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Review

# A review into the use of ceramics in microbial fuel cells

Jonathan Winfield [a], Iwona Gajda [a], John Greenman [a,b], Ioannis Ieropoulos [a,b,*]

[a] Bristol BioEnergy Centre, Bristol Robotics Laboratory, University of the West of England, T-Building, Frenchay Campus, Bristol BS16 1QY, UK
[b] School of Life Sciences, Faculty of Health and Life Sciences, University of the West of England, Frenchay Campus, Coldharbour Lane, Bristol BS16 1QY, UK

## HIGHLIGHTS

- Ceramics an inexpensive option for building microbial fuel cells (MFCs).
- Viable structural material, medium for proton exchange and electrode.
- Maintains healthy environment for electro-active bacteria.
- Benefits energy harvesting.
- Several examples of practical implementation using ceramic MFCs.

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## ABSTRACT

Microbial fuel cells (MFCs) offer great promise as a technology that can produce electricity whilst at the same time treat wastewater. Although significant progress has been made in recent years, the requirement for cheaper materials has prevented the technology from wider, out-of-the-lab, implementation. Recently, researchers have started using ceramics with encouraging results, suggesting that this inexpensive material might be the solution for propelling MFC technology towards real world applications. Studies have demonstrated that ceramics can provide stability, improve power and treatment efficiencies, create a better environment for the electro-active bacteria and contribute towards resource recovery. This review discusses progress to date using ceramics as (i) the structural material, (ii) the medium for ion exchange and (iii) the electrode for MFCs.



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* Corresponding author at: Bristol BioEnergy Centre, Bristol Robotics Laboratory, University of the West of England, T-Building, Frenchay Campus, Bristol BS16 1QY, UK.
*E-mail address:* ioannis.ieropoulos@brl.ac.uk (I. Ieropoulos).

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## 1. Introduction

### 1.1. Historical use of ceramics

Ceramic materials have played an important role in shaping the cultures of ancient civilisations. Historically, distinct communities, thousands of miles apart developed ceramic products using the same basic methods; i.e. the excavation of earthy clay, mixing with water, crafting into shape, drying in the sun before finally baking in fire. The final product was a hard but brittle construct, described as 'earthenware' (Richerson et al., 2005). The earliest evidence of kiln-fired clay art and tools dates back 28,000 years (Vandiver et al., 1989) to the Czech Republic region. Perhaps one of the most stunning examples of ancient ceramic use, is the 5000 year-old Terracotta Army that was built to represent the armies of the first Emperor of China.

A ceramic discovery, which captures the imagination of both archaeologists and electrochemists is that of the Baghdad (or Parthian) battery; an ancient terracotta object believed to be about 2000 years old. This clay structure housing a copper cylinder isolated from an iron rod, resembles a modern day battery when filled with vinegar, or any other electrolyte solution. The Baghdad battery has all the necessary components of an electrochemical device although its purpose is not fully known. It is believed that it might have been used as a power source to electroplate gold or silver or disinfect water (Kraft, 2008).

### 1.2. Historical use of ceramics in electrochemical technologies

Ceramics are still used to this day for the electrochemical treatment of wastewater, particularly by transforming pollutants into non-toxic materials. This can be performed in a number of ways by using ceramic diaphragms, for example polluted river streams can be treated through electrocoagulation (Li et al., 2011) as well as ultrafiltration (Gringer et al., 2015). Ceramic membranes can be modified to achieve increased selectivity, for cation transfer, enabling treatment through effective electrodialysis (Linkov and Belyakov, 2001), whilst microporous ceramic diaphragms offer stability against oxidising agents, enabling their use in the electrodialytic removal of heavy metal cations (Dzyazko et al., 2007). Ceramic microfiltration membranes can be customised using an array of potential ingredients including alumina, mullite, cordierite, silica, spinel, zirconia and other oxides. These can influence the nature and magnitude of the interactions between the membrane surface and the solution, thus affecting the permeating fluxes of solvent and solute through the membrane pores. They can be used as basic water filters, as ultrafiltration units and for cleaning oily wastewaters (Abbasi et al., 2010).

An alternative use is through the electroosmotic flow, a phenomenon first reported in 1809 by F.F. Reuss who showed that water could be made to flow through a porous clay plug, by the application of an electric field (Reuss, 1809). When an electric field acts on an electrolyte solution, cations move to the cathode and anions move to the anode. Hence, a transfer of momentum between moving ions and surrounding solvent molecules takes place with the flow of liquid through the membrane, leading to an electro-osmotic transport. Electro-osmosis is an effective process of water treatment by removing water-soluble organics from clay-rich soil (Schultz, 1997). It is also an important feature of fuel cell applications, which is something that will be discussed later with respect to ceramic microbial fuel cells.

### 1.3. The use of ceramics in fuel cells

Ceramic membranes have been increasingly used in a broad range of industries including: biotechnological, pharmaceutical, dairy, food and beverage, as well as the chemical and petrochemical, microelectronics, metal finishing, and power generation (Sondhi et al., 2003); in the latter case, ceramics have been employed in high temperature fuel cells for many years.

The principles of fuel cell operation were first reported by Sir William Grove in 1839 (Minh and Takahashi, 1995) using hydrogen and oxygen as the reactants. Ceramics were first used in fuel cells in 1937 when a ceramic solid-oxide fuel cell (SOFC) was operated (Baur and Preis, 1937). SOFCs employ an all-solid construction comprising 3 ceramic layers; two electrodes, and an electrolyte (which is the medium for proton conduction) in the middle. Ceramic is the material of choice for SOFCs because it is tolerant to the high temperatures required for operation, and in addition it provides a useful electrode material, because both its porosity and permeability can be customised. As will be discussed later, these are attributes, which can also be beneficial for operation in ambient temperatures.

The next section will discuss the emergence of the use of ceramics in microbial fuel cells, which are a form of biorefinery utilising wastewater as a source of renewable energy.

## 2. Microbial fuel cells

### 2.1. Introduction to microbial fuel cells

In order to combat the challenge of climate change, renewable energy technologies need to be identified and optimised. Another immediate environmental challenge is pollution via the accumulation of anthropogenic waste. Bio-transformation systems can help tackle these issues, and microbial fuel cells (MFCs) are one such technology that can be particularly advantageous, due to the ability to utilise low grade waste that is too wet to burn. MFCs employ electro-active bacteria, which generate electricity by consuming organic pollutants, as part of their anaerobic metabolism. As will be discussed later, there are additional products and benefits that can be exploited through MFC operation.

For several decades there has been a focus on optimising MFC performance in terms of power production and organic load removal. These efforts have seen a fairly rapid improvement with power generation now several orders of magnitude greater than a few years ago (Li et al., 2011). However, a major consideration that has not received as much attention as possible, until recently, is the employment of inexpensive and sustainable materials for the construction of MFCs. This is imperative for scaling up, not only in terms of the cost benefit, but also because one of the major contributors to the accumulation of toxic waste comes in the form of old electronic components, plastics and batteries (Irimia-Vladu, 2014). Building sustainable energy devices from materials that may themselves contribute to the accumulation of waste build-up, would be a paradox.

Until recently most of the materials, components and configurations used for constructing MFCs originated from other fuel cell technologies such as proton exchange membrane fuel cells. These chemical fuel cells operate in distinctly different conditions to MFCs and environments which would be hazardous for the electro-active bacteria. In order for MFCs to progress from laboratory curiosities to real-life practical implementation, research must move away from using high maintenance chemicals (e.g. potassium permanganate and ferricyanide), expensive catalysts (e.g. platinum) and sub-optimal, costly components such as the polymeric ion exchange membrane (IEM).

Another obstacle that the MFC community has had to overcome, has been the reliance on artificial mediators. Up until the mid-2000s, chemicals such as neutral red, methylene blue and thionine were added into the anode chamber to enable the trans-

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