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The use of carbon dioxide in microbial electrosynthesis: Advancements, sustainability and economic feasibility

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ABSTRACT

This study examines the latest advancements in the field of Microbial ElectroSynthesis (MES) and reports a unique sustainability and economic assessment for the production of five alternative compounds (formic, acetic, propionic acids; methanol and ethanol). Different chemical production conditions were compared by modelling a 1000 t per year production plant. Three sustainability indicators; net energy consumption (NEC), energy gain (EG) and global warming ratio (GWR), were used; along with three economic indicators: production cost, pay-back period and discounted cash flow rate of return. NEC analysis revealed substantial energy requirements in the MES reactor and rectification unit. The former due to the energy required to synthesise $CO_2$to longer chains and the later due to increased water molecules formed during synthesis. EG values suggested that producingformic acid and methanol using MES were lower than conventional processes. MES was shown to use more carbon dioxide for methanol, ethanol and formic acid synthesis than those produced. The economic analysis showed that formic acid and ethanol had a long pay-back period of 15 years. However, production costs were found to be competitive with the market only for formic acid (0.30 £/kg) and ethanol (0.88 £/kg). Moreover, high returns were evaluated for formic acid (21%) and ethanol (14%) compared to the minimum requirements of the industry (11.60%) making these products economically attractive. Our findings reveal insights about the use and scale up of MES for a sustainable and economically viable chemical production process.

1. Introduction

Interest in bioelectrochemistry has peaked in the quest to determine how bacteria transfer electrons to solid state electrodes and how we can benefit from this process. According to Scopus, the period between 2005 and 2015 had a linear growth in the number of publications in this field from 100 to 1000 per year. The process occurs in so-called bioelectrochemical systems (BES); a technology that was initially aimed at converting organic and inorganic waste into energy products [1]. Traditional BES consist of an anode and a cathode which are separated by an ion exchange membrane, however membrane less reactors are also available [2]. An electrode reduction occurs in the anode compartment, the opposite, an electrode oxidation, occurs in the cathode compartment. Redox reactions are driven by electroactive biocatalysts; bacteria that interact with solid state electrodes connected through an electrical circuit that defines the cell's mode.

Novel applications of BES have emerged which can be divided into: microbial fuel cells (MFCs), microbial desalination cells, microbial solar cells and microbial electrolysis cells [3]. In microbial electrolysis cells, bacteria reduce organic or inorganic compounds with the use of external energy to produce hydrogen [4]. To assess how bacteria deal with electrical current, it is important to understand how electrons may be transported from the electrode to the cell. Electron transfer mechanisms can occur directly or indirectly and have been fully discussed in literature ([87,5]). Even that the performance of electron transfer mechanisms in bioanodes has been extensively explored ([88,6]), only recently it was found that the electron transfer mechanisms are bidirectional and are also used in biocathodes [7–9].

Even though MFCs have been the most commonly studied application, they present practical and theoretical energy production limitations. Recently, researchers have focused on microbial electrosynthesis (MES) and their ability to reduce substrates into usable chemicals [10]. MES has gained increased attention for the conversion of carbon dioxide (CO_2) to methane [11,10], acetate [12] and other higher biofuels [13,14]. Enzymes are also used to perform

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such bioproduction [15], however, enzymes are not in the scope of this article and are thus not further discussed. MES fits within the green chemistry as they operate under mild conditions (designed for energy efficiency), use bacteria as catalysts (less hazardous chemical synthesis) and CO_2 as raw material. MES is a technology with the potential of becoming a high atom economy process needed for sustainable development. Therefore, MES is a feasible solution and should be embedded to set up a framework for contributing towards meeting the CO_2 emission reduction targets; i.e. the 2050 CO_2 reduction target [16].

MES is at an early stage of development and its feasibility has not met rates close to that required for an efficient electrosynthesis [17]. In MES electrons are exclusively supplied by an external power source. These electrons are then used by the micro-organisms for CO_2 reduction to e.g. acetate (reaction (1)) [18]. When this power source comes from renewable sources, the concept is also known as an 'artificial form of photosynthesis' [19]. Fuels and chemicals produced via MES (from CO_2) are referred to as electrobiocommodities [20].

$$2CO_2 + 6H_2O + 8e^- \xrightarrow{Biocatalyst} CH_3COOH + 4H_2O + 2O_2 \quad \text{(Reaction(1))}$$

Using CO_2 as a substrate in MES offers advantages. CO_2 is an abundant source as it is available in the atmosphere, oceans and soils. It can be considered as subsidized cost by government funding [21]. However, using such a substrate also presents disadvantages, the main one being that CO_2 requires a significant amount of electrons for synthesis of organic compounds due to its thermodynamic stability. In addition, energy is needed to activatethe bacteria pathway for autotrophic growth, resulting in increased costs. Efficient electron use is a major concern, from both an economic and an environmental point of view. It can be noted that the use of renewable energy, mixed culture biofilms with varied metabolism and/or redox mediators may help solve this problem.

1.1. Empirical determination of microbial electrosynthesis

Autotrophic microorganisms that are capable of accepting electrons were initially targeted as catalysts for MES [22]. Acetogenic microorganisms were adopted based on their ability to convert CO_2 into acetyl-CoA which then can be used for biosynthesis [23]. Microorganisms that meet autotrophic requirements often do not meet electron acceptor requirements. In this

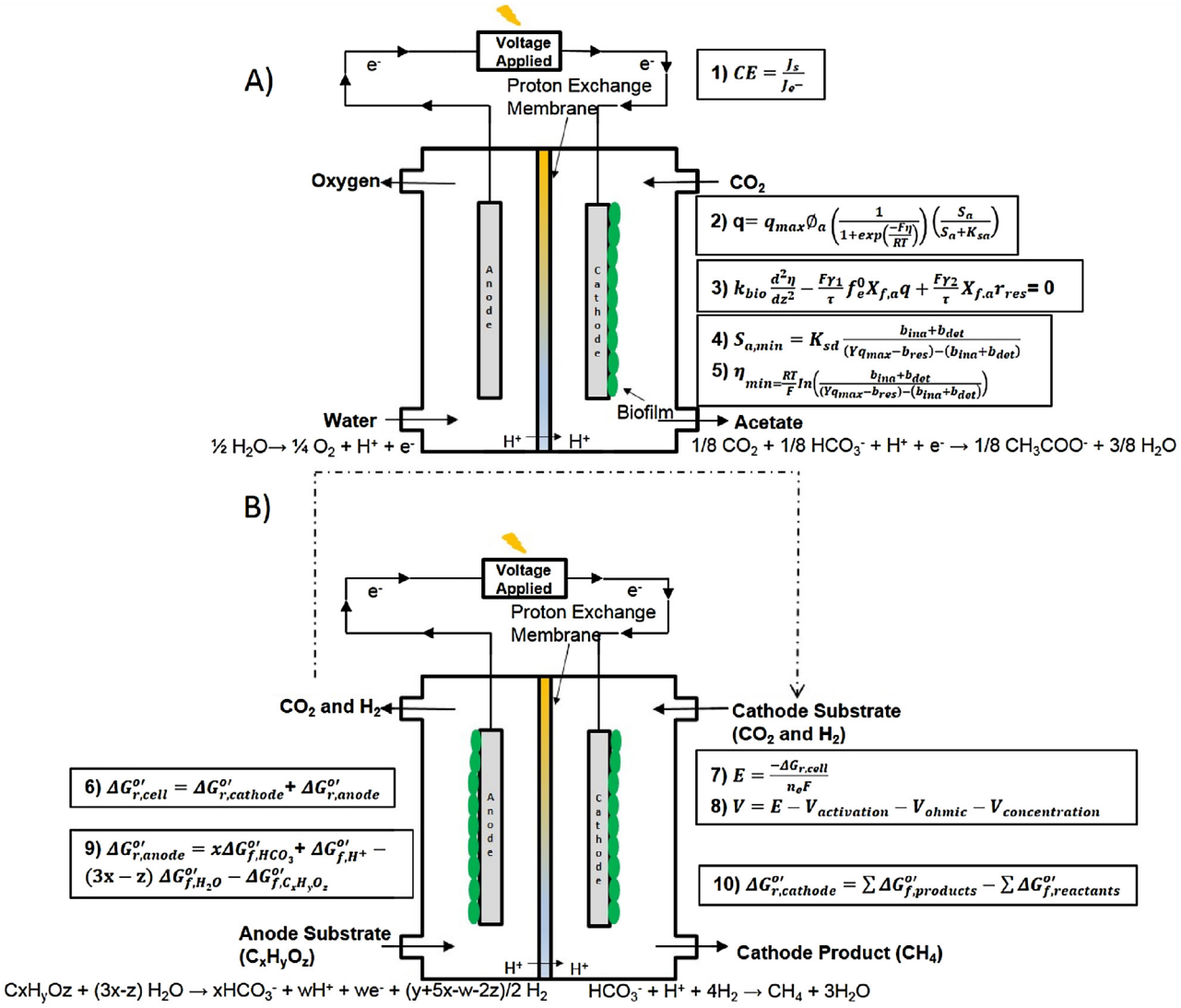

Fig. 1. Diagrams obtained from mathematical models A) Kazemi model and B) Sadhukan model [41,42].