# Review: Can bioelectrochemical sensors be used to monitor soil microbiome activity and fertility?

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**Abstract**
This review presents current knowledge on applying bioelectrochemical sensors to monitor soil fertility through microbial activity and discusses future perspectives. Soil microbial activity is considered an indicator of soil fertility due to the interconnected relationship between soil nutrient composition, microbiome, and plant productivity. Similarities between soils and bioelectrochemical reactors provide the foundation for the design of bioelectrochemical sensors driven by microorganisms enriched as electrochemically active biofilms on polarized electrodes. The biofilm can exchange electrons with electrodes and metabolites with the nearby microbiome to generate electrochemical signals that inform of microbiome functions and nutrient bioavailability. Such mechanisms can be used as a bioelectrochemical sensor for proxy monitoring of soil fertility to address the need for real-time monitoring of soils.

**Keywords:** Bioelectrochemical, soil, electrochemically active biofilm, electron transfer.

## Introduction: Can soil be a bioelectrochemical reactor?

Soil is a spatially heterogeneous mixture of inorganic minerals, organic matter, and dissolved compounds. Approximately 45% of total soil volume is composed of three primary inorganic minerals: sand, silt, and clay [1], whose relative percentages determine soil texture and structure. Soil porosity, the void space in soil which is filled with gases or water, constitutes approximately 50% of total soil volume [2]. Organic matter accounts for the remaining 5% of soil and includes living and decaying plants and animals, microorganisms, and humic substances [2]. Collectively, organic and inorganic materials provide nutrients to microorganisms, either as dissolved compounds moving through the soils or immobilized on soil surfaces. Chemotactic and motile behaviors allow microorganisms to migrate towards nutrient rich areas in soil, such as near plant roots [3]. Soil microorganisms are critical to the cycling of nutrients essential for plant growth, including nitrogen, carbon, phosphorus, and potassium [4]. Soil microbes improve bioavailability of nutrients for plant uptake and plants roots secrete nutrients that symbiotically support microbial growth and diversity [5]. The high density of microbes in the soil and near plant roots (the rhizosphere) interact with one another to develop surface-attached communities known as biofilm. By linking nutrient availability in soil to plant productivity, the soil microbiome activity becomes a dynamic indicator of soil fertility [6]. For this reason, there is great interest in harnessing the symbiotic activities of soil microbiomes to enhance crop health and resilience, and to improve nutrient availability without the use of chemical fertilizers [7].

Like bioelectrochemical reactors, soil contains electrolytes, microorganisms, nutrients, and redox active compounds which can generate electrical current through an electrochemical system. For example, soil microbial fuel cells (SMFC) harness the electrochemical activities of the local soil microbiome and are operated as bioelectrochemical reactors. SMFCs have been developed for energy harvesting and bioremediation of soil contaminants through biofilm enrichment on buried electrodes [8]. Whether viewed on a macro or micro scale, soils share the features of a bioelectrochemical reactor; however, many of these features are dynamic in soil. Novel applications are being developed to operate SMFCs under reduced moisture, an important consideration for performance under dynamic hydration levels [8]. To monitor other dynamic properties of soil, sensors have been developed to quantify specific nutrients, redox active compounds, and physical properties of soil. A bioelectrochemical sensor is yet to be developed for monitoring the collective activities of the soil microbiomes, both in terms of structure and functionality.

## Importance of microbial biofilms in soil and dissolved organic matter

Biofilms in soils consist of multi-species microbial consortia attached to soil particles and biotic surfaces including roots, fungal hyphae, and decomposing organic material [9]. Approximately 40-80% of the $3 \times 10^{29}$ bacterial and archaeal cells present in the soil are estimated to reside in biofilms [10]. Biofilms encase cells in a self-secreted matrix of extracellular polymeric substances (EPS), which enhances biofilm resilience, extracellular electron transfer (e-transfer), and soil stability [11,12]. Biofilms formed on soil particles and biotic surfaces (such as roots) are critical for nutrient mobilization and provisioning, pathogen defense, and modulation of plant morphology and physiology [13,14].

Nutrient availability in soil contributes to the formation and function of soil biofilms. For example, dissolved organic matter (DOM) is a critical carbon source which soil biofilms convert into intermediate chemicals or gases essential to other organisms in the soil ecosystem. Redox-active components of DOM contribute to the local redox state of soil, thereby influencing redox-controlled activities of soil microbiomes. The addition of DOM increases soil respiration rates, an indicator of microbial activity, and alter local soil microbial community functions across several soil types [15,16].

**Microbial electron transfer in soil**

Microbial metabolic interactions that drive nutrient cycling and biogeochemical processes in soil are made of e-transfer processes between electron donors and acceptors [6]. Soil organic matter, dissolved oxygen availability, soil moisture, and pH can modulate these redox activities [12]. Physical parameters of soil such as structure and texture control oxygen penetration, indirectly influence local redox activities [13]. Some of the most abundant redox-active fractions of DOM, humic substances, and other redox-active soil compounds can be detected using electrodes [17,18]. Through the detection of these redox-active compounds, electrodes indirectly measure shifts in the metabolic activities of the local microbiomes and electrochemical gradients in soil. Thus, soil microbiomes may serve as indicators of many physical, chemical, and biological soil parameters.

Soil microbes are also capable of changing macro-scale soil properties through e-transfer. For example, cable bacteria (discovered in 2012) form cm-long filaments that conduct electrons vertically across sediments [19-21]. A study published in 2020 showed inoculating cable bacteria to rice fields reduces anthropogenic methane emission by 93% [22]. Similarly, in 2023, cable bacteria were identified as an important microbe in the regulation of phosphorus release in sediment by altering soil pH gradients [23]. Moreover, cable bacteria can interact with electrodes [24,25], so their presence and activity can be monitored. Cable bacteria connected to oxygen sources attract flocks of bacteria to the anoxic section when e-transport in cable bacteria is active, but if the cable bacteria are cut (interrupting e-transport), these microbes disperse [26]. These studies illustrate how modulation of e-transfer processes impacts microbiome composition and influence soil properties.

**Harnessing the bioelectrochemical properties of soils**

The presence of redox-active compounds, e-transfer mediators (ETMs), and electrochemically active biofilms (EABs) allows us to consider soils as a bioelectrochemical reactor and each component can be electrochemically probed. DOM represents one of the most mobile and reactive organic compounds in the ecosystem and plays an important role in the transport of soil organic content and nutrient cycling [27-30]. Cyclic voltammetry (CV) and chronoamperometry (CA) demonstrate the e-transfer capability of some redox-active DOMs in soil [27]. Furthermore, differential pulse voltammetry (DPV) and CV in combination with spectroscopic techniques (FT-IR, UV-Vis and fluorescence spectroscopy), effectively determined the electrochemical and redox properties of DOM in soil [28]. Since the discovery of e-transfer in soil, researchers have focused on how to improve this process. For instance, pyrogenic carbon or other conductive carbon-based materials have been proposed as soil amendments to improve e-transfer [31]. The addition of pyrogenic carbon is expected to improve soil fertility by increasing the amount of ETMs, but this relationship is yet to be validated. It is also unclear how other biological components of terrestrial belowground systems, notably plant roots, modulate electrochemical signals or e-transfer of associated biofilms.

Soil bacteria have significant variations in metabolic capabilities, which is observed as variance in electrochemical potentials, e-transfer mechanisms, and the electrical currents they generate [17,22,32,33]. Microbial activities and nutrient availability can be monitored by the current (e-transfer rate) of an electrode colonized by EAB, which can exchange electrons with the inert electrode [34,35]. Polarized electrodes therefore can be used for *in situ* detection of microbial life in soils [36]. Amending soils with electron donors enhances the biologically produced current and allows for the stimulation and detection of dormant electrochemically active microbes [29,30,37,38]. Polarized electrodes in soil provide a method to detect local metabolisms without prior knowledge of the microbiome present and determine if signals are biological through electrochemical measurements [37]. Photosynthetic metabolisms can also be monitored in this manner in remote areas using custom electronics [39],[40,41]. Polarized electrodes have facilitated the isolation of electrochemically active bacteria and soil microbes with extracellular e-transfer ability [32].

Enriched electrochemically active microbial communities growing on polarized electrodes respond to the local soil electrochemistry [21,42]. Previous research demonstrates biofilm grown on electrodes can monitor microbe-environment interactions in sediment systems [34,35]. Through the selective enrichment of local electrochemically active species, the electrode-associated biofilm alters the local microbiome structure and function and opens opportunities for engineering soil activities [42-44]. With increasing interest in utilizing natural microbiomes in place of chemical fertilizers, electrochemical enrichment may have applications in supporting plant-growth-promoting microorganisms, stimulating nutrient cycling, and promoting the bioremediation of contaminated soils [7,45]. Thus, studies to date demonstrate that soil is a dynamic redox-active bioelectrochemical system, that can be probed using electrochemical techniques.

An attractive property of measuring bioelectrochemical signals in soil and linking them to specific processes is that they can be precisely tuned in multiple dimensions. In this review, electrochemical signals are defined as a set of multidimensional e-transfer measurements: 1) CA measures anodic or cathodic current generation at a set potential to monitor EAB metabolism, 2) CV can inform metabolic/redox activity across a range of applied potentials, 3) square wave voltammetry signals can be related to the activity or concentration of redox mediators, 4) conductance shows e-transfer ability of soil, and 5) electrochemical impedance spectroscopy (EIS) identifies mass transport limitations or reaction kinetic limitations at the electrode surface. Some of these measurements are illustrated in **Figure 1**, which shows electrodes in soil selectively enriching EABs with a reductive (electron-accepting) or oxidative (electron-donating) metabolism on the cathode and anode, respectively. Linking the electrochemical signals to specific properties of the soil microbiome is critical to develop a new generation of bioelectrochemical sensors informing of soil microbiome metabolic activities and available metabolites.

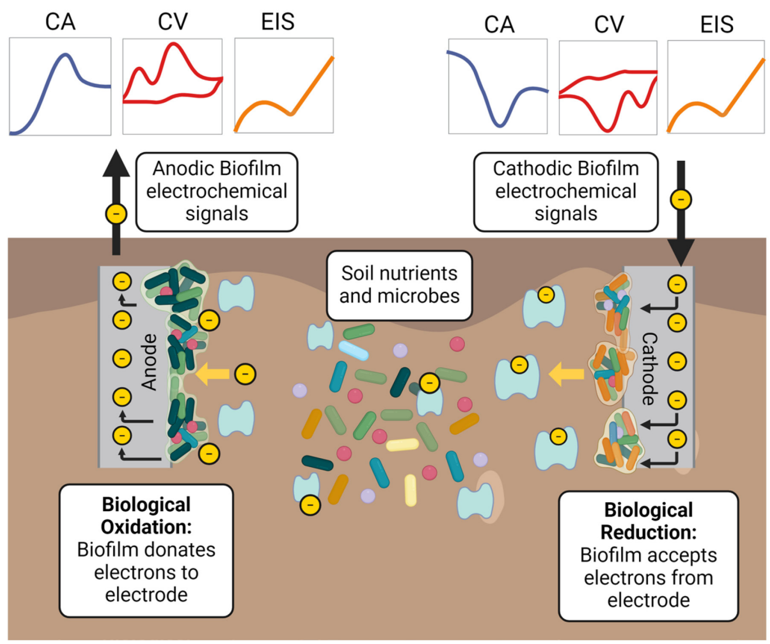


**Figure 1.** EABs are selectively enriched on polarized electrodes at positive (anode) or negative (cathode) potentials, producing electrochemical signals based on their interactions with the bulk soil microbes and nutrients.

**Electrochemically active biofilms as bioelectrochemical sensors**

Bioelectrochemical sensors provide real-time measurements of microbial activity through current measurements. EABs have been utilized to quantify microbial activity and available nutrients. For example, microbiosensors using the EAB, *Geobacter sulfurreducens,* effectively detected acetate (electron donor) and fumarate (electron acceptor) at concentrations as low as 79 µM and 258µM, respectively [46,47]. EABs have also been used to monitor microbial activities in hot springs located in Yellowstone National Park [44] and in a hypersaline lake [41]. Biofilm-based sensors have also been used for measuring formaldehyde toxicity in water, dissolved oxygen, and volatile fatty acids [48,49]. Overall, these works of literature provide a strong foundation for harnessing EABs as bioelectrochemical sensors in soil.

A recent study determined electrochemical signals of EAB can be used to distinguish fertile and less fertile soils (determined by plant productivity) within two days by monitoring current generation and observing an increase in redox peaks in CV measurements [42]. Addition of glucose (carbon source and electron donor) to both soils increased anodic current, indicating nutrient availability may limit microbial activity, even in fertile systems [42]. Micrographs of the electrodes surface confirmed biofilm enrichment in more fertile soils. Similarly, another study in 2024, demonstrated high levels of DOM enriched more diverse, weakly electrochemically active bacteria from soil on polarized electrodes; while low DOM samples exhibited a higher relative abundance of strong electrochemically active bacteria such as *Geobacter* on polarized electrodes [50]. The availability of DOM influenced the microbial community structure and generated distinct electrochemical signals through CV and CA measurements, indicating a correlation between nutrient availability, microbial community, and electrochemical signals.

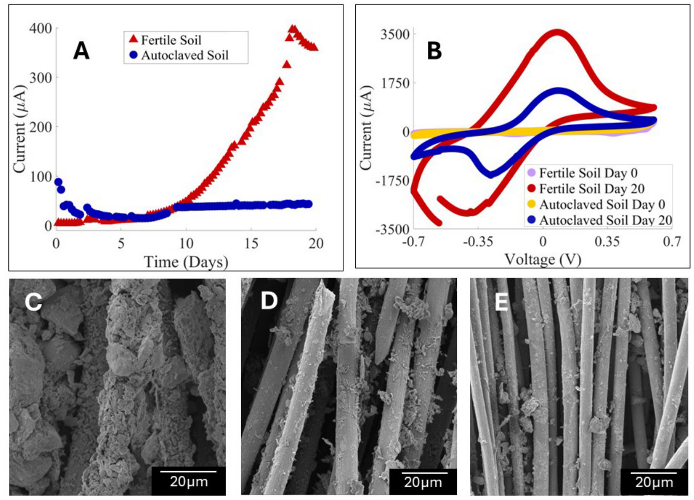


**Figure 2. A)** Current generated by biofilms enriched from fertile soil (red) in reference to autoclaved soil controls (blue). **B)** Cyclic voltammograms showing increased redox peaks in fertile soils compared to controls. Scanning electron micrographs of biofilms enriched on polarized electrodes with **C)** fertile soil and **D)** triple autoclaved soil, in reference to **E)** non-polarized electrode in fertile soil.

The electrochemical protocol of Mohamed et al. (2021) was followed to evaluate the difference in biotic and abiotic electrochemical signals generated by fertile soil and triple autoclaved fertile soil (**Figure 2**) [42]. Fertile soil with microbes generated significantly greater current and increased redox peaks in the CV than autoclaved soil. Abiotic redox active compounds in soil may explain the increased redox peak over time in autoclave soil at day 20 (**Figure 2 b**). Scanning electron micrographs (**Figure 2 c-e**) confirmed biofilm enrichment on the polarized electrode in fertile soil compared to the autoclaved soil. Biotic electrochemical signals from soil may be differentiated from abiotic electrochemical signals through a combination of electrochemical measurements. However, further research is required to 1) quantify distinctions between abiotic and biotic electrochemical signals in soil systems, and 2) characterize EAB.

**Perspectives on the use of bioelectrochemical soil sensors as a new tool to monitor soil microbiome activity and proxy for soil fertility**

Soil sensors provide quick, non-destructive measurements of individual soil parameters including water content, electrical conductivity, temperature, pH, and soil water potential [51]. However, measurements of multiple physical and chemical properties are often required to quantify soil fertility and do not measure biological properties of the soil. Current methods for characterizing soil biofilm communities and functions require meta-omic studies and advanced microscopy techniques [14]. However, these approaches are limited in their ability to rapidly monitor biological activities and their correlation to other soil parameters. Biodegradable sensors have been developed to correlate measured electrical resistance to microbial decomposition ability [52]. These sensors provide information on biological activity but have limitations in monitoring microbiome structure, selectivity for identification of beneficial microbes, and changes in the soil microbiome. New sensory modalities are thus needed to monitor the microbial activities of soil.

Soil microorganisms respond rapidly to changes in their physical and chemical environment. Bioelectrochemical sensors can provide continuous monitoring of biological activities in response to physical and chemical fluctuation in space and time through CA measurements. However multiple parameters, such as water content, temperature, pH, and available nutrients, will affect the measured EAB signals, limiting our ability to distinguish the cause (**Figure 3**) [53]. Integration of bioelectrochemical sensors with other sensors to measure the most influential parameters (e.g., water content or temperature) could overcome some of these challenges and enable integrative approaches for the monitoring of soil fertility. Such capability would enable real-time monitoring of microbial activities in soil, potentially allowing farmers to make faster decisions regarding soil amendments for crop yield optimization.

Bioelectrochemical sensors have the potential to correlate EAB with nutrient content in soil. Monitoring microbial activity and nutrient availability requires both nutrients and microbes to be present to produce a sensor response. These sensors are currently unable to distinguish between the absence of nutrients or microbes. Bioelectrochemical sensors also face reproducibility challenges due to the heterogeneity of soil, as electrochemical responses are likely to vary spatially. Many soil types of multiple fertility standards need to be evaluated and correlated with relative crop yield to verify the range of soil fertility a bioelectrochemical sensor can measure. Optimization of a sturdy sensor design, polarization potential for different soil types, and analytical methods are required for development of a field-deployable bioelectrochemical sensor. These challenges highlight that research on bioelectrochemical sensors to monitor soil fertility is in the early stages of development and the need for continued advancement. Overcoming these challenges could lead to improved understanding of soil microbiome functions and the development of sensors that provide farmers with valuable, real-time information of soil properties needed for strategic management.

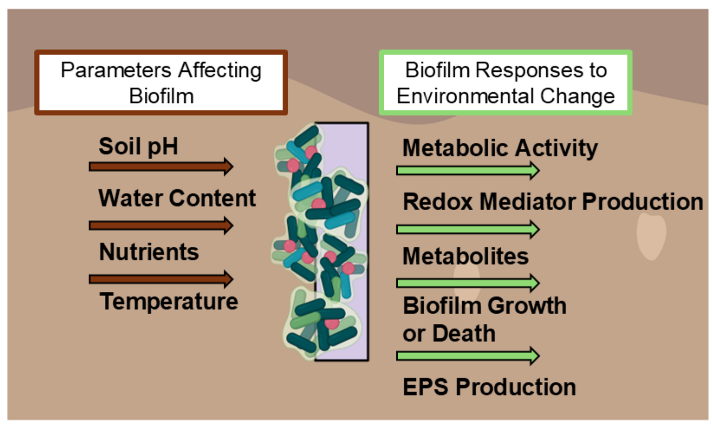


**Figure 3.** Bioelectrochemical sensors measure EAB activity, which can be affected by many environmental factors including soil pH, water content, availability of local nutrients, and temperature.

**Acknowledgments**
This work was supported by the National Science Foundation [grant number 2226680]. CFW acknowledges support from the NIGMS Biotechnology Training Program [T32 GM 8336]. MLF

by the USDA National Institute of Food and Agriculture [Hatch project 1014527]. GR was supported by the Army Research Office [award W911NF2210297].

## Author contributions

Conceptualization (Webster, Won-Jun, Friesen, Beyenal); Data curation (Won-Jun); Formal analysis (Webster, Won-Jun); Funding acquisition (Friesen, Beyenal, Reguera); Investigation (Webster); Methodology (Webster, Won-Jun); Project administration (Friesen, Beyenal); Resources (Friesen, Beyenal); Software; Supervision (Friesen, Beyenal); Validation (Beyenal);; Roles/Writing - original draft (Beyenal, Won-Jun, Webster); and Writing - review & editing (All authors).

## References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:
• of special interest
•• of outstanding interest

## Annotated references

•• **Qin2024:** Authors demonstrated weak electrochemically active bacteria are more prominent in soils rich in DOM and increased total biological current generation. Electroactive microbial communities in soil are influenced by DOM abundance in soils.

• **Atreya2023**: Biodegradable soil sensor measures resistive signals that correlates with microbial decomposition activity, which is critical to maintaining soil fertility through carbon cycling.

•• **Mattila2024**: Redox processes in soil which drive microbial community functions are controlled by several factors including soil structure. Redox measurements of soil can be utilized as an additional measurement in soil mapping because of correlation with soil structure and biological activity.

• **Miele2023**: Soil column experiments demonstrate the relationship between redox potential in soil and the soil saturation dynamics and authors identified saturation velocity as a major driver in redox potential changes.

•• **Bjerg2023**: Diverse bacteria move towards the anoxic part of cable bacteria and disperse rapidly when it is cut off from oxygen, suggesting cable bacteria's electron transfer chain may influence surrounding microbial community and act as an electron donor.

• **Xu2023**: Cable bacteria activity can influence phosphorus (P) mobility in freshwater by acidification of the suboxic zone, releasing dissolved $Fe^{2+}$ and $Mn^{2+}$. The formation of a metal oxide layer in the sediment traps dissolved P in sediment which may counteract eutrophication in freshwater.

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