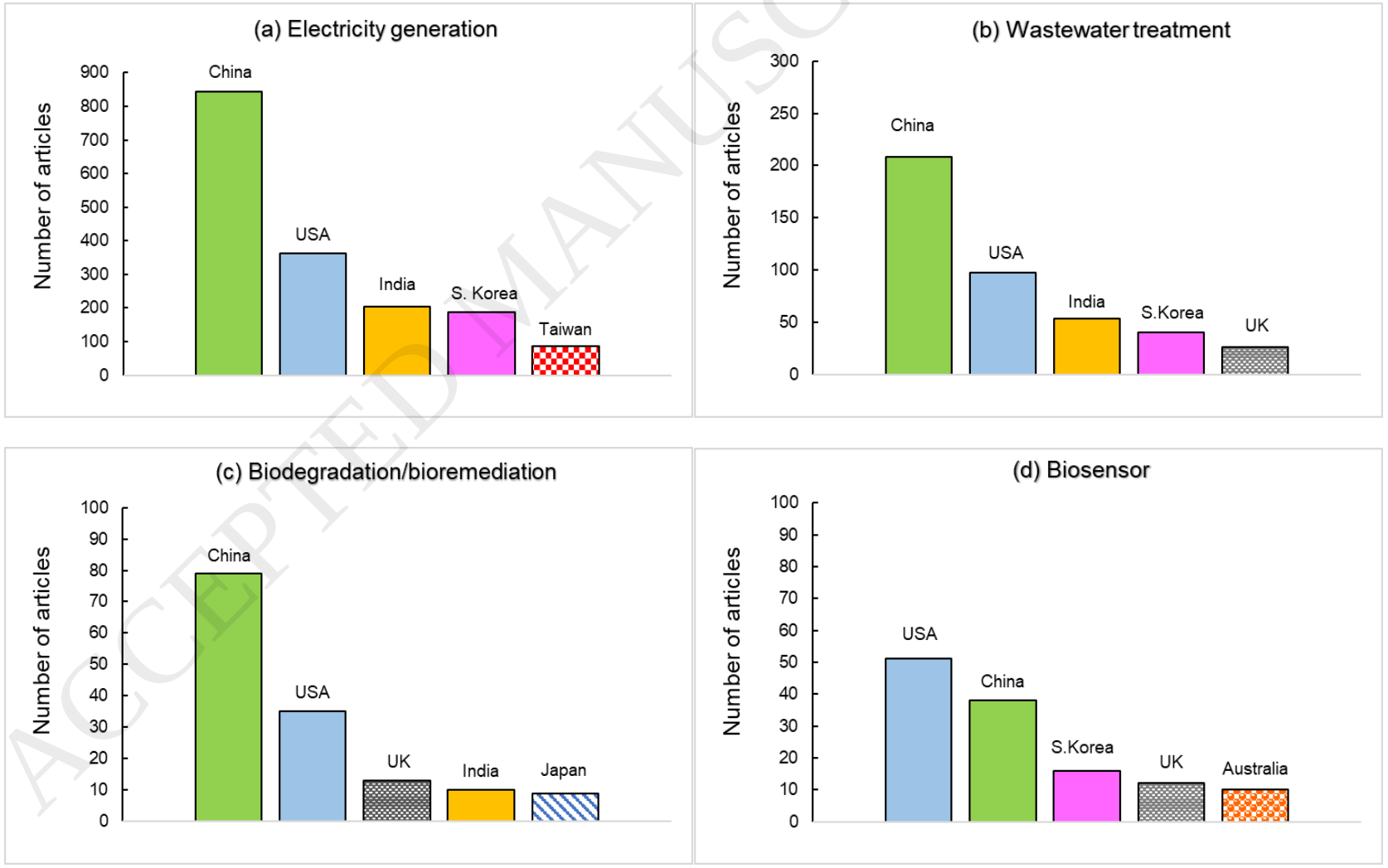

Figure 7: Five countries with the most publications on the selected MFC major applications.

Table 1: The top 10 most productive journals on MFC research with their most cited article.

	Journal	TP (%)	TC	CiteScore 2016	The most cited article (reference)	Times cited	Publisher
1	Bioresource Technology	458 (11.1)	12976	5.94	Effect of different substrates on the performance, bacterial diversity, and bacterial viability in microbial fuel cells [32]	255	Elsevier
2	Journal of Power Sources	260 (6.3)	8777	6.22	Enhanced Coulombic efficiency and power density of air-cathode microbial fuel cells with an improved cell configuration [33]	390	Elsevier
3	International Journal of Hydrogen Energy	161 (3.9)	2749	3.74	A mediatorless microbial fuel cell using polypyrrole coated carbon nanotubes composite as anode material [34]	136	Elsevier
4	Environmental Science and Technology	139 (3.4)	20056	6.26	Electricity generation using an air-cathode single chamber microbial fuel cell in the presence and absence of a proton exchange membrane [35]	1170	ACS
5	Biosensors and Bioelectronics	115 (2.8)	5891	7.22	Operational parameters affecting the performance of a mediator-less microbial fuel cell [36]	612	Elsevier
6	RSC Advances	97 (2.4)	651	3.06	Development and evaluation of carbon and binder loading in low-cost activated carbon cathodes for air-cathode microbial fuel cells [37]	58	RSC
7	Electrochimica Acta	84 (2.0)	1719	4.74	Non-catalyzed cathodic oxygen reduction at graphite granules in microbial fuel cells [38]	164	Elsevier
8	Chinese Journal of Environmental Engineering	64 (1.6)	37	0.31	Comparison of power generation performance of different types of anodes in microbial fuel cells [39]	5	Science Press
9	Bioelectrochemistry	59 (1.4)	1706	3.45	Effect of electrolyte pH on the rate of the anodic and cathodic reactions in an air-cathode microbial fuel cell [40]	165	Elsevier
10	Chemical Engineering Journal	59 (1.4)	1015	6.34	Phenol degradation in microbial fuel cells [41]	142	Elsevier

TP: total publications; TC: total citations; ACS: American Chemical Society; RSC: The Royal Society of Chemistry

Table 2: List of the 15 most prolific authors in MFC research area.

	Author	Scopus author ID	Year of 1st publication*	TP	h-index	TC	Current affiliation	Country
1	Logan, Bruce E.	55762454700	2004 [c]	175	71	20205	Dept. of Civil & Environmental Engineering, Pennsylvania State Uni.	USA
2	Ieropoulos, Ioannis	55880836000	2005 [a]	84	24	1854	Bristol BioEnergy Centre, Uni. of the West of England	UK
3	Greenman, John.	26643533700	2005 [b]	73	22	1613	Bristol BioEnergy Centre, Uni. of the West of England	UK
4	He, Zhen	55868901500	2005 [a]	66	29	2985	Dept. of Civil & Environmental Engineering, Virginia Polytechnic Institute and State Uni.	USA
5	Chang, In Seop	7201742306	1999 [b]	61	32	5651	School of Environmental Science and Engineering, Gwangju Inst. of Science and Technology	South Korea
6	Zhou, Shungui	23981875800	2008 [c]	59	31	2148	Guangdong Inst. of Eco-environmental Science & Technology	China
7	Huang, Xia	26643260700	2007 [b]	57	25	1920	State Key Joint Lab of Environment Simulation and Pollution Control, Tsinghua Uni.	China
8	Ghangrekar, Makarand M.	55932469000	2007 [a]	55	18	1285	Dept. of Civil Engineering, Indian Inst. of Technology Kharagpur	India
9	Cheng, Shaoan	7404684913	2005 [b]	55	35	7459	Dept. of Energy Engineering, Zhejiang Uni.	China
10	Liang, Peng	55701008300	2007 [a]	54	23	1639	State Key Joint Lab of Environment Simulation and Pollution Control, Tsinghua Uni.	China
11	Ren, Nanqi	7004987612	2007 c	52	23	1324	State Key Lab of Urban Water Resource and Environment, Harbin Inst. of Technology	China

12	Yuan, Yong	55139390300	2008 [a]	49	26	1490	School of Environmental Science and Engineering, Guangdong Uni. of Technology	China
13	Li, Baikun	17343971400	2009 [c]	49	24	1392	Dept. of Civil & Environmental Engineering, Uni. of Connecticut	USA
14	Feng, Yujie	7404543985	2007 [a]	48	19	2383	State Key Lab of Urban Water Resource and Environment, Harbin Inst. of Technology	China
15	Kim, Byung Hong	36063137000	1999 [c]	42	31	5618	Fuel Cell Institute, Universiti Kebangsaan Malaysia	Malaysia

*Role in co-authorship, superscripts a: First author, b: Co-author, c: Last author