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Microbial electrolysis cells: An emerging technology for wastewater treatment and energy recovery. From laboratory to pilot plant and beyond

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ABSTRACT

Microbial electrolysis cells (MECs) are cutting edge technology with great potential to become an alternative to conventional wastewater treatments (anaerobic digestion, activated sludge, etc.). One of the main features of MECs is that they allow organic matter present in wastewater to be converted into hydrogen thus helping to offset the energy consumed during treatment. There are already some large-scale experiments under way but MECs are far from being a mature technology; important challenges, mostly techno-economic in nature (cost of materials, hydrogen management, etc.) remain. This study provides an up-to-date review of the latest developments in MECs, paying special attention to those aspects that may be critical to the commercial viability of MECs for wastewater treatment and hydrogen production. It explores the suitability of different cell configurations and the scalability of MEC designs; it also reviews many of the laboratory, semi-pilot and pilot scale experiments. The review provides a critical analysis of the current state and the future prospects for MECs; it highlights factors crucial to the development of successful MEC designs, identifies potential application niches and discusses the integration of MECs with energy transportation systems.

Contents

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1. Microbial electrolysis cells for sustainable wastewater treatment

Strong population growth coupled with modern societies' ever-increasing appetite for energy has changed the way we consider what have traditionally been regarded as wastes. Wastewater (WW) in particular is now considered as a 'misplaced resource' from which valuable products and energy can be obtained [1]. It has been estimated that domestic wastewater (dWW), for instance, can contain 7.6 kJ l^{-1} [2] or 23 W per capita [3]. Due to their robustness and flexibility, biological anaerobic treatments, i.e. anaerobic digestion (AD), have become the preferred technology for recovering some of this energy. During the past decade a new generation of biobased technologies, known as bioelectrochemical systems (BESs), with great potential for wastewater treatment and resources recovery have emerged. BESs can be broadly classified as microbial fuel cells (MFCs) or microbial electrolysis cells (MECs) depending on whether they operate in galvanic (MFCs) or electrolytic mode (MECs) (Fig. 1). There has been some debate as to which method is the most convenient way of recovering energy from WW [4], although it seems that from economic, environmental, and technical perspectives MECs offer substantial advantages over MFCs [5–10]. Obviously, the validity of this statement depends largely on the product obtained from the MEC (hydrogen, methane, ethanol, hydrogen peroxide, etc). Hydrogen, in particular, represents an interesting option: it is a critical resource in many strategic industrial sectors (metallurgy, fertilisers, chemical and petrochemical industry, etc.) [11], and its high energy yield has led to suggestions that it will be the energy carrier of the future [12].

There have been several previous reviews of MECs, although the number remains small when compared with the number of research papers available [6]. Most of these reviews have focused on the substrates used for MECs [13], the use of BESs as a flexible platform for various engineering functions and for the production of high value chemicals and bio-inspired nanomaterials [6,14–18], cathodic catalysts [19,20], ion exchange membranes [21,22], electrode materials [23–25], and electroactive biofilms [26,27]. This study focuses instead on exploring practical applications of MECs in wastewater treatment and hydrogen production; it provides a critical analysis of current challenges and future opportunities. We begin our discussion by briefly reviewing the electrode materials and MEC configurations that are more likely to be of practical use, highlighting their weaknesses and strengths. We continue by reviewing experiments in which real WWs were used as substrates for hydrogen production at laboratory, semi-pilot and pilot level, paying special attention to parameters that would be critical on a commercial scale and therefore have the strongest influence on the techno-economical feasibility of this technology. This is followed by a brief discussion of some environmental and economic issues and we finish with a critical analysis of the prospects for MEC technology, evaluating application niches, alternatives to hydrogen, and discussing the integration of MECs with energy transportation systems.

1.1. Basic principles of MECs

BESs can be regarded as electrochemical systems, in which at least one of the electrode reactions involves electrochemical interactions with microorganisms. Most frequently it is the anodic reaction that requires the presence of certain microorganisms, usually referred to as anode respiring bacteria (ARB), which have the ability to transfer electrons from a biodegradable substrate to a solid electrode.

Fig. 1 is a schematic representation of the working principles of MFCs and MECs. The reactions at biotic anodes are quite similar in MECs and MFCs. Electrons, one of the main by-products of ARB metabolism – alongside protons and CO_2 – are transferred to the anode and flow through an external circuit to the cathode. When the BES is operated as an MFC, oxygen (or another oxidant) is present at the cathode and electrons flow freely through an electrical load

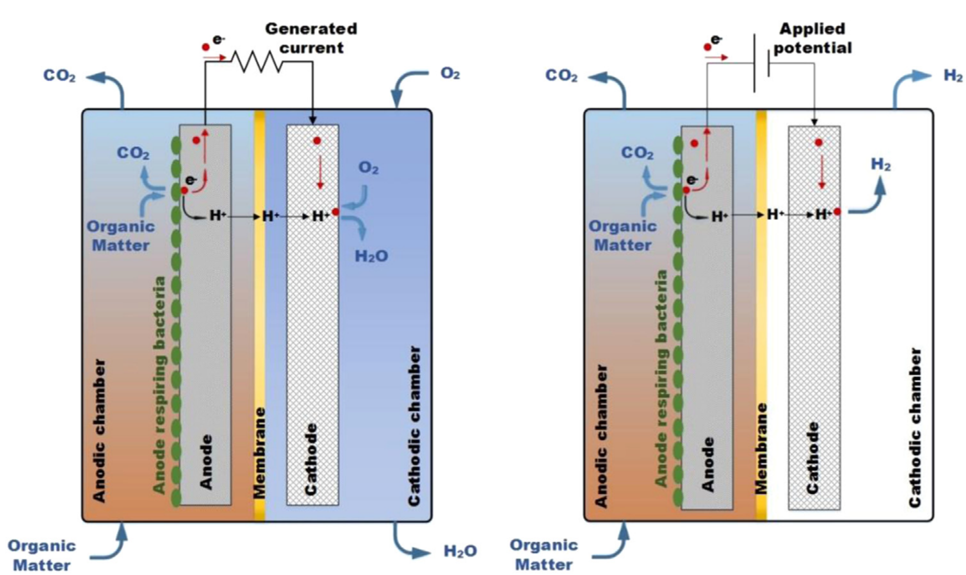

Fig. 1. Schematic representation of electricity production (left) and hydrogen production (right) through MFC and MEC respectively.