Artificial photosynthesis coupled with electricity generation – microbial fuel cells as artificial plants

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Abstract

To meet the global goal of carbon reduction process there is a need to develop an artificial system that may act as an autonomous CO_2 scrubber. This paper describes the direct electricity generation by the Microbial Fuel Cell with the simultaneous bioelectrosynthesis of active solution resulting in further carbon capture and storage. The microbial biotransformation of organic waste results in direct current that may be used to drive peripheral circuitry of the system such as LED lights, dc motors or a mobile phone, whist the synthesised product *in situ* recreate some aspect of chemically driven carbon capture. While the biotic biofilm anode portraits the 'living engine', the abiotic cathode simultaneously produces a caustic agent that is able to fix CO_2. In the context of artificial life, this system mimics photosynthesis and recycles CO_2 into useful chemicals via the process of electrosynthesis. In a way it behaves like an artificial tree and if implemented in practice, it would be performing a similar function.

Introduction

While the photosynthesis is a natural way to remove carbon dioxide, it is very challenging to reproduce artificially in any practical way. However, the carbon fixation can be performed through Carbon Capture and Storage (also known as Carbon sequestration) process, which is a method of mitigating the CO_2 emitted from the combustion of fossil fuels. Currently, CO_2 removal involves exposing air containing carbon dioxide to a fluid with alkaline properties, which absorbs carbon dioxide and produces carbonate salts. Air capture technology provides an important tool for carbon management through the development of the innovative concept of artificial trees (Lackner et al., 2009). The same function can be performed and driven by the Microbial Fuel Cell, where CO_2 is removed by the microbial utilisation of organic waste, to generate electrical current directly.

The Microbial Fuel Cell is a technology that harnesses energy from waste by the use of microbial metabolic oxidation processes. In terms of practical implementation, the technology has been demonstrated onboard the EcoBot robots for energy autonomy (Ieropoulos et al., 2010), as well as a power source for charging a mobile phone (Ieropoulos et al., 2013). The concept of self-powered scrubbing with additional energy generation is novel and may present a new opportunity for artificial life, in terms of tree-like systems that capture carbon dioxide and generate electricity. As a concept, it may contribute to the energy balance and economics of CO_2 recycling in the future.

Materials and Methods

Microbial Fuel Cell Operation During the MFC operation, electric current is generated when for every electron donated by microbes to the electrode surface, a proton is transferred from the anode to the cathode. Other cations such as Na^+ or K^+ are also likely to be transferred through a cation exchange membrane (Rozendal et al., 2006) resulting in the caustic environment on the cathode half-cell. The cathodic oxygen reduction reaction (ORR) results in the formation of alkaline liquid sorbent that naturally removes CO_2 from the ambient air by producing dissolved carbonate ions. The caustic conditions driven by the MFC electron flow may result in further removal of carbon dioxide, known as wet scrubbing.

Here the experimental MFC was made from terracotta caves (Orwell Aquatics, UK), with a wall thickness of 3mm, (cost of £4.75) and assembled with porous carbon based anode and cathode electrodes. The MFC was placed in a bucket filled with 500mL of activated sludge provided by the Wessex Water Scientific Laboratory (Cam Valley, Saltford, UK) and supplemented with 20mM sodium acetate at pH 6.6; periodic feeding was performed for maintaining carbon-energy replete conditions.

Driving the external circuitry The MFC was left to establish an anodic biofilm for a period of 2 months. In order to demonstrate the viability of an individual ceramic MFC as a power source, a single red LED was connected via a Texas Instruments energy harvester (TI BQ25504EVM-674, Farnell, UK) and a 6800µF super-capacitor. The output voltage from the single ceramic MFC was insufficient to power the LED directly, which is why the energy harvester was necessary; this allowed constant energising of the LED. Data were logged using a multichannel Agilent 34972A, LXI Data Acquisition/Switch Unit (Farnell, UK). Current and Power were calculated as previously described (Ieropoulos et al., 2008).

Results

To show the potential of a single MFC to power real applications, the described ceramic MFC was used to operate

a red LED, which was successfully performed at a constant voltage of ~1.7V through an energy harvester system (Figure 1). During the experiment, the MFC performance showed stable current generation (3.2 mA) at the constant voltage of 250mV. The LED operated continuously, for as long as the MFC was fed, during the 7-day period.

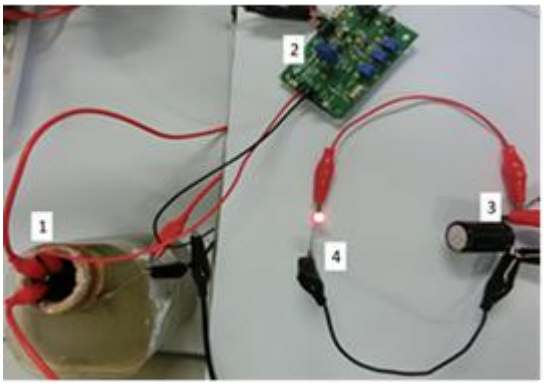

Fig.1. The experimental set-up during the 7-day operation continuously powering a LED (1-MFC, 2-TI energy harvester, 3-capacitor, 4- LED)

Catholyte generation

During the continuous powering of the LED light, the formation of transparent liquid was observed on the cathode electrode surface, as droplets and further accumulation of the liquid. The measured volume at the end of operation was 60mL of catholyte formed at a pH of 12.34 and with a conductivity of 27.11mS/cm. The catholyte was allowed to evaporate, and the crystallised salt was analysed further.

Conclusions and outlook

The MFC design described in the present study represents a true integration of two bio-inspired technologies such as microbial oxidation and artificial photosynthesis (oxygen reduction reaction). The proposed MFC with open to air cathode coupled with ceramic membranes could be used both for electricity generation, wastewater treatment, filtration and production of absorbent to demonstrate carbon sequestration through wet scrubbing. A similar activity has been reported using amine-based resins (Gray et al., 2008), however the novelty of the presented system lies in the strong base that is being generated by the MFC *in situ* on the cathodic electrode surface.

The flux density of the solute (the formed salt) is proportional to the electric current, which is akin to the ion transport processes within living plant cells, where the metabolic energy is driving the system. There are many examples of biological membranes within plant cells that function on electro-potential gradients, which are regulating the metabolic processes. Ions can be actively transported across membranes in which case metabolic energy is involved.

The inspiration for the process herein, comes from the anatomy of the leaf where CO_2 enters the epidermal layer through stomata (pores), which are regulated by the guard cells into the intercellular air space. This is where the gases enter the mesophyll cells through their cell wall and plasma membranes. The anolyte would therefore be analogous to the mesophyll cells (the engine of the process), the ceramic separator is likened to the plasma membrane and finally the cathode chamber functions as the intercellular air space where the air flow can be further regulated. It is now possible to illustrate a process where the CO_2 is absorbed into the catholyte, as the sodium carbonate/bicarbonate salt driven off the porous electrode by moisture and gravity.

The presented "artificial leaf" scrubber in the form of the porous cathode electrode has a high specific surface area increasing the gas diffusion rate of carbon dioxide, as well as allowing the transport of water to rinse the carbonic salt in the chamber. The capture must not only work chemically, but it must also be practical, cost-effective and energy-efficient. The MFC system is driving the process through the microbially assisted electrosynthesis of chemical sorbent on the cathodic electrode leaf. Considering advances in material science of carbon-based materials (graphene for example) in the future, the MFC driven CO_2 capture seems feasible and very attractive.

Real autonomy, especially in the context of artificial photosynthesis is presented here by the simple ceramic-based MFC design that does not involve expensive catalysts. This is particularly important to exploit in real-life applications independent to the main energy grid, operating offline and utilising the energetically rich waste. It is envisaged that such systems could be deployed in various natural environments, where they can be performing the triple action of carbon dioxide removal, electricity generation and green chemistry. Depending on the architecture, these can be mobile (autonomous robots) or stationary (artificial trees/plants).

References

Ieropoulos I., Melhuish C., Greenman J., Horsfield I. (2010). EcoBot-III: a robot with guts. In Fellermann H, Dörr M, Hanczyc M, Laursen LL, Maurer S, Merkle Daniel, et al., editors, *Artificial Life XII*, pages 733-740. MIT Press, Cambridge, MA.

Ieropoulos, I., Ledezma, P., Stinchcombe, A., Papaharalabos, G., Melhuish, C., Greenman, J. (2013) Waste to real energy: the first MFC powered mobile phone. *Physical Chemistry Chemical Physics.* 15:15312-15316.

Rozendal, R. A., Hamelers, H. V., & Buisman, C. J. (2006). Effects of membrane cation transport on pH and microbial fuel cell performance. *Environmental science & technology*, 40(17): 5206-5211.

Lackner, K. S. (2009). Capture of carbon dioxide from ambient air. *The European Physical Journal Special Topics*, 176(1):93–106.

Gray, M. L., Champagne, K. J., Fauth, D., Baltrus, J. P., & Pennline, H. (2008). Performance of immobilized tertiary amine solid sorbents for the capture of carbon dioxide. *International Journal of Greenhouse Gas Control*, *2*(1): 3–8.

Ieropoulos, I., Greenman, J., & Melhuish, C. (2008). Microbial fuel cells based on carbon veil electrodes: stack configuration and scalability. *International Journal of Energy Research*, 32(13): 1228-1240.