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Research review paper

A comprehensive review of microbial electrochemical systems as a platform technology

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ABSTRACT

Microbial electrochemical systems (MESs) use microorganisms to covert the chemical energy stored in biodegradable materials to direct electric current and chemicals. Compared to traditional treatment-focused, energy-intensive environmental technologies, this emerging technology offers a new and transformative solution for integrated waste treatment and energy and resource recovery, because it offers a flexible platform for both oxidation and reduction reaction oriented processes. All MESs share one common principle in the anode chamber, in which biodegradable substrates, such as waste materials, are oxidized and generate electrical current. In contrast, a great variety of applications have been developed by utilizing this *in situ* current, such as direct power generation (microbial fuel cells, MFCs), chemical production (microbial electrolysis cells, MECs; microbial electrosynthesis, MES), or water desalination (microbial desalination cells, MDCs). Different from previous reviews that either focus on one function or a specific application aspect, this article provides a comprehensive and quantitative review of all the different functions or system constructions with different acronyms developed so far from the MES platform and summarizes nearly 50 corresponding systems to date. It also provides discussions on the future development of this promising yet early-stage technology.

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1. Introduction

Microbial electrochemical systems (MESs) are a rapidly growing environmental technology at the nexus of water and energy (Harnisch and Schröder, 2010; Logan and Rabaey, 2012; Rozendal et al., 2008; Torres et al., 2010). While this platform technology has only been intensively studied and developed in the past decade, it opens up a new interdisciplinary field for research and development which integrates microbiology, electrochemistry, materials science, engineering, and many related areas together. MESs not only provide a unique environment to understand the largely unexplored microbial electrochemistry, they also offer a flexible platform for many different engineering functions to be developed. While many existing environmental technologies have only one or two functions, the MES platform is so flexible that

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dozens of functions have been discovered. Almost all MESs share one common principle in the anode, in which biodegradable substrates, such as waste materials, are oxidized by microorganisms and generate electrical current. The current can be captured directly for electricity generation (microbial fuel cells, MFCs) (Fornero et al., 2010; Liu and Logan, 2004; Ren et al., 2007), or used to produce H_2 and other value-added chemicals (microbial electrolysis cells, MECs) (Cheng et al., 2009; Liu et al., 2010; Logan et al., 2008). The electrons can also be used in the cathode chamber to synthesize organic compounds (microbial electrosynthesis, MES) or remediate contaminants (microbial remediation cells, MRCs) (Aulenta et al., 2008; Butler et al., 2010; Gregory and Lovley, 2009; Lovley and Nevin, 2011; Rabaey and Rozendal, 2010). The potential across the electrodes can also drive desalination (microbial desalination cells, MDCs) (Cao et al., 2009; Jacobson et al., 2011; Luo et al., 2011; Luo et al., 2012c; Mehanna et al., 2010). The production of current associated with microbial catabolism was first reported a century ago by Potter (1911), but research interests in this concept have only blossomed in the past decade, resulting in an exponential growth in the number of journal articles (Fig. 1). There are several excellent reviews that provided information on the history and development of MESs (Borole et al., 2011; Schröder, 2011, 2012; Sleutels et al., 2012) and the substrates, materials, and microbial communities in different systems (Hamelers et al., 2010; Logan, 2009; Lovley, 2006; Pant et al., 2010; Wei et al., 2011), but there has been no comprehensive or quantitative review that directly addresses one fundamental factor: where all the known functions were originated from and all future functions will be based upon. As shown in Table 1, this article aims to provide the first complete review with the goal to summarize all the functions with different acronyms that have been developed using this platform to date, and shed light on future system development for energy and environmental science and engineering. Different groups have also used bioelectrochemical systems (BESs) or MXCs for this technology platform, but because BESs were also used in other studies to represent cell free enzyme based systems, while system acronyms have far beyond the “X” of MXCs, this review uses MESs to represent the overall technology platform (Harnisch and Schröder, 2010; Logan and Rabaey, 2012; Rozendal et al., 2008; Torres et al., 2010).

2. The shared principle in the anode chamber

Compared to traditional chemical fuel cells, the MES platform uses low-cost and self-sustaining microorganisms to oxidize organic and inorganic electron donors, mainly waste materials, and transfer electrons to the anode electrode. The electrons can be captured directly through an external circuit for electricity generation or used for chemical production. The microbial oxidation reaction in the anode chamber is a shared principle for almost all MES reactors, as shown in Table 1. However, how to use these electrons on the cathode side shows the beauty of this platform technology, because any reduction-based reaction can be realized in the cathode chamber, which creates numerous possibilities. Based on the different functions, the MES platform has been specified into many different names that some researchers name them MXCs, where X stands for different applications (Harnisch and Schröder, 2010; Torres et al., 2010). Table 1 summarizes all the reactor acronyms to date and demonstrates the shared principle on the anode and the versatile functions on the cathode.

Ideal anodic reactions in MESs generally include dynamic and effective microbial activity and community, higher substrate conversion rate and electron transfer efficiency, and lower material and system costs. MESs employ a unique group of microbes called electrochemically active bacteria (EAB), exoelectrogen, electricigen, or anode respiring bacteria (ARB) to convert the chemical energy stored in organic or inorganic substrates to electrical energy during their anaerobic respiration (Logan, 2009; Lovley, 2006; Park et al., 2001; Torres et al., 2009). Such microorganisms are able to transfer electrons out of cell membranes to the electrode either directly through membrane-bound protein structures, such as pili, *c-type* cytochrome and filaments, or using mobile electron shuttles, such as mediators for indirect electron transfer. For example, recent studies showed that *Geobacter sulfurreducens* requires conductive pili as nanowires for cell-to-cell electron conduction and *c-type* cytochrome *OmcZ* to promote electron transfer onto the electrode (Lovley, 2011; Summers et al., 2010). In contrast, *Shewanella* species were reported to make both direct electrode contact through conductive filaments and indirect electron transfer *via* mediators, such as riboflavin or flavin adenine mononucleotide (FMN) (Canstein et al., 2008; Gorby et al., 2006; Marsili et al., 2008). Many other bacteria can produce and use soluble redox mediators or electron shuttles, which transport the electrons from the cell to the electrode. For example, *Pseudomonas* species can produce phenazines as extracellular electron shuttles, and other bacteria can use externally provided mediators, such as neutral red, anthraquinone-2,6-disulfonate (AQDS), thionine, methyl viologen, methyl blue, and some humics (Aulenta et al., 2008; Milliken and May, 2007; Park and Zeikus, 2000; Rabaey et al., 2005a; Scott and Murano, 2007; Thurston et al., 1985).

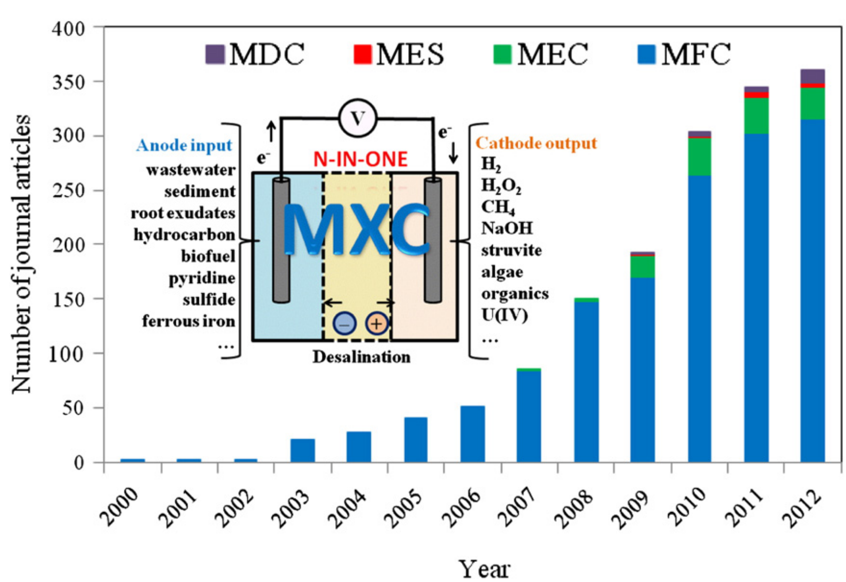

Fig. 1. Number of published journal articles on MESs containing the phrases “microbial fuel cell”, “microbial electrolysis cell”, “microbial electrosynthesis” or “microbial desalination cell”. Source: Scopus on 7/1/2013; document type: Journal; Language: English; duplicates were removed from searching results.