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Research review paper

A logical data representation framework for electricity-driven bioproduction processes☆,☆☆

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ABSTRACT

Microbial electrosynthesis (MES) is a process that uses electricity as an energy source for driving the production of chemicals and fuels using microorganisms and CO_2 or organics as carbon sources. The development of this highly interdisciplinary technology on the interface between biotechnology and electrochemistry requires knowledge and expertise in a variety of scientific and technical areas. The rational development and commercialization of MES can be achieved at a faster pace if the research data and findings are reported in appropriate and uniformly accepted ways. Here we provide a framework for reporting on MES research and propose several pivotal performance indicators to describe these processes. Linked to this study is an online tool to perform necessary calculations and identify data gaps. A key consideration is the calculation of effective energy expenditure per unit product in a manner enabling cross comparison of studies irrespective of reactor design. We anticipate that the information provided here on different aspects of MES ranging from reactor and process parameters to chemical, electrochemical, and microbial functionality indicators will assist researchers in data presentation and ease data interpretation. Furthermore, a discussion on secondary MES aspects such as downstream processing, process economics and life cycle analysis is included.

Contents

1. Introduction . . . 0
 1.1. Requirements in rational development of MES field: data presentation and essential performance indicators . . . 0
2. Reporting on MES experiments: reactor and process parameters . . . 0
3. Key production parameters . . . 0
 3.1. Product titer and yield . . . 0
 3.2. Production rate . . . 0
 3.3. Coulombic efficiency and electron recovery . . . 0
 3.4. Energetic efficiency . . . 0
4. Other parameters . . . 0
 4.1. Microbial parameters . . . 0
  4.1.1. Start-up . . . 0
  4.1.2. Growth yield . . . 0
  4.1.3. Turnover per cell . . . 0
 4.2. Techno-economic evaluations . . . 0
  4.2.1. Downstream processes or product recovery . . . 0
  4.2.2. Techno-economic analysis (TEA) . . . 0
  4.2.3. Life cycle analysis (LCA) . . . 0
5. Conclusions . . . 0

☆ SI-1 Supplementary information (SI) available.
☆☆ SI-2 Excel tool for the calculations of key production parameters of several microbial bioelectrochemical systems available.
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Box 1
Q4 *Definitions* (adapted from Harnisch and Freguia, 2012).

Electrocatalysis: An effect by virtue of a catalyst leading to an increase in the rate of an electrochemical reaction at a given potential.
Bioelectrocatalysis: Electrocatalysis driven by biological entities such as microorganisms or enzymes.
Microbial electrochemical technologies (METs): All technologies or concepts that exploit microorganisms for the bioelectrocatalysis of anodic and/or cathodic reactions in the electrochemical systems. The electrochemical devices that are used to explore such reactions are usually referred to as bioelectrochemical systems (BESs).
Microbial fuel cell (MFC): A BES that exploits microorganisms to facilitate the conversion of chemical energy to electrical energy, generally but not exclusively from the microbially-driven oxidation of organic compounds at the anode and the oxygen-reduction reaction at the cathode. The oxygen-reduction reaction in this case can be either abiotic or microbially catalyzed.
Microbial electrolysis cell (MEC): A BES that uses electrical energy and microorganisms for the (reductive) synthesis of chemical products at the cathode. The anodic reaction in this case can be either abiotic water splitting or microbial oxidation of organic matter.
Microbial electrosynthesis (MES): A concept based on MEC principle for microbially catalyzed, electricity-driven synthesis of chemicals or fuels from CO_2 or organic feedstocks in BESs.
Note: The polarity of the anode and the cathode depends on the type and operation of the device (galvanic or electrolysis cell).

1. Introduction

The capability of microorganisms to exchange electrons directly or indirectly with electrodes and thus drive novel oxidative and reductive reactions at electrodes has led to the development of multiple microbial electrochemical technologies (METs) over the last decade (Logan and Rabaey, 2012). Attempts were made during the last decade for scaling-up of microbial fuel cells (MFCs) and microbial electrolysis cells (MECs) from lab-scale to pilot-scale (Logan, 2010), which paved the way for larger-scale applications for these systems. The practical application of these METs has taken considerable time but at present there are several larger-scale demonstrations that are operational for the production of methane (Cambrian Innovation Inc., 2013), for producing power in remote locations (Parry, 2013), for energy-efficient wastewater treatment (www.emefcy.com), and for powering LEDs (light emitting diodes) with plant-MFCs (www.plant-e.com). MFCs have also been demonstrated for charging electronic devices such as mobile phones (Ieropoulos et al., 2013). In 2013, a pilot MEC demonstrated the feasibility of this technology for the on-site treatment and conversion of urine into ammonia and hydrogen (Rodriguez Arredondo et al., 2015). Other potential applications that have been envisaged for METs include bioremediation, energy efficient desalination, bioproduction, and biosensors (Patil et al., 2012).

In recent years much attention has been focused on the production of other valuable products such as hydrogen (Cheng and Logan, 2007), methane (Cheng et al., 2009) caustic soda (Rabaey et al., 2010) and hydrogen peroxide (Rozendal et al., 2009) at the cathode of microbial electrolysis cells (MECs). While MEC-based processes require a modest amount of electrical energy, this is increasingly available from sustainable sources such as wind and solar, or possibly by using salinity gradient energy from natural or engineered systems (Hatzell et al., 2014). When MECs are used for autotrophic processes, the required CO_2 is becoming increasingly available on the market and its capture into chemicals for many diverse reasons is desired. This creates an opportunity to use electricity as energy source for the fixation of CO_2 into chemicals (Nevin et al., 2010).

This approach of using electricity and microorganisms, in concert with fixing CO_2 or transforming organic chemicals, is termed microbial electrosynthesis (MES) (Rabaey and Rozendal, 2010). Electrically steered fermentation can lead to better redox balancing and production of more complex or reduced products. Examples include the conversion of acetate to butyrate (Choi et al., 2012) or longer chain fatty acids (van Eerten-Jansen et al., 2013), fatty acids into alcohols (Sharma et al., 2013), glycerol to 1,3-propanediol (1,3-PDO) (Dennis et al., 2013), glycerol to ethanol (Speers et al., 2014), CO_2 to butyrate (Ganigué et al., 2015) and the accumulation of polyhydroxyalkanoates (Srikanth et al., 2012). For detailed information on the recent progress in several other BESs, readers are directed to these review articles (Li et al., 2014; Mohan et al., 2014a,b; Wang and Ren, 2013).

In comparison to other processes, MES offers novel opportunities for land-independent conversions of wind or solar power to commodity and fine chemicals in a carbon positive process (Lovley, 2011; Rabaey and Rozendal, 2010). Apart from the challenges associated with interdisciplinary research (see Fig. 1 for an overview of key aspects) and scale-up, inadequate reporting of data, poor quality of data representation, and universal acceptance of sufficient data inclusion can in part delay the technological realization of these processes (Logan and Rabaey, 2012; Sharma et al., 2014). In order to address these issues we provide here a framework for reporting on MES research and propose several important performance indicators to describe these processes.

1.1. Requirements in rational development of MES field: data presentation and essential performance indicators

All BESs are unique combinations of a volume-based technology (environmental and industrial biotechnology) with an intrinsically surface-based process (electrochemistry), and thus performance parameters must accommodate both fields (Fig. 2). MES differentiates itself from typical METs such as MFCs as chemical formation is the main product. This requires detailed information on product formation rate, concentration, and specificity. These parameters have a major impact on aspects such as downstream processing and overall process economics.

Technical and microbiological hurdles exist towards maturing and developing MES for industrial applications (Logan and Rabaey, 2012) In addition to scientific and engineering breakthroughs, the rational development and commercialization of this technology can be achieved at a faster pace if research experiments and findings are reported in a way that allows cross-comparison of data. In order for this comparison to occur, the broad community needs to agree on what information needs to be reported.

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