The Electrobiome™ Platform: Synthesis of Electrofuels and Chemicals from CO₂

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ABSTRACT

The Electrobiome™ converts CO₂, water, and electricity into hydrogen (H₂), formic acid, and acetic acid while serving as a biocathode in an electrochemical cell [1-3]. Synbiohm LLC and MUSC researchers are now working to expand the capability of this microbial platform to increase product yield, rates, and titers and to produce ethanol, butanol, caproic acid, long-chain hydrocarbons, and polyesters (bioplastics) (Fig. 1). The Electrobiome has been continually operating for >3 years and the electrical input can be intermittent, allowing it to operate with stranded, intermittent, or curtailed power. Therefore, the Electrobiome could be used to convert and store electricity into higher value fuels or chemicals.

Keywords: electrofuels, biofuels, CO₂ utilization, bioenergy

Figure 1. Chemicals and fuels produced (red) and targeted for production (white) by the Electrobiome

1 INTRODUCTION

Microbes have been shown to facilitate electron transfer from a cathode linked to the reduction of O₂ [4,5], nitrate [6], fumarate [7], protons [8], and CO₂ [9,10,11]. When reducing CO₂ at a cathode the process is commonly referred to as microbial electrosynthesis [9,12]. The Electrobiome consists of a community of anaerobic microorganisms including Acetobacterium, Sulfurospirillum, Desulfovibrio, and Rhodobacteraceae [3]. This microbial community lowers the overpotential of a graphite cathode by more than 200 mV, thereby lowering the energy needed to drive the system. We hypothesize that this is due to the biofunctionalization of the cathode with redox active proteins and metals in an extracellular matrix deposited by the microbes onto the cathode (Fig. 2). This is consistent with recent reports of extracellular proteins supporting extracellular electron transport (EET) at a cathode [13].

2 ELECTROCHEMICAL BIOREACTORS

The Electrobiome operates without rare earth elements at the cathode of an electrochemical cell. It also operates without food crops, arable land, fossil fuels, or large amounts of water. Much of the research has been done with graphite granule electrodes within an H-cell reactor consisting of an anode and cathode chamber separated by an ion exchange membrane (Fig. 3). Details of these bioreactors can be found in Marshall et al. [2] and LaBelle et al [3]. High rates of hydrogen or acetate production along with high electron recovery were achieved with these reactors, but energy efficiency and productivity can be improved. More optimized reactors with new materials are now being tested to address these issues (Fig. 3). These reactors are designed to be modular as well as to be tested at a larger scale.
3 HYDROGEN PRODUCTION

Hydrogen can be a sole product of the platform, or electrons can be diverted to the production of other chemicals while utilizing CO₂. H₂ is ordinarily produced commercially by reformation of fossil fuels [15]. Other means of production include the pyrolysis of biomass [16], water electrolysis [17], and microbial processes such as photosynthesis, dark fermentation, and microbial electrolysis cells (MECs) [18-20]. While each of these approaches has its advantages, each has drawbacks: fossil fuels are finite and the their burning releases CO₂ that contributes to climate change, biomass requires large amounts of arable land and pyrolysis results in the release of CO₂, conventional water electrolysis requires rare earth catalysts, photosynthesis suffers from low efficiency at capturing photon energy and oxygen sensitivity lowering H₂ production, dark fermentation has a low energy recovery and yield [18,19,21]. MECs often require expensive cathodes and efficient, cost-effective production of H₂ at high enough rates remains a challenge.

H₂ production with the Electrobiome Platform has none of the aforementioned problems and performance has been promising (see Fig. 4, LaBelle et al. [3] and associated video). The Electrobiome has already sustained H₂ production at and up to 38 Lₜₐ₀ H₂/L catholyte/day or >1 kg per m³ of reactor per day (1 kg H₂ = 1 gasoline gallon equivalent, gge). The proof of concept validation and technical feasibility of H₂ production with a laboratory-scale prototype of the platform indicates that the system stands at Technology Readiness Level (TRL) 4 to 5. At this stage, further prototype development with scaling followed by demonstration can be pursued. Based on $0.05 per kilowatt-hour (kWh), 3 Volt (V) applied to the cell (new energy efficient reactor designs are operating with less than 3V), and costs for water and nutrients, the platform produced H₂ for an estimated $4.04 per kg or gge (excluding delivery, dispensation, and taxation). The cost for H₂ production may be reduced to <$2/kg by using stranded, off-peak, or intermittent power (a conundrum often faced by electric companies). The rates and yields of production are promising and the electron capture into H₂ at the cathode is very high (>95%).

Another way to reduce the cost for producing H₂ or higher value chemicals is to couple the Electrobiome biocathode with a biowaste-consuming bioanode. Such a combined system stands at TRL 3 and it is estimated that the cost for the waste biomass feedstock (estimated for food waste) will be $0.457 per kg H₂ produced. Including the cost of the electricity projected to operate the system, based on $0.05 per kWh; the total production cost is estimated at $1.50 per kg of H₂ with a bioanode/biocathode system and lower still when using low-cost stranded or off-peak power. By using waste biomass potentially including food waste; fats, oil, and grease (FOG); farming wastes (e.g. manure); food and beverage industry wastes; pulp and paper wastes; and municipal wastewater treatment sludge; the biomass feedstock cost is greatly reduced. Food waste generation alone amounts to 36 million tons/year (~6,000 megawatts [MW]) in the U.S. and represents about 14.5% of the solid waste stream currently sent to landfills resulting in GHG emissions (methane [CH₄]) [22], but with the proposed process could be directed to the production of H₂. Currently these wastes are sent to landfills, composted, treated using energy-intensive aerobic processes, or anaerobically digested to low-value methane.

The H₂ production rates already achieved, the consumption of waste biomass, plus the advances in the production of additional chemicals, indicate that the Electrobiome system could be a game-changing technology.

4 ACETATE PRODUCTION

Acetate, or acetyl CoA, production from CO₂ is central to the production of any other chemical, and it is a valuable commodity in of itself [23]. In fact, the goal of much of
this research has been focused on the production of acetate to then be able to move on to other fuels and chemicals. Beginning with no capability to microbially electrosynthesize acetate or anything else, we were able to rapidly improve the rate of electroacetogenesis with the Electrobiome over 3 years (Fig. 5). The *Acetobacterium* sp.

![Figure 6. Increasing electroacetogenic productivity by the Electrobiome with research.](image)

of the Electrobiome is the primary CO₂ fixing, acetogenic, microorganism of the community. Details of the progress with electroacetogenesis with this system can be found in Marshall et al. [1,2] and LaBelle et al. [3]. We are also completing revisions of a review on the bioelectrosynthesis of acetate [24], and a metagenome/metatranscriptome study with new information on gene expression in relation to electroacetogenesis by the Electrobiome has been submitted for publication [14].

5 PRODUCTION OF OTHER FUELS AND CHEMICALS

It is predicted that the cost of production can be reduced further when higher value chemicals are produced in addition to H₂ and acetate (e.g. butanol, caproate, polyesters). The TRL for producing these other chemicals with the Electrobiome stands at 2 to 3. Recent analysis of the metagenome of the Electrobiome revealed the metabolic capability to produce butyrate, ethanol, butanol, and polyhydroxyalkanoates (biopolymers, Fig. 6). The production of these compounds has been confirmed in the laboratory. Caproate synthesis may also be possible. Research is ongoing to improve the production of these compounds as well as work aimed at producing liquid hydrocarbons. The latter is a project being pursued by Dr. May at MUSC with funding from the Office of Naval Research as a proof of concept project.

6 REMAINING TECHNICAL CHALLENGES

Scaling issues remain at the top of the list of challenges and support is needed to address them. Development of the biocathodes has been the focus of nearly all studies done to date on microbial electrosynthesis. Therefore, linking the biocathodes with more existing and more efficient anodes is needed to improve energy efficiency, and progress is being made in this direction. Mass transfer and harvest approaches need to be addressed, e.g. the organic acids and alcohols are produced in water and will require energy efficient means of extraction. New ideas are being examined here as well. For hydrogen production, gas hold up within the cathode needs to be avoided while maximizing cathode surface area for the biocatalysts, but progress is being made here as well with the new reactor designs. Overall productivity and current densities need to continue to be enhanced, but performance has improved impressively since the first report of microbial electrosynthesis in 2010 [9] with rates per cathode surface increasing 18-fold to 25.2 g acetate m⁻² d⁻¹, volumetric rates rising 69-fold to 3.1 g acetate L⁻¹ catholyte d⁻¹, titers reaching 13.5 g L⁻¹ catholyte , and electron recovery in acetate has reached 100% [3,11,25]. Acetogenic microbes such as *Acetobacterium* are capable of producing acetate from H₂:CO₂ at > 6 g L⁻¹ d⁻¹ [26], which is on par with production rates for bioethanol from starch. Of course, bioethanol from crops requires arable land and months for growth, harvest, and transport of the starch for processing, all of which will be avoided with the Electrobiome Platform. The discovery that the Electrobiome possesses the capability to produce alcohols and biopolymers opens up new opportunities and new challenges as the methods to optimize production of these chemicals from CO₂ remains to be determined. In addition, there is the possibility to produce caproate, a higher value longer chain fatty acid, and hydrocarbons. Caproate and hydrocarbons will require modification of the Electrobiome microbiologically or genetically, perhaps with additional bioreactor engineering to match these targets.

7 MARKET TRANSFORMATION

Product Description. The Electrobiome Platform would transform the H₂ market by producing on-site, on-demand H₂ generation at the point of use. The same goal is envisioned for the production of other chemicals while utilizing CO₂. For the discussion here we present information focused more on H₂ since the system is at the highest TRL for that product. However, some of these insights can be considered in relation to the production of other chemicals when using CO₂ as a substrate.

The Platform could operate at a size that would be appropriate for an individual user or scalable to larger applications such as fueling stations, local depots, or
chemical processing plants. It also may be coupled with the feedstock of biomass waste (food, agricultural, manure, paper, breweries, and municipal wastewater) to further lower the cost of producing H₂ or other chemicals. The Electrobiome Platform for the production of fuels and chemicals is covered by a patent application that is pending in the United States, Europe, and Canada (PCT US2013/060131), and the Electrobiome trademark was published in the US Trademark Office’s *Official Gazette* on May 26, 2015.

**Comparative Advantage and Value to Customer.** The Electrobiome Platform may be used for on-site, on-demand production of H₂, which would avoid the building of a technically and economically infeasible, hydrogen distribution pipelines. Using biological treatment processes, the Electrobiome produces H₂ without fossil fuels, which may result in a future financial benefit when a competitor faces a charge for carbon in the future.

**Potential Customers.** The Electrobiome represents an alternative, sustainable method to produce H₂ for the hydrogenation of chemicals. In addition, it could be used to produce fuel for the H₂ fuel cell industry, which contributed hydrogenation of chemicals. In addition, it could be used to produce fuel for the H₂ fuel cell industry, which contributed to revenue generation in excess of $1 billion in 2013 [27]. To date, the market for fuel cells in the transportation sector has been driven by H₂-powered forklifts and a few mass transit vehicles [28]. With the recent rollout of the Toyota Mirai, however, there will be an ever-growing demand for H₂ for personal vehicles. So the vehicles exist, as do the end users. The missing element is ready access to H₂.

The Electrobiome stands at TRL 3 to 5 for the production of various products and further development will demonstrate the feasibility of the approach and attract the interest of a commercial partner with the financial means to get the system to market. With the total hydrogen market predicted to reach $138.2 billion by 2019 [27], there are substantial funding opportunities to support the final stages of development of the system.

8 **SYNBIOHM LLC**

Synbiohm is a newly formed start-up company that is focused on the commercial development of the Electrobiome™ Platform. The principal owner is Dr. May, who is an environmental microbiologist at the Marine Biomedicine and Environmental Science Center of the Medical University of South Carolina. He has led teams of scientists and engineers on projects in bioremediation, bioenergy, and bioelectrochemistry and has published 58 papers and patents in these fields. The company holds an option to exclusively license the patent supporting the technology and it has financial backing from SCRA Technology Ventures.

**REFERENCES**

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