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Is it time to start moving soil microbial fuel cell research out of the lab and into the field?

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Soil microbial fuel cells (SMFCs) function as bioelectrochemical energy harvesters that convert electrons stored in soil organic matter into useful electrical energy. Broadly, an SMFC comprises three essential components: an anode buried in the soil (the negative terminal), a colony of exoelectrogenic microorganisms residing on this anode, and a cathode (the positive terminal). As the exoelectrogens respire, they release electrons to the anode, which acts as an external receptor. These released electrons then flow through a load (e.g. a resistor), connecting the anode and cathode. Though minuscule, the electrical power produced by SMFCs has a number of potential applications such as sustaining low-power embedded electronics, pollutant remediation, or as a bio-sensing proxy for soil qualities and microbial activity. This discussion aims to emphasize the potential of SMFCs in addressing real-world environmental issues and to generate interest in the larger scientific community for broad interdisciplinary research efforts, particularly in field deployments.

Figure 1: Soil microbial fuel cell staged for deployment at the University of California, Santa Cruz Center for Agroecology.

At the time of writing, we found approximately 200 articles on SCOPUS with the keywords 'soil' and 'microbial fuel cells'. Of these articles, as shown in Figure 2, 38% of the literature address the need to improve SMFCs as power supplies, 44% investigate SMFCs as a method for soil or groundwater pollutant remediation (9% of which target heavy metals), and 9% discuss direct environmental sensing of factors and processes like pH, soil moisture content, and nutrient cycling. Approximately 9% fall outside these categories, and tend to focus on general improvements to SMFC technology. We noticed a recurring pattern: there are few SMFC publications focused on field deployments. This scarcity hinders the progress of various promising applications for SMFCs. In the remainder this article we discuss some of these applications (energy harvesting, soil remediation, and biosensing), and discuss the limitations of the current literature and suggest a path forward.

Energy harvesting: Batteries are the most common choice of power in remote outdoor settings. Unfortunately, batteries require periodic replacement and produce high environmental impact. Wind and solar can be employed as alternatives, but might not be feasible for certain settings, such as underneath dense foliage canopy. Researchers have found that SMFCs deployed on a farm can produce enough energy to sustain ultra-low power electronics.[1,2] Another set of researchers demonstrated that SMFCs connected in parallel can power even more energy-intensive applications by stacking 64 SMFCs to power a water treatment reactor in Brazil.[3] SMFCs could potentially fill the gap in sustainable power production left by the limitations of batteries and more conventional forms of energy harvesting.

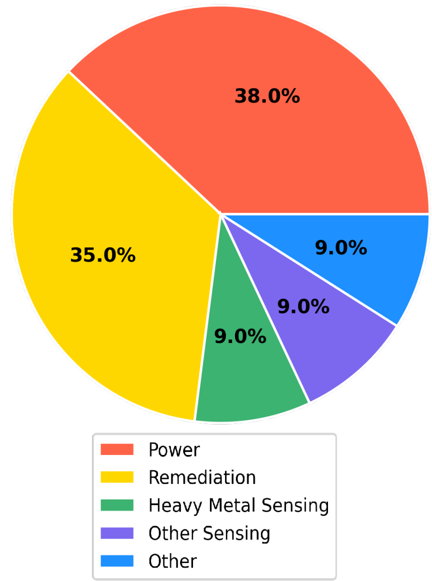

Figure 2: SCOPUS distribution of SMFC literature.

Soil remediation: SMFCs have shown promise in soil remediation, especially with regard to heavy metal contamination. SMFC-driven remediation is accomplished through two concurrent pathways. Firstly, exoelectrogenic microorganisms on the SMFC bioanode oxidize heavy metal ions, transforming them into immobile or less toxic species. Secondly, SMFCs generate an electric field, which migrates heavy metal cations from the subsoil to the surface layer. These combined effects result in the remediation of heavy metals in soil.[4,5] Concern for heavy metal contamination will only continue to grow alongside anthropogenic activities such as agriculture, mining, and industrial processes.[6,7] These activities are known to result in heavy metals leaching into soil and water,[8] eventually becoming hazardous to human health as they are incorporated into crops, livestock, and wildlife.[9] Despite the significant impact SMFCs could have as *in situ* heavy metal remediators, studies to date have been limited to laboratory contexts. Progression to preliminary field studies is urgently needed.

Biosensing: In the author's viewpoint, the most promising avenue for SMFC development is real-time soil health assessment in agriculture, which offers a significant opportunity for optimizing farming practices. It could enable more efficient nutrient management, precise irrigation, and enhanced pest control, ultimately leading to increased crop yields and reduced environmental and operational costs.[10] As the global population continues to grow amidst the challenges posed by the climate crisis, soil health monitoring emerges as a critical tool to address food security issues.[11] Electrical current is produced as a direct result of the metabolic relationships between microbes and soil organic matter and has been shown to reflect bulk soil microbial activity, which has been widely discussed as a metric for monitoring soil health[12] and for which there is no commercial *in situ* sensor. Some research has established links between SMFC power output and factors like soil organic carbon and pH,[13] which influence the efficiency of exoelectrogens in generating electricity. Heavy metal contamination in soil has also been shown to have a quantifiable impact on SMFC power output.[14] Efforts to develop SMFCs for soil moisture sensing applications have been stymied by the high moisture conditions required for non-zero signal production, about 40% VWC in sandy clay loam,[2] but these relationships are not fully understood. Elucidating the relationships between exoelectrogenic microbial activity associated with SMFCs and soil qualities such as pH, soil moisture, carbon, soil taxonomy, heavy metal contamination and plant available phosphorous is the first step in potentially leveraging SMFCs in the design of novel and sustainable *in situ* soil quality monitors. This represents a promising avenue for making working lands (e.g. pastures, agricultural fields, forests) more efficient and sustainable.

Call to action: As outlined above, there are numerous compelling real-world applications of soil microbial fuel cells. However, a significant limitation is the scarcity of SMFC field deployments. By beginning to move SMFC research into the field, the scientific community stands to gain a more realistic understanding of the capabilities of the technology and an understanding of what constrains the biologically generated electrical signal in different soils and climates. Practical deployments of SMFCs will require a wide range of expertise– MFC research is rooted in the fields of chemistry and microbiology, and SMFC research is similarly oriented. Growing interest in IoT and low power sensing has brought electrical engineers to the table. But broadly interdisciplinary publications that have expertise spanning across soil science, chemistry/microbiology and electrical engineering, are rare. We urge the larger scientific community of electrical engineers, microbiologists, environmental engineers, soil scientists, and beyond to reach past the borders of their discipline and work collaboratively towards moving soil microbial fuel cell research out of the lab and into the field.

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