Plant Microbial Fuel Cells: Energy Sources and Biosensors for battery-Free Smart Agriculture

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***Abstract*—Smart sensors used for intensive crop monitoring require minimal maintenance and should prioritize ecological sustainability. Consequently, battery-free energy harvesting represents a key aspect of sustainable development in smart agriculture. Plant microbial fuel cells (PMFCs) introduce a cutting-edge renewable energy source that scavenges energy from the symbiotic relationship between a plant and electron-generating bacteria in the soil, potentially supplying power as long as the plant lives. Characterizing PMFCs' power production is challenging, as it depends on many factors, such as soil impedance and plant condition. Electrochemical impedance spectroscopy (EIS) is often used in laboratory tests, but it is inefficient to deploy in off-grid contexts. This article introduces an ultralow power EIS biosensor architecture that utilizes PMFCs as an energy source and for the EIS measure. We prove that ultralow-power EIS is compatible with PMFCs' mW-level power production through an implementation that integrates an EIS analog frontend and PMFC-tailored harvesting electronics. The architecture also facilitates PMFC unloading periods, crucial for PMFC recovery and durability. Experimental results show that a full-range EIS sweep (21.3 mHz–21.8 kHz, 19 points) executed with the proposed architecture requires only 3.64 J. We highlight the potential of cost-effective, self-powered EIS in assisting PMFCs' development into reliable energy sources for battery-free nodes. We also demonstrate that plant state, as well as maximum power point could be monitored through ultralow power EIS measurements.**

***Index Terms*—Biological systems, biosensors, electrochemical impedance spectroscopy, energy harvesting, power conditioning, system-level design.**

I. Introduction

PRECISION farming relies on environmental monitoring wireless sensor networks to collect data on the crops and soil and then to control and optimize the use of resources, such as water and pesticides. Thanks to the advancement of ultralow power computing paradigms and hardware [1], more environmentally friendly and maintenance-free supply solutions are gaining momentum, such as in *battery-free* electronics [2], [3]. Typically, battery-free devices [4] harvest energy from the environment and store it in a supercapacitor, sporadically executing tasks [5] whenever energy is sufficient, in an *intermittent* fashion [6].

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Aside from common energy harvesting sources, such as wind and solar power, plant microbial fuel cells (PMFCs) [7], [8] are sources of particular interest to the agricultural world. The simplest form of a PMFC consists of two conductive electrodes placed in the soil at a distance from one another and of a suitable plant, placed right above the electrodes. PMFCs rely on the energy-producing metabolism of naturally present exoelectrogenic bacteria and their symbiotic relationship with plants. These microorganisms release electrons as they consume organic matter (e.g., glucose), which is continuously provided at the roots thanks to plant photosynthesis. The conductive electrodes placed in the soil support the formation of a microbial biofilm, which catalyzes naturally occurring redox reactions in the soil, enabling energy production from the bacterial cell as long as the plant lives.

Although incredibly promising for their low environmental impact and maintenance costs, PMFC technology is still under development. These biofuel cells have several dependability issues that limit their widespread use and industrialization. We can articulate the nature of their shortcomings into three main points as follows.

1. *Low voltage, low power output:* Single PMFCs output a voltage below 1 V and mW/cm^3 power densities, meaning that efficient conversion electronics and/or output scaleup strategies are required for powering electronics from these sources.
2. *Low stability and predictability:* PMFCs are very sensible to the surrounding environment and have unpredictable power yields. They require a startup phase ranging from days to weeks before they can source power and have a highly variable lifetime. Their voltage polarity output can also switch suddenly and irreversibly in what is termed *voltage reversal* (VR) [9].
3. *Indirect fuel cell state measurement:* Bacteria, plant, and electrode state, which are the most important factors in determining future power outputs, cannot be measured *directly* and *nondestructively*, as collecting samples from the cell would heavily alter its state.

A promising strategy to obtain voltage and power scaleup consists in connecting cells together in series/parallel [10]. Unfortunately, the efficiency of this solution to ① is limited by ②, as stacking is linked to a higher probability of VR [9]. The cause of ② must be sought in the complex electrobiochemical nature of PMFCs, whose understanding *in real deployment scenarios* is limited by the difficulties posed by fuel cell state

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