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Energy by Microbial Fuel Cells: Scientometric global synthesis and challenges

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ABSTRACT

The scarcity of natural resources and the growing need for electricity requires the development of new technologies that can provide alternatives to traditional energy sources in a sustainable fashion. One of the promising opportunities currently under development is Microbial Fuel Cell (MFC) technology. The aim of our study was to analyze the relevant literature related to MFCs through a scientometric approach in order to produce a comprehensive synthesis, something that is lacking. We identified 19671 relevant studies in the field and examined 3427 papers in detail in a systematic review performed in the ISI database Web of Science. Our primary goals were to: (i) determine the temporal evolution of publications, (ii) reveal which journals publish on the subject, (iii) show the global distribution of MFC research and funding perspectives, (iv) uncover the scales of application of the technology, (v) account for the most commonly used substrates, (vi) find out whether pure or mixed cultures of microorganisms are involved and (vii) determine the major species used. We detected a substantial increase in publications after 2006. We found that the US and East Asia are the most promising locations for the development of MFCs, given both the number of publications and the amount of financial investment in research and development. The main technological barrier to the wide-spread use of MFCs is the scale of application, restricted to small prototypes insufficient to generate electricity for practical purposes. The most cited substrate was wastewater, both domestic and industrial, demonstrating the great potential of MFCs in wastewater treatment. Finally, our results demonstrated that there is a wide variety of microorganisms capable of generating electricity, although the great majority of papers focus on a few well-established species. Taken together, our results can help research and application in this field on a global level perspective.

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1. Introduction

The global demand for energy has grown considerably in recent decades [1]. The massive growth of the human population [2] is associated with huge increases in energy consumption, resulting largely from the energy available from fossil fuels and also from the energy used to obtain those fuels [3]. Moreover, the traditional sources of energy, such as fossil fuels, are becoming scarce [4]. Because of this upcoming energy crisis, there is a need for technological innovation [3] or renovation of the current patterns of energy use by humanity. It is, therefore, mandatory that we find innovative energy sources that are environmentally less damaging and can be used in a sustainable fashion [5]. Several alternative sources of clean and renewable energy, which currently represent around 20% of total world energy demand, are under development and have enormous potential [6].

The production of electricity using Microbial Fuel Cells (MFCs) is a renewable and sustainable technology that is becoming more efficient [7,8]. MFCs are devices that produce electricity using the metabolic energy of bacteria, the catalysts that oxidize organic and inorganic matter [9]. Typical designs or modes of operation for MFCs consist of two or one chamber components [10]. In a two-chamber set up, an anaerobic anode chamber and an aerobic cathode chamber separated by a membrane are connected through an external circuit. The membrane does not allow the exchange of oxygen between chambers. The protons generated by the process of oxidation migrate from the anaerobic (anode) to the aerobic (cathode) compartment through the membrane, while the generated electrons move to the cathode through an external circuit. A wide variety of bacteria are able to both oxidize organic components and provide electrons for the fuel cell, and MFCs have been designed using either pure or mixed cultures of bacteria [11]. The choice of microbial species and the subsequent efficiency of the MFCs depend on the cell configuration and on characteristics such as substrate composition and concentration [10,12]. MFCs could be adaptable to a sustainable pattern for wastewater treatment and production of domestic energy [13], so they are a promising sustainable technology with huge advantages over other technologies, including lower energy consumption, small environmental footprint, and operational stability. However, there are some drawbacks in the practical feasibility of MFCs, especially with respect to costs, large-scale system development, and energy recovery [14]. In previous reviews [i.e. 10,15–20] of the topic there has not been an unbiased and replicable scientometric synthesis of MFC research with the goal of assessing its advances and its gaps. In this sense a systematic review of the subject is lacking. Systematic reviews specify search criteria on a particular issue and use predefined protocols, aiming at reducing bias, allowing rigorous replication, and diagnosing gaps [21]. Systematic reviews provide high-quality results, identifying, appraising, and synthesizing all relevant studies on a particular topic [21,22].

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The major aim of our study was to use a systematic review to identify, appraise and synthesize the empirical evidence concerning MFCs in order to answer some questions about the use of MFCs to generate electricity, highlighting tendencies and major gaps in our knowledge of the topic. Our specific aims were to (i) determine the temporal evolution of publications, (ii) reveal which journals publish on the subject, (iii) show the global distribution of MFC research and funding perspectives, (iv) uncover the scales of application of the technology, (v) account for the most commonly used substrates, (vi) find out whether they are based on pure or mixed cultures of microorganisms and (vii) determine which are the species used. Our research used explicit methods designed to minimize bias in the discovery of the trends and major gaps in MFC research. This approach allows us to identify the strengths and weaknesses of this new technology in a way that produces results that can be trusted and that will help to support new research and application in this field in a global level perspective.

2. Methodology

Web of Science database publications were collected covering a period of 31 years from 1985 to 2015. The survey was based on the simultaneous use of three WoS search fields, each referring to a relevant sub-theme to build the central theme. We used Boolean operators, quotation marks, wildcards and query sets to create our query. The sub-themes were: 1) generation of energy by microorganisms, search field code: fuel$ OR biofuel$ OR bioenergy OR "energy generat*"; 2) technology associated, search field code: cell* OR biofilm$ OR batter* OR electr*; 3) microorganisms of interest, with search combination: microbial OR microbe$ OR biological OR bacteria* OR fung* OR algae; Because of the large number of articles initially found, 19,671 records, the query was restricted to the title of the publication. We then refined the survey by research area to the areas "microbiology" and "marine freshwater biology". We focused on the areas of microbiology and marine freshwater biology since these research fields cover the great majority of microorganisms used in MFCs and, therefore, provide a good subsampling. The remaining articles were evaluated by their relevance to the topic of interest by reading the titles and abstracts. To guarantee that we maintained our focus on the aims proposed above we excluded publications whose contents were not related to our aims, for example, articles dealing with specific electrochemical processes or the material composition of the electrodes.

After completing the initial screening, the remaining articles were analyzed by abstract, keywords, and by reading the full article. The following information was extracted from each article:

a) *Year*: The data are provided in the column "year of publication" in WoS.
b) *Journal*: We determined the distribution of articles by journal, with the results weighted by dividing the number of relevant publications by the number of issues of the journal published each year. To identify which journals published more papers on MFCs regardless of the total number of papers published by each journal, which is very heterogeneous, we calculated a relative weight w [23]:

$$w=\left(\frac{n}{pey}\right)1000 \quad (1)$$

where p is the mean number of papers published in the first issue of each year , e is the number of issues per year, y is the number of years of analysis, and n is the number of papers resulting from our survey for the journal. We used $y=8$ years, from 2008 to 2015.
c) *Country*: We considered the article's country of origin to correspond with the university address of the lead/first author, obtained through the WoS field "reprint address". The number of publications by country was related to the country's investment in Research and Development (R&D) in terms of the percentage of invested Gross Domestic Product (GDP) normalized by the Purchasing Power Parity (PPP). The gross expenditures on R&D were obtained from the 2014 Battelle report "2014 Global R&D Funding Forecast", which is based on data from the World Bank, International Monetary Fund, and CIA Fact Book [24].
d) *Technology range of application*: We classified the eletro-biochemical devices studied into three broad categories: (1) bench scale, for laboratory small MFCs; (2) large scale, for studies carried out in large MFC plants; and (3) other applications (pilot projects), for studies involving electricity generation with microorganisms through other technologies (e.g. solar microbial cells).
e) *Type of substrate*: The substrates used in the aqueous solution of the MFCs were classified according to their chemical composition. We classified them as natural (consisting, for most part, of organic compounds) or synthetic (artificial/inorganic compounds).
f) *Pure or mixed cultures or comparative studies*: We determined whether (1) the studies used a single microorganism to generate electricity, (2) the studies used a association of microorganisms (mixed) or (3) the studies compared the generation and/or efficiency between pure or mixed cultures in MFCs.
g) *Microorganism(s) under study*: For each bacterium, we searched the specific taxonomic classification, the Gram stain and the degree of pathogenicity to man. For non-transgenic microorganisms we used the *MicrobeWiki* database [25] (Kenyon College, Ohio, United States), for genetically modified microorganisms we used *LPSN* database: "List Of Prokaryotic Names With Standing In Nomenclature" [26] (British Society for General Microbiology). The quoted frequency for each organism was compared to the frequency of appearance in previous reviews [10,15–20].

We conducted the Pearson correlation test and graphical analysis to show tendencies and relationships, and to examine the relationship between the number of publications screened and the number of MFC publications in WoS. The same tests were also used to investigate the relation between the number of publications and the amount of R&D investment in US$ and between the number of publications and the percentage of GDP invested in R&D.

3. Results

The initial search resulted in 19,671 articles, from which 3427 passed the first screening in the ISI Web of Science database (Fig. 1). Of these, only 116 were actually directly related to microbiology and marine freshwater biology. A total of 98 (0.5%) articles met the inclusion criteria during the third and final screening, they are all listed in Appendix.

All studies matching our criteria were published after 1999, and we detected a substantial increase in the number of publications after 2007 (Fig. 2). 84.7% of the studies were concentrated in the nine-year period from 2006 to 2014. In addition, a positive correlation was found between the number of publications screened

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