Biosensors and Bioelectronics 90 (2017) 558–576

Contents lists available at ScienceDirect

Biosensors and Bioelectronics

journal homepage: www.elsevier.com/locate/bios

Recent advances in the development and utilization of modern anode materials for high performance microbial fuel cells

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A R T I C L E I N F O

Keywords:
Microbial fuel cells
Air-cathode
Wastewater
Biofilm
Biocatalyst
Stainless steel

A B S T R A C T

Microbial fuel cells (MFCs) are novel bio-electrochemical device for spontaneous or single step conversion of biomass into electricity, based on the use of metabolic activity of bacteria. The design and use of MFCs has attracted considerable interests because of the potential new opportunities they offer for sustainable production of energy from biodegradable and reused waste materials. However, the associated slow microbial kinetics and costly construction materials has limited a much wider commercial use of the technology. In the past ten years, there has been significant new developments in MFCs which has resulted in several-fold increase in achievable power density. Yet, there is still considerable possibility for further improvement in performance and development of new cost effective materials. This paper comprehensively reviews recent advances in the construction and utilization of novel anodes for MFCs. In particular, it highlights some of the critical roles and functions of anodes in MFCs, strategies available for improving surface areas of anodes, dominant performance of stainless-steel based anode materials, and the emerging benefits of inclusion of nanomaterials. The review also demonstrates that some of the materials are very promising for large scale MFC applications and are likely to replace conventional anodes for the development of next generation MFC systems. The hurdles to the development of commercial MFC technology are also discussed. Furthermore, the future directions in the design and selection of materials for construction and utilization of MFC anodes are highlighted.

1. Introduction

The growth in the use of energy has a direct link with the well-being, quality of life and prosperity of a society. There is an increasing need for not only generating sufficient energy, but also to find energy from new sources that are safe, sustainable and environmentally friendly. As the availability of coal, oil and gas are being exhausted (Aziz et al., 2013), there is a growing need to consider alternate energy sources. A reliance on the current renewable energy sources alone will not sufficiently meet the required needs in the future. It would be increasingly necessary to rely on the discovery of new energy sources in order to continue to meet future energy needs (Sukhatme, 2011).

One of the promising solutions for addressing this energy problem is to develop and deploy specific energy sources for different utilities. This will involve developing strategies that enable derivation of energy from waste materials. For example, across the world, huge volumes of wastewater are continuously pumped directly into rivers, streams and the oceans. The impact of this huge wastewater disposal is severe, ranging from damage to the marine environment and to fisheries. Such disposal of wastewater does little to preserve water at a time when we are facing serious global water shortage and the problem is likely to be exacerbated with the impact of climate change. Yet, in many cases, the

Abbreviations: 3D, three-dimensional; 2D, two-dimensional; ACNFN, activated carbon nanofiber nonwoven; ARB, anode respiring bacteria; BMFCs, benthic microbial fuel cells; CC, carbon cloth; CC-A, concentrated nitric acid; CNF, carbon nanofiber; CNFs/GF, carbon nanofibers modified graphite fibres; CNT, carbon nanotube; CNT-textile, carbon nanotube-textile; COD, chemical oxygen demand; CP, carbon paper; CS–CS–GR, open-celled carbon scaffold; CV, carbon veil; EET, extracellular electron transfer; EWP, egg white protein; FBMF, flow fixed-bed microbial fuel cell; GAC, granular activated carbon; GF, graphite felt; GMS, graphene modified stainless steel mesh; GNRs, graphene nanoribbons; GPM, gold/poly (e-caprolactone) microfiber; GPM, gold/poly (e-caprolactone) microfiber; GPN, gold/poly(e-caprolactone) nanofiber; IL-GNS, ionic liquid functionalized graphene nanosheets; G–S, graphene–sponge; LCC, layered corrugated carbon; LSC, loofah sponge carbon; MCM 41, mobil catalytic materials number 41; MFC, microbial fuel cell; MFC-GFB, graphite fibre brush; MFC-GG, graphite granules; MPL, micro-porous layer; MWCNTs, multi-walled carbon nanotubes; m-WO3, mesoporous tungsten trioxide; PAN, polyacrylonitrile; PAN–GR, PAN/graphite composites; PANI, polyaniline; PG, planar gold; PTFE, polytetrafluoroethylene; RACNT, randomly aligned CNT; rGO/SnO_2, reduced graphene oxide; rGO–CNT, reduced graphene oxide/carbon nanotube; SS, stainless-steel; SSFFs, stainless steel fibre felt; SSLbL, spin-spray layer-by-layer; SSM, stainless steel mesh; VACNT, vertically aligned CNT; WW, wastewater

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http://dx.doi.org/10.1016/j.bios.2016.10.014
Received 1 September 2016; Received in revised form 28 September 2016; Accepted 4 October 2016
Available online 05 October 2016
0956-5663/

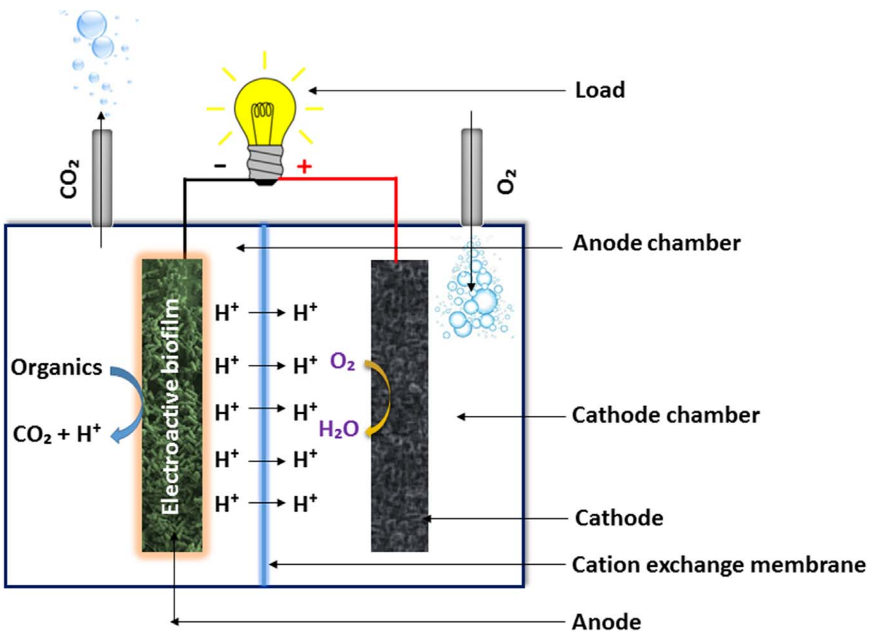

Fig. 1. Working principle and basic construction of MFC.

effluent contains significant amount of organic substances which are potentially significant source of energy. One way of achieving this is by using microbial fuel cell (MFC) which is capable of directly converting chemical energy present in the organic materials to electricity by using microorganisms as catalysts (Thepsuparungsikul et al., 2012; Tsai et al., 2009; Zhao et al., 2010). The electricity generated can be used for maintenance and operation of the wastewater treatment facility, and, thus, creating a self-sustaining energy supply for the water treatment facility and, hence, to reduce operational costs (Liu et al., 2004).

A typical microbial fuel cell consists of an anode and a cathode compartments separated by proton exchange membrane, as illustrated in Fig. 1. The anode is the site where biocatalyst grows in the form of biofilm which promotes the decomposition of organic materials to produce electrons and protons. The electrons are transferred to the cathode compartment through an external circuit, while the protons are transferred to the cathode compartment through the proton exchange membrane (PEM). The electrons and protons are consumed in the cathode compartment with the protons combining with oxygen to form water (Min and Logan, 2004; Torres et al., 2010), as shown in Fig. 1. The chemical reactions which occur in the anodic and cathodic chambers, respectively, are given by Eqs. (1) and (2) below (Rahimnejad et al., 2015):

$$\text{Anodic reaction - } C_2H_4O_2 + 2H_2O \rightarrow 2CO_2 + 8H^+ + 8e^- \quad (1)$$

$$\text{Cathodic reaction - } 2O_2 + 8H^+ + 8e^- \rightarrow 4H_2O \quad (2)$$

The chosen electrode materials play a significant role in the performance of the MFC and it is critically important for successful utilization of this technology for efficient energy generation. In past two decades, many different materials have been explored as anodes for MFCs. While most of the earlier studies focused on the use of carbon based material, such as graphite rod, graphite felt, carbon cloth, flexible graphite sheets, graphite granules and activated carbon (Li et al., 2010; ter Heijne et al., 2008; Wang et al., 2009; Wei et al., 2011), recent studies have found that these two dimensional electrode materials have many limitations, such as low surface area, high internal resistance, high activation and mass transfer over-potential which hinders their ability to achieve high performance with MFCs. With recent advances in materials science and nanotechnology, the use of second generation three-dimensional (3D) electrode material has attracted considerable interest for the development of MFCs. In 2007, Logan et al. (2007) developed a graphite fibre brush anode electrode with a 3D structure. They achieved a maximum power density of 2400 mW/m^2 with a single chamber air cathode. 3D surface anodes offer high surface areas for efficient colonization of bacterial communities and, hence, for increasing substrate access to the anode respiring bacteria (ARB) and, consequently, minimizing mass transfer limitation (Liu et al., 2010). In addition to this surface characteristics, 3D surface anodes are very quintessential in adhesion of bacterial colonies, have high volume to surface ratio, and good biocompatibility (Cui et al., 2015; Garcia-Gomez et al., 2015).

The anode surface also plays a significant role in promoting and maintaining bio-catalytic activity. Surfaces can be modified to become favourable habitats for biofilms which are capable of enhancing electron transfer from bacteria to anode surface. Generally, the achievement of more bacterial adhesion enables the generation of more power with minimum loss (Jiang and Li, 2009). It has been demonstrated in a recent study that surface modification not only increases MFC system performance, but also decreases the MFC start-up time (Luo et al., 2013).

Many studies have also recently developed and extensively studied the use of graphene-based anodes, composite anodes, and surface modified anodes (Kumar et al., 2013). Each electrode material has its own merits and demerits. Metal based or metal composite anodes have not been thoroughly studied or explored for MFCs. Most of the metals failed to pass the set criteria for best anode electrodes for MFC because of their tendency to corrode (Wei et al., 2011). Pocaznoi et al. (2012) claimed recently that, of most metals, stainless steel is the most promising material for MFC anodes. However, there is still a lot of scope for further improvement in the use of stainless steel for MFC anode development, as well as other new low cost efficient materials (Pocaznoi et al., 2012).

The achievement of large scale development and economic viability of MFCs systems requires the availability of cost effective anodes capable of achieving higher performance for long term operation, while also involving easy maintenance or, where possible, to be completely free of maintenance (Chen et al., 2012b).

This paper reviews the recent advances in the development of anode materials and configurations over the past five years. The considerable developments in anode materials for microbial fuel cells within this period is illustrated in Fig. 2 and this clearly demonstrates that the