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Publication Date

2022-06-01

DOI

10.1109/iscas48785.2022.9937297

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Early Characterization of Soil Microbial Fuel Cells

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***Abstract*—This paper discusses experiments on soil-based microbial fuel cells (MFCs) as energy scavenging sources. We explain the mechanism of operation for MFCs, perform controlled laboratory experiments of MFCs, and deploy a small-scale in-situ pilot in an active farm. We find that traditional energy harvester ICs draw power too aggressively, which reduces overall energy capture. We show that isolated MFCs can be combined in series or parallel to improve the voltage or current output of the harvesting source. Lastly, we observe that under a real-world, drip-irrigated agricultural setting, MFC output is appreciably lower, but consistent at 0.5-2 microwatts.**

***Index Terms*—MFC, microbial fuel cell, energy harvesting, maximum power point tracking.**

I. INTRODUCTION

Sensors in agricultural settings do not have ready access to reliable power infrastructure. Existing wide-area sensing systems rely on batteries or harvest the required energy, most often from solar or wind sources. One problem with solar, wind, and other common sources of power is that they are not always available or reliable. This has led to growing interest in new, non-traditional energy scavenging sources.

The burgeoning set of low-power energy harvesting chips now available can harvest power from voltage sources as low as $25\,\mathrm{mV}$.[1] While most of these energy harvesters target thermoelectric, piezoelectric, RF, and solar energy sources, their ability to extract power from low-voltage sources facilitates the exploration of novel energy sources, like tree trunks [1], and the re-visitation of old ideas, such as microbial fuel cells (MFCs). MFC energy harvesting has been well-studied in wastewater management [2]–[4], but there has not been a similar focus for soil MFCs. We re-examine the viability of soil MFCs to produce sufficient power to be useful for sensor applications. Specifically, due to the low but relatively constant power available, we find that soil MFCs may be a good fit for the new "reliable but intermittent" sensor class [1]. However, there is a need for energy harvesters that leverage the unique properties of soil MFCs to maximize the harvesting efficiency [5].

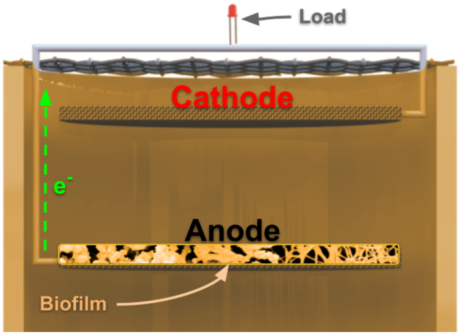

Fig. 1. System diagram of a soil-based MFC. Microbes colonize the carbon anode to form a biofilm and donate electrons to cause a potential difference.

MFCs are made of electrogenic bacteria that release electrons as they metabolize their food. Normally, these bacteria use metals in the soil as electron acceptors, but the bacteria can form a "biofilm" on the electrically conductive anode to colonize it and discharge waste electrons into it. This allows us to capture the electrons they expel and harvest power. As the source of power is the activity of living organisms, MFC performance can vary drastically based on local environmental conditions [5]. We explore a best-case soil MFC in the laboratory, and some initial field tests, to see if soil MFCs are capable of powering modern sensors. We see a long line of exciting future work towards the question of what it would take to realize viable and reliable MFCs everywhere.

II. BACKGROUND

MFCs have been studied for many years [4], [6], with recent work focusing on civil and environmental engineering applications [3], [7]. Late 1990s research shows some electrogenic bacteria have natural mechanisms to expel electrons into metals and other conductive materials [8]. Modern designs use these bacteria to simplify cell construction. Fig. 1 illustrates the basic construction of a soil MFC, including ours, with an anode buried under soil and a cathode near the surface. Electrogenic bacteria colonize the anode and use it as an electron acceptor, which produces the electricity we harvest.

Bacteria from the genus *Geobacter* dominate the anode of soil MFCs, and their presence is correlated with higher power production [9], [10]. These bacteria are common in

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[1] Examples include MCRY12-125Q-42DI and related MATRIX chips.

many soils and subsurface environments [11], so much so that no special effort is required to acquire them for use in soil MFCs. As *Geobacteriaceae* are almost completely obligate anaerobes [12], cell designs must ensure the anode is in an anaerobic environment, Early work identified that waterlogging soil works to exclude oxygen from the buried anode [13]. As this is not practical for large-scale deployments, we explore the effects of reduced water content in Section IV.

Many materials can be used for the cathode and anode of MFCs. Examples range from mercury and platinum [6], [13], to graphite felt [14], to tungsten carbide on reduced graphene oxide nanolayers [15], and many more [3]. When selecting materials, Josephson highlights that galvanic corrosion can confound electrical measurements [16], as galvanic corrosion is also a potential source of power [1]. To build a renewable soil MFC (rather than an earth battery [17]), care must be taken to select materials for the electrodes that are galvanically inert. Examples of inert electrode materials include carbon and graphite based cloths, felts and foams.

Looking forward, one of the biggest open questions we will face when trying to deploy soil MFC-powered sensors is an absence of extant, longitudinal studies. There are a few experiments and deployments that span months to years [7], [18]. More recent studies describe sensor applications which use MFCs for power, and demonstrate that it is now possible to architect low-power sensor nodes powered off solely an MFC [19], [20]. However, all of these studies focus on non-soil MFCs, such as sediment or aqueous. In this work, we focus on soil MFCs and the laboratory and field experiments we are doing to understand both soil MFC performance and the energy harvesting operation itself, to gain insight on maximizing energy harvesting for future long-term deployments.

III. LABORATORY EXPERIMENTS

A. *Energy harvesting using COTS components*

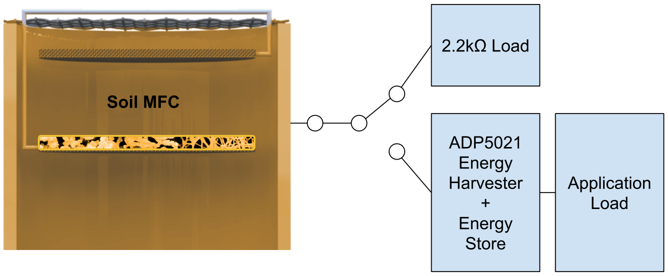


Fig. 2. Prototype block diagram.

This first experiment demonstrates the feasibility and highlights the problems of using commercial off the shelf (COTS) components to build a soil MFC-based energy harvesting system. To these ends, we use an experimental setup identical to that presented by Marcano [5]: two 12 cm diameter circular carbon felt electrodes, separated by approximately 5 cm and connected to the load using titanium wire. Fig. 2 provides an overview of the experimental setup.

The energy harvested from the cell drives an intermittent application managed by a microcontroller. Once fully charged, the energy store holds 450 mJ while maintaining a voltage above 2 V. Each application event consumes 55 mJ, which allows up to four events to occur on a full charge. Separately, we also connect a 2.2 kΩ resistor as a load directly to the cell to compare the cell behavior when driving an intermittent load through the harvester versus a direct constant load.

The initial logarithmic charging burst observed in Fig. 3a in the first half hour stems from the cell being in a rested and "overcharged" state. Once it reaches steady-state charging, charging is largely linear. The effective empirical charging rate is approximately 80 mJ/h or 20 µW. Of note, this is less than the 100 µW steady-state power draw achieved by the simple 2.2 kΩ load.

Fig. 3b is a close-up of the behavior of the ADP5091 energy harvester. The harvester runs a maximum power point tracking (MPPT) algorithm which targets 80% of open-circuit voltage. In practice, however, this set point is too aggressive, and the cell repeatedly drains to the point of harvester failure.

To try to ameliorate the strain on the cell, we increase the MPPT set point. At an MPPT target of 90%, the cell takes longer to discharge below the 80 mV threshold, but it still consistently drains to the point of failure. At 95%, most of the asynchronous phase[2] of the harvester operates well. The harvester draws an average of 60 µW off the cell. However, as the harvester approaches the threshold to switch to its synchronous mode[2] it begins to draw significantly more power off of the cell, which again drains to the 80 mV failure point. We are unable to find any MPPT threshold that enables continuous operation of the harvester, despite the cell's ability to support a static 2.2 kΩ load at over 100 µW seemingly indefinitely.

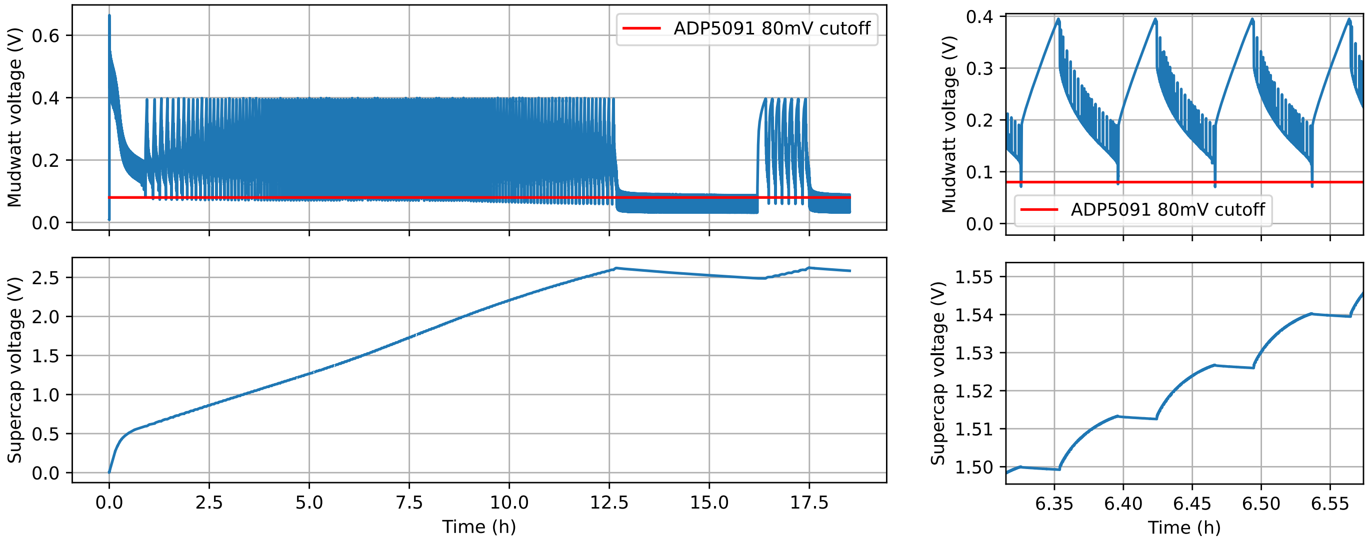
There is a promising body of recent work that look at designing harvesting algorithms specifically for MFCs [21], [22]. These works focus on wastewater MFCs, not soil MFCs, but they may provide a good starting point for designing future harvesting algorithms for soil MFCs.

B. *Chaining Soil MFCs for Increased Voltage and Power*

Prior work demonstrates that as soil MFCs dry out, power output decreases [5]. We do not expect soil MFCs in real-world deployments to remain saturated in water, so we need to compensate for the drop in electricity production. Additional prior work shows that submerged sediment MFCs can be stacked to increase voltage and power [23], but to the best of our knowledge this experiment has not been performed with soil MFCs. This experiment confirms the strategy of stacking soil MFCs to increase the available power.

We construct four new cells, and after achieving maturity, connect them in series and parallel through a breadboard. We use a RocketLogger to record voltage and power measurements. The experimental configurations are shown in Fig. 4.

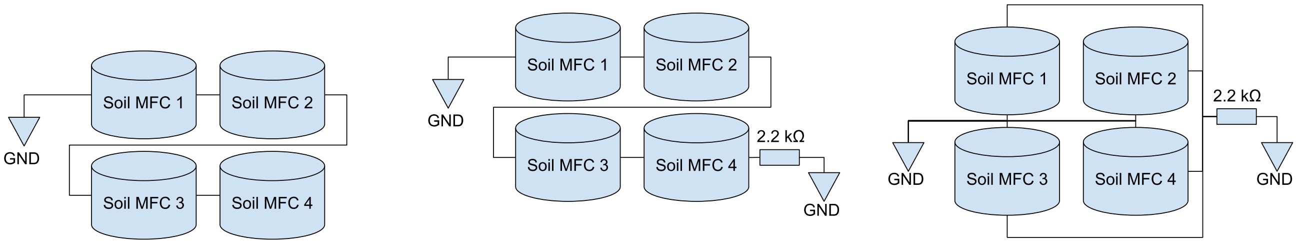
[2] In asynchronous mode, the energy store is disconnected from the boost converter, which allows it to charge without the draw of powering the boost converter. In synchronous mode, the harvester connects the energy store to the boost converter, which allows the converter to draw power from the energy store to sustain its operation. See the ADP5091 datasheet for more information.



(a) Charging profile from cold-start to steady-state. The ADP5091 energy harvester charges the energy store to its target in 12.5 hours. During initial charging, the harvester operates in "asynchronous mode". When the input voltage dips below 80 mV, the harvester can no longer operate. The harvester restarts once input voltage exceeds the 380 mV cold-start voltage. This "input-falls-below-operation, bacteria recovers" cycle accounts for the spiky operation, shown in detail in (b). Once the target charging threshold (2.5 V plus some hysteresis margin) is reached, the harvester switches to "synchronous mode". Here, the harvester no longer browns out, resulting in a constant load on the biological cell (which never recovers) and slow, constant drain on the storage supercapacitor. In hour 16, the energy reserve depletes enough that the harvester returns to "asynchronous mode," which causes the system to enter a macro-level steady state.

(b) Detail view of harvester cycles. At 380 mV, the cold-start circuitry of the harvester activates, and the system begins charging. Every 16 s, the MPPT algorithm detaches the harvester for 256 ms to measure the open-circuit voltage, accounting for the voltage spikes during harvesting. When the input falls below 80 mV (red line in graph), the harvester shuts off. With no load, the cell recovers until it reaches 380 mV and the cycle restarts.

Fig. 3. Energy harvesting behavior over time. (a) shows the cell voltage as the supercapacitor is charged. (b) shows a zoomed-in portion of (a), demonstrating the ADP5091 shutting down and restarting as available power from the cell falters and recovers. Voltage of the supercapacitor rises as power is harvested.



(a) Open voltage cells in series diagram.

(b) 2.2 kΩ load with cells in series diagram. Note that both grounds are the same.

(c) 2.2 kΩ load with cells in parallel diagram. Note that both grounds are the same.

Fig. 4. Configurations of cells in series and parallel tested.

TABLE I
MEASURED VOLTAGE AND POWER WHEN CHAINING FOUR CELLS.

Experiment	Voltage (V)	Power (µW)
Open circuit with cells in series	2.84	-
2.2 kΩ load with cells in series	0.389	68.7
2.2 kΩ load with cells in parallel	0.666	202

The first experiment uses the design in Fig. 4a. Additionally, we shorted the cells in series to ground to observe their recovery behavior. It took approximately four hours for the cells to recover from being shorted, rising to a maximum of 2.84 V.

The second experiment uses the design in Fig. 4b. This experiment was performed soon after the first, with the cells already charged. We see that the load drains the cells in series, before stabilizing at 389 mV with 67 µW dissipated through the 2.2 kΩ resistor load.

The third experiment uses the design shown in Fig. 4c. The cells were disconnected from a load for 30 minutes before this experiment, to allow them to recover from the previous experiment. Voltage and power started at 480 mV and 100 µW. Left alone over the course of two days, the voltage and power draw continued to rise. After 48 h, the voltage reached 666 mV with the resistor dissipating 202 µW, which is more than double both previous experiments.

These early experiments are encouraging in that we may be able to compensate for the low power and voltage of each individual cell by stacking them in series and parallel. However, the series voltage of the cells in series when under load is not simply additive, which bears further investigation. The parallel cells perform much better than anticipated. We hypothesize that the power dissipated by our test load is lower than the power being generated in parallel from our cells, leading to an accumulation of charge in each cell.

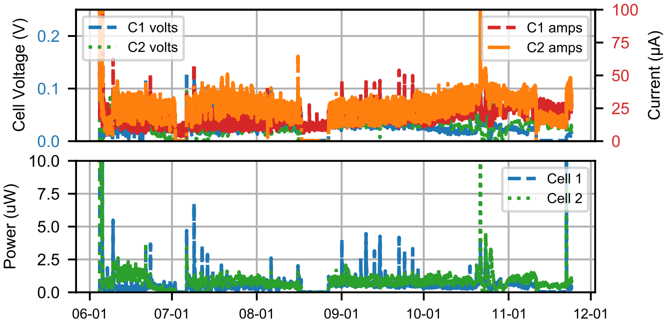
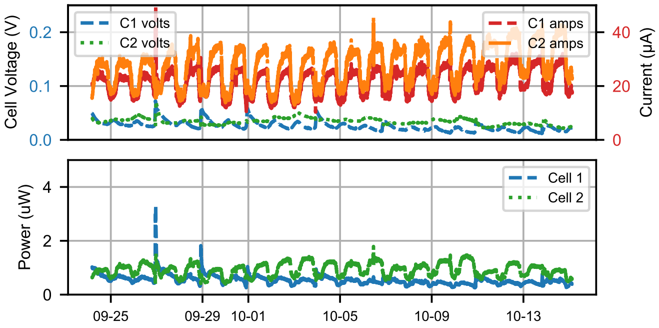
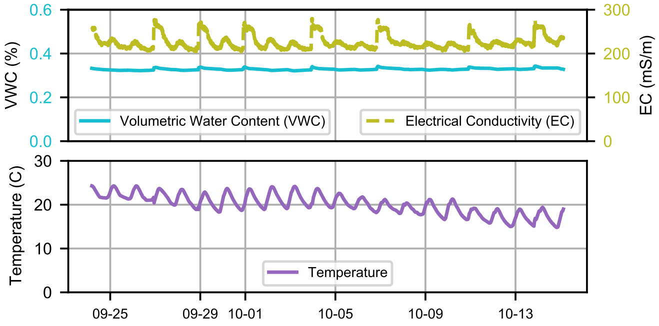


Fig. 5. Power output of two MFCs deployed in the field for six months. After initial deployment, the cell power output rapidly drops from > 10 µW to 0.5-2 µW and remains mostly steady, with brief periods of higher output during drip irrigation on alternating days. Brief periods of zero power output in July and August are due to temporary logging hardware issues.



(a) Three weeks of detailed power output for deployed MFCs



(b) TEROS-12 soil sensor data from field

Fig. 6. Zooming in, we see that MFC power output is remarkably cyclic. The cells exhibit diurnal behavior caused by day/night temperature differences in the soil, as well as spikes of higher activity during irrigation. We also see a slight downward slope in power output that follows the seasonal decrease in average soil temperature. EC = electrical conductivity, VWC = soil moisture.

IV. FIELD EXPERIMENTS

One of the limitations of laboratory studies of MFCs is that closed-system cells eventually deplete their nutrient supply. In the long term, we are interested in embedding MFCs in environments such as farm fields or wetlands, where natural or agricultural processes will restore nutrients.

To that end, after successfully incubating MFCs in the lab, we deployed two cells outdoors in a California farm field. The deployed cells have the same structure as the laboratory cells. We have also installed a TEROS-12 [24] soil sensor to monitor soil moisture, electrical conductivity and temperature. As of this writing, we have six months of data on the deployment.

Unsurprisingly, Figs. 5 and 6 show significantly reduced power output in field conditions compared to laboratory conditions. The laboratory setting serves as an upper-bound that shows how cells perform in optimally moist conditions with high-nutrient soil. The field is drip irrigated and has an average moisture content of about 22%, vs 50-60% in the lab. Consequently we measure 0.5-2 µW (with brief spikes to 5-20 µW during irrigation), compared to 40-100 µW in the lab.

Though our field deployment exhibits lower power output than the laboratory, it is remarkably stable over the course of six months. With the advances in ultra-low power electronics, even just 0.5 µW is enough to support UWB backscatter tags [25], which when deployed underground can be used for high-accuracy soil moisture sensing [26], [27]. Furthermore, the results in Section III-B show that higher power output is possible by chaining multiple cells, which will expand the possibilities of what we can power with outdoor deployments.

We acknowledge that leveraging the power output of a single field cell is difficult, due to the voltages being beneath the cold-start voltage of most commercially available harvesters. However, we suspect that this will change soon as research works like [28], [29] introduce ultra-low power harvesting chips that can begin harvesting at 10-30 mV and leverage overall power levels under a microwatt. In addition to the possibility of reaching cold-start voltage by chaining cells, it may also be possible to leverage the voltage spikes caused by irrigation. These brief periods of heightened voltage often reach or exceed 10 mV, providing a potential way to kickstart harvesting on a single cell with next-generation ICs.

V. CONCLUSION

We have established that soil MFCs can produce over 100 µW with a 2.2 kΩ load in optimal conditions, but current harvester algorithms lead to sub-optimal performance. In realistic outdoor conditions, the cells reliably produce 0.5-2 µW. The ability to chain cells can amplify this small but steady source of renewable power, making it feasible to power ultra-low power electronics like underground backscatter tags. Much exciting work remains in how to optimize cell and harvester design for realistic outdoor settings, from the field deployments of chained cells, field deployments in more diverse environments, the exploration of alternative cell designs optimized for soil, and the design of specialized energy harvesting algorithms to maximize the energy harvested from these soil cells.

VI. ACKNOWLEDGEMENTS

We thank the anonymous reviewers for their feedback, as well as the Stanford Educational Farm for providing space for our long-term MFC deployment.

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