Supporting Online Material

Harnessing Electric Power from Sugar —

A Simple Carbohydrate-Oxygen Alkaline Fuel Cell Mediated by Redox Dyes

Daniel Scott and Bor Yann Liaw*

Hawaii Natural Energy Institute, SOEST, University of Hawaii at Manoa, 1680 East-West Road, POST 109, Honolulu, HI 96822, USA

* Correspondence and requests for materials should be addressed to bliaw@hawaii.edu

Additional experiments—In Fig. S1, results from two control experiments are shown. In Fig. S1(a), the power from a cell without methyl viologen (MV) is shown. In Fig. S1(b) the power is collected from a cell containing 3 M KOH, 2 M glucose and 28 mM MV but using only the same Pt wire connector as the anode without the carbon felt. The Pt wire is submerged in the solution about 1 cm. The Pt wire has a diameter of 0.75 mm. In Fig. S2, we show that alternative dyes can be used as mediators in the cell, including Meldola's blue (MB), methylene blue, methylene green, indigo carmine, and safranin O. The example shown in the figure is an experiment with indigo carmine (6 mM indigo carmine, 2 M glucose and 3 M KOH solution), which is much more environmental friendly than others mentioned above. Other monosaccharides were tested as well, including but not limited to arabinose, sorbose, fructose, etc. Table S1 shows power production from some other monosaccharides with 3 M NaOH, 1 M monosaccharide and 10 mM MV. In Fig. S3, we compare the results from a pair of experiments with a glassy carbon electrode with and without mechanical stirring. In Fig. S4, a string of 6 rudimentary glucose fuel cells generates about 3.45 V. In Fig. S5, we show a durability test of a cell undergoing a galvanostatic polarization at 0.7 mA with 1.6 mL of 400 mM glucose in a 6 mM MV and 1 M KOH solution. The open-circuit voltage was 0.64 V. The cell runs for more than 18 hours. In Fig. S6, the current response from a 5.3 mg carbon-felt electrode under short circuit condition imposed by the VMP3 was monitored as aliquots of 10 mM glucose were intermittently added to a solution containing only 1 M KOH and 4 mM MV initially. The responses in current production by varying glucose concentration illustrate that the glucose is truly the fuel that generates the electric power. The solution was stirred to improve response time.

The power density and current density reported in this work are based on the geometric area of the electrodes in the cells. Although reporting such values in accessible electrode surface area would be more relevant in the consideration of kinetics, it has been difficult to determine such an accessible surface area accurately in solution with the carbon felt used in the experiments. To further address this issue so we can provide more accurate assessment of the power and current density with the electrode surface, we conducted additional experiments with a conventional glassy-carbon electrode (GCE). The GCE presents more well-defined accessible surface area, which is the same as the geometric area. The polarization results of a cell with GCE anode, with and without stirring, are shown in Fig. S3. The results show that the maximum current density under the short-circuit condition and without mechanical stirring are about 0.4 mA cm^{-2}, while the maximum power density is about 130 μW cm^{-2}. In contrast, with mechanical stirring, the same electrode can exhibit short-circuit current about 2.4 mA cm^{-2} and a maximum power density of 650 μW cm^{-2}. It is worth noting that without stirring, the polarization progresses from the maximum power generation to the short-circuit condition very rapidly, signalling that the cell was performing at the maximum power generation (rate) whenever the mass transport can support it. Once the polarization current exceeds the mass transport limitation, the cell can only operate under short circuit at the mass transport limitation. With mechanical stirring, the current density was improved by more than six times leading to the power density increasing more than five times. The stirring also makes the end of the polarization curve conclude with a more "gradual tail-off" behavior often observed in conventional fuel cell under limiting mass transport.

The best enzymatic biotic design is exemplified by the work of Mano and Heller and their co-workers.[1-5] Mano has recently reported[5] the highest power density biofuel cell to date, 0.28 mW cm^{-2} (+0.88 V) while operating at 37 °C at pH 5 and 5 mM glucose with glucose oxidase from *Penicillium pinophilum*. The recent work reported by Saiki et al.[6] have shown an improved glucose–oxygen enzymatic cell operation and achieved 1.45 ± 0.24 mW cm^{-2} at 0.3 V. Notable recent work on abiotic design is represented by Kerzenmacher et al.[7] who reported abiotically catalyzed glucose fuel cell for implants that can generate 1-3 μW cm^{-2} at 37°C. Regarding microbial designs, the best example often cited by others is the design reported by Rabaey et al.[8] Their biofuel cell operated out of microbial consortia with self mediate electron transfer can generate 0.431 mW cm^{-2} (at 664 mV).

References:

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[Table]

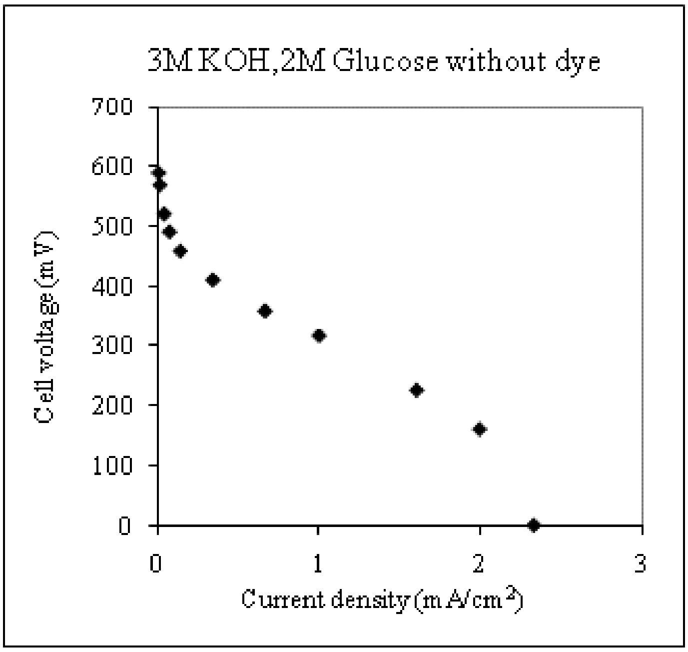
Table S1. Power generation from other monosaccharides with 3 M NaOH, 1 M monosaccharide and 10 mM MV.

Monosaccharide	**Max. Current ($mA\ cm^{-2}$)**	**V at Max. Current (V)**	**Power ($mW\ cm^{-2}$)**
Galactose	**2.5**	**0.446**	**1.1**
Mannose	**4.5**	**0.390**	**1.8**
Fructose	**15.0**	**0.250**	**3.8**
Arabinose	**3.5**	**0.425**	**1.5**
Xylose	**5.0**	**0.360**	**1.8**

[Figures]

Fig. S1. Operation of a cell with (a) 3M KOH, 2 M Glucose and no dye, and (b) 3M KOH, 2 M Glucose and 28 mM MV with only the Pt wire connector as the anode.

(a)



(b)

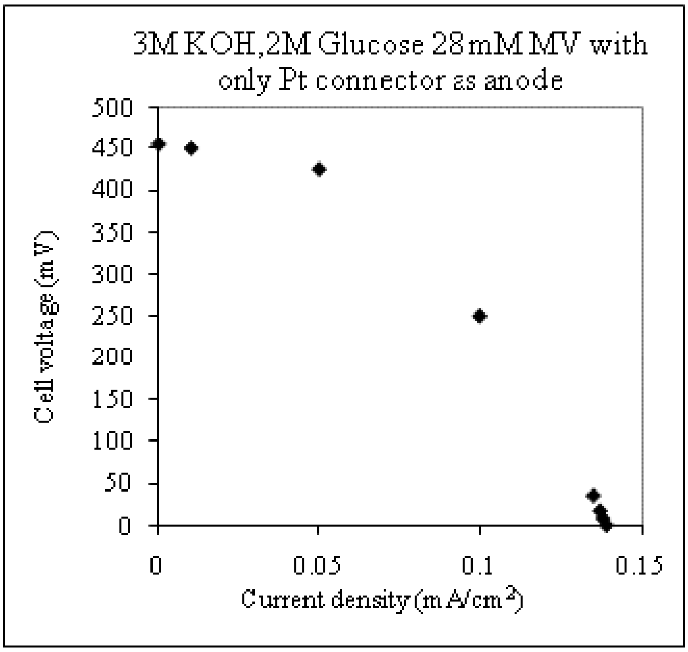


Fig. S2. Operation of a cell that is made of indigo carmine as the active dye, which is less toxic and more environmental friendly than other dyes demonstrated in the work.

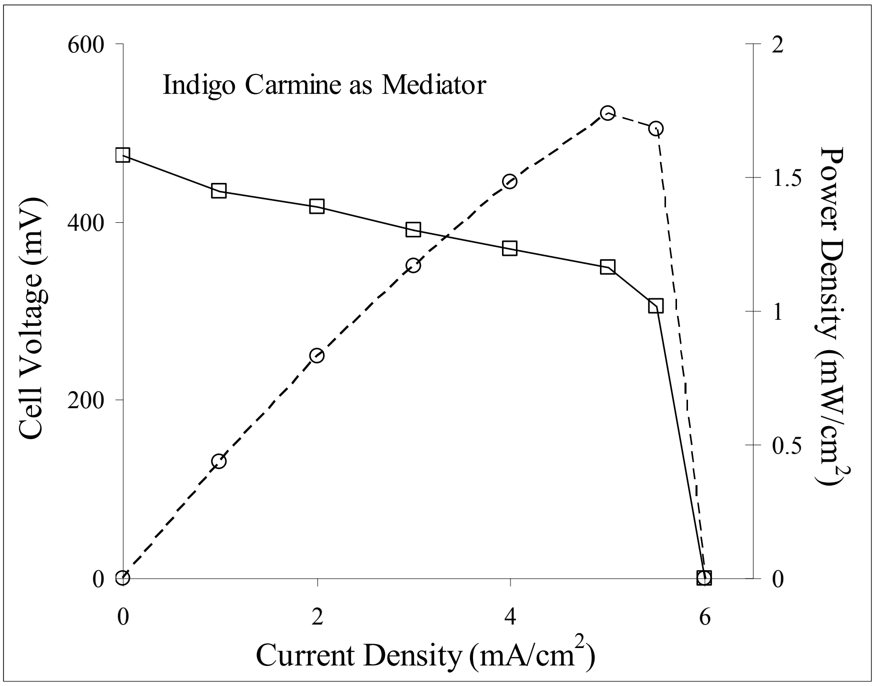


Fig. S3. Galvanostatic polarization curves and the respective power profiles of a glassy-carbon electrode without and with stirring. With mechanical stirring, the cell performs much better than without. The mass transport tail is also more profound in the voltage and power profiles under the stirred condition.

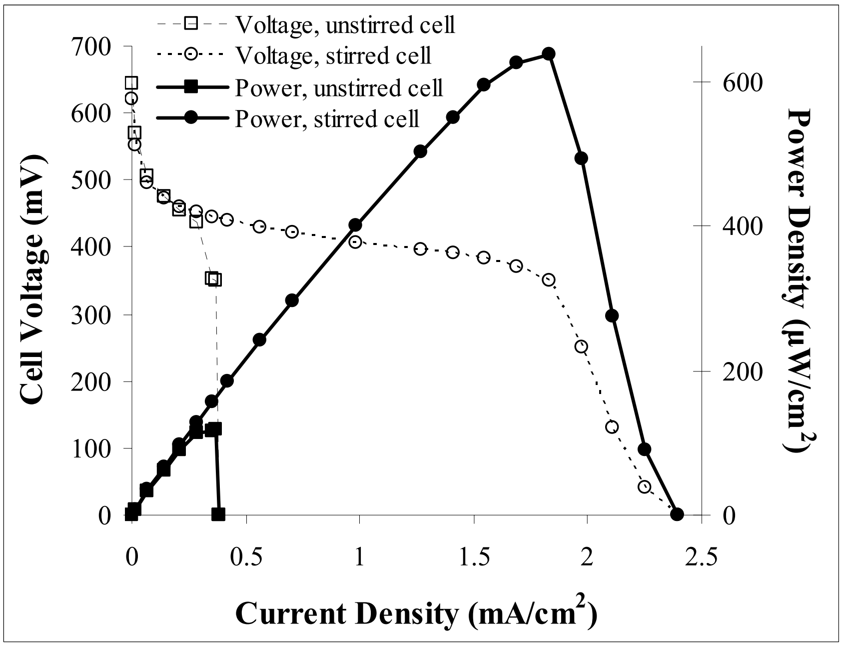


Fig. S4. A six-cell string that produced 3.45 V.

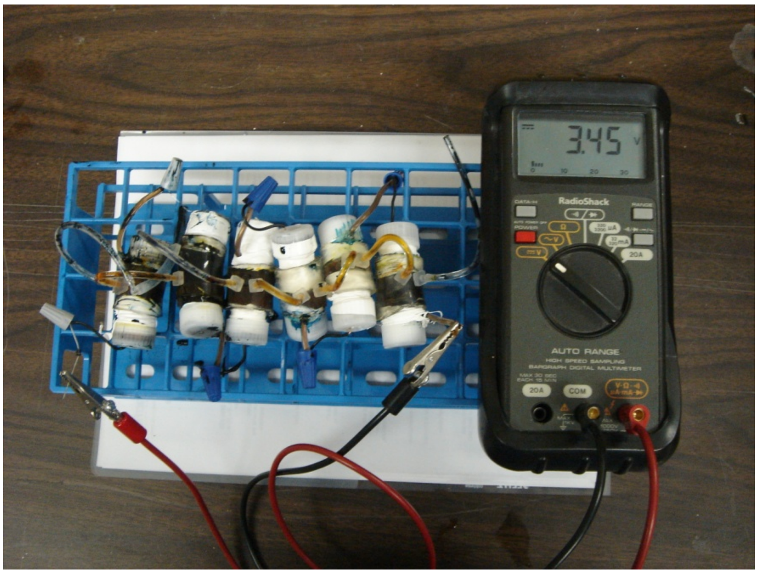


Fig. S5. A duration test of a glucose dye-catalyzed alkaline cell under a galvanostatic polarization at 0.7 mA (1.6 mL of 400 mM glucose in 6 mM MV and 1 M KOH solution).

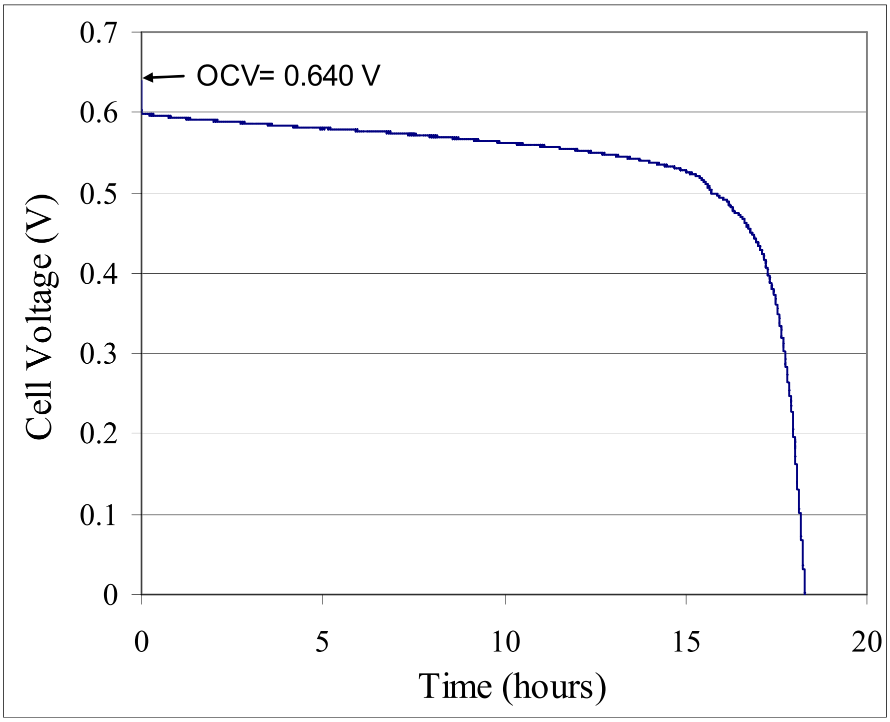


Fig. S6. Current responses upon additions of aliquots of glucose to increase the glucose concentration with 10 mM increments.