SoilSense: Appropriating Soil-based Microbial Fuel Cells to Create Tangible Interfaces

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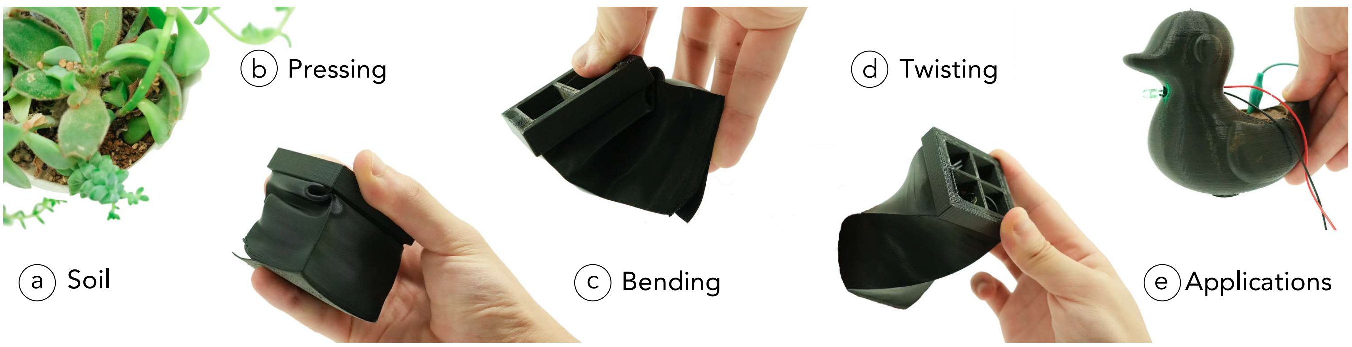

Figure 1: When pressure is applied to the cathode of an SMFC, its output voltage varies with the force. As a result, using soil as the core material (a), we can create a tangible interface that responds to (b) pressing, (c) bending, and (d) twisting, opening new design space for bio-based design and (e) applications.

Abstract

Soil-based Microbial Fuel Cells (SMFCs) offer a sustainable method for powering low-energy computing devices by harnessing electricity from microbial activity in soil. In this paper, we introduce SoilSense, a novel approach that repurposes SMFCs as tangible interfaces, transforming soil into an interactive, computationally responsive medium, instead of energy sources. We explore the voltage variations that occur when pressure is applied to the cathode and systematically characterize this mechanism across different electrode configurations and soil moisture levels. To demonstrate the feasibility of SMFC-based interfaces, we present a series of modular and proof-of-concept prototypes that support diverse interaction modalities. We further illustrate how SoilSense enables interactions through example applications and provide implications and envision for future studies to employ soil as an ecologically compatible material in interactive system design.

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CCS Concepts

• **Human-centered computing → Interaction techniques**.

Keywords

Soil-based Microbial Fuel Cells, Tangible Interface, Sensing Technique, Biodesign

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1 Introduction

Soil, a ubiquitous material, has been extensively explored across disciplines such as microbiology [37, 46, 61], agriculture [15, 85], and renewable energy [23, 89]. In HCI, the Do-It-Yourself (DIY) and biodesign communities have also embraced soil for its accessibility and ecological value [11, 58]. Among its various uses, Soil-based Microbial Fuel Cells (SMFCs) have emerged as potential energy sources for low-power IoT devices, by converting the metabolic activity of microorganisms into electricity via embedded electrodes in the soil. Although SMFCs have demonstrated output power up to hundreds of μW [33, 34], their performance under ideal conditions and in real-world scenarios is still underexplored and remains the focus of current SMFC-related research[47, 82, 89]. However, in its current capacity, SMFC has unique affordances that can be used in interactive applications, but they have rarely been examined through the lens of interaction design as a computationally responsive component.

In this paper, we introduce *SoilSense*, a novel approach to repurposing SMFCs not merely as passive energy sources, but as active components within interactive systems. Our key observation is that when the cathode is subjected to pressure, a combination of contact and internal changes in SMFCs leads to a measurable voltage variation, which could effectively enable sensing without the need for additional electronics. Additionally, unlike conventional sensors that rely on nano-engineered materials [75, 92], SMFC rely on soil and low-cost carbon electrodes. While SMFCs' capabilities in energy harvesting have been well-studied [45, 47], this paper focuses on exploring SMFCs as a new interaction modality and examines how their material properties and environmental responsiveness can inform the design of tangible interfaces. This perspective opens new opportunities in sustainable HCI, particularly for low-power or DIY-friendly applications, and aligns with the emerging interest in biodesign and ambient interaction.

To validate our approach, we propose design patterns based on soil and SMFC's unique characteristics and systematically examine how the output voltage of SMFCs responds to the inputs across diverse electrode configurations, responsiveness to pressure, and moisture conditions. Based on these insights, we develop and demonstrate a set of proof-of-concept prototypes and example applications that enable tangible gesture interactions (e.g. pressing, twisting, and bending), highlighting how SMFCs can be effectively embedded as sensors within various containers. Our contributions are as follows:

- We adapt soil as an active sensing material using SMFCs.
- We characterize the voltage response of SMFC-based soil tangible sensors to interaction under varying conditions.
- We present three proof-of-concept interactive containers for SMFCs to support tangible interactions, including pressing, twisting, and bending. We also demonstrate the feasibility of SMFC-based interfaces through exemplary applications.

2 Related Work

To contextualize our work, this section begins by reviewing key background on SMFCs, including their basic structure, factors affecting output performance, and empirical findings from previous studies. We then explore how soil and SMFCs intersect with the key themes in sustainable HCI, structured around self-powered interfaces, bio-based materials, and biodesign.

2.1 Soil-based Microbial Fuel Cell

Figure 2 (a) illustrates a typical structure of an SMFC, which consists of a *cathode*, an *anode*, and the *electrolyte* (soil) situated between the electrodes. The anode is placed in an anaerobic environment under the soil, in contact with microorganisms that are typically present in the form of a biofilm, and receives electrons released by the oxidation of organic compounds; the cathode is positioned in an aerobic environment on the surface, where electrons generated at the anode flow through an external circuit and react with protons transported through the electrolyte with oxygen to produce water [66, 82, 89]. The energy output from SMFCs typically ranges from a few μW to several hundred, depending on the specific scale and setup [33, 34, 65]. Previous studies have introduced applications derived from SMFCs, such as integration with plants to increase output [6, 59], or using SMFCs to power IoT systems [18, 45].

Carbon felt is a popular choice for SMFC electrodes due to its high specific surface area, durability, affordability, and recyclability with minimal environmental impact [89]. As the anode, the fine porous structure of carbon felt facilitates the attachment and growth of biofilms; while as the cathode, carbon felt's permeability allows oxygen to efficiently participate in the reduction reactions [32, 91]. Due to the occurrence of over-potential and the presence of factors including activation losses, Ohmic losses, and mass transport losses, the efficiency of the cathodic reaction is considered the bottleneck that determines the energy output of the SMFC devices [44, 69]. Electrodes are typically connected to external circuits using insulated wires (e.g., copper or silver) and serially with loads. In this paper, we used carbon felt as both the anode and cathode, consistent with prior SMFC literature, and connected them using copper wires with stainless steel crocodile clips, with details in Section 4.1.

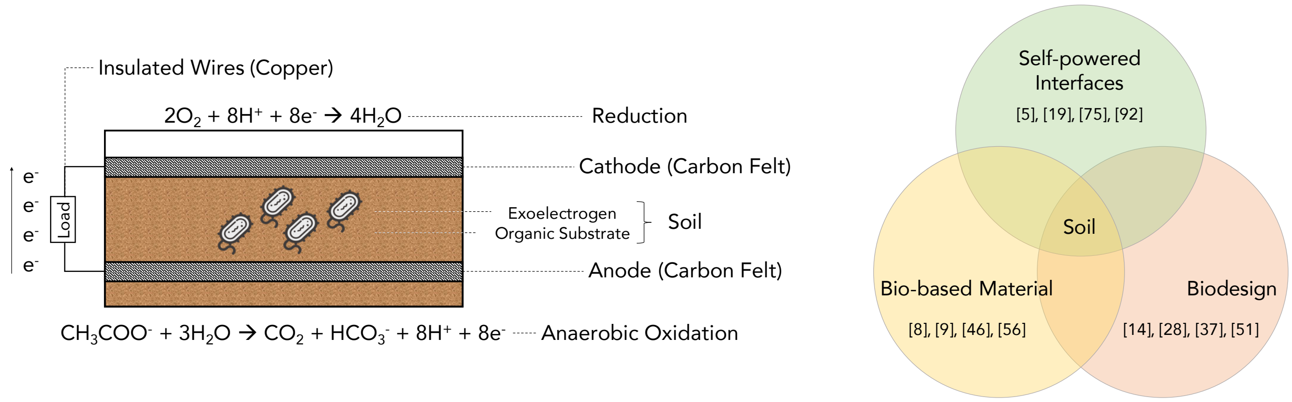
The performance of SMFCs is influenced by various environmental factors, primarily because their energy generation process relies heavily on microbial activity and the soil condition, which is highly sensitive to environmental factors, including temperature, moisture, chemical composition, pH value, and so on [12, 82, 93]. To date, due to the complex biochemical composition of natural soil, it is still challenging for us to accurately model the relationship between environmental factors and energy output or identify broadly applicable conclusions. However, the energy output of SMFCs is positively correlated with temperature [93], volumetric water content (VWC) [12], and the organic content in the soil [22] in general.

2.2 Sustainable HCI

While SMFCs are traditionally studied from an energy-harvesting perspective, integrating these devices within HCI frameworks remains unexplored. In this section, we make connections between SMFCs and sustainable HCI from the aspects of self-powered interfaces, bio-based materials, and biodesign (Figure 2 (b)).

Self-powered Interfaces. Energy remains a fundamental challenge for all computing systems, and one promising solution is an emerging class of self-powered interfaces [19]. These systems leverage energy harvesting techniques, together with ultra-low power computing, to achieve autonomous operation. Many of these interfaces exploit material properties to convert ambient stimuli — such as light [94], sound [5], deformation [75, 92], or motion [72, 87] — into analog signals. SoilSense follows a similar approach, leveraging the voltage fluctuations naturally generated by SMFCs under pressure to support sensing through the system's own electrical output.

Bio-based Materials. The production of the aforementioned self-powered interfaces is often sophisticated, such as Photovoltaic



(a) A Schematic Diagram of SMFC (b) Survey Map

Figure 2: (a) A schematic diagram of the functioning principle of an SMFC. (b) A survey map that motivates soil as a potential interactive medium from the perspectives of self-powered interfaces, natural materials, and biodesign.

(PV), Triboelectric Nanogenerators (TENG), which involve acrylamide or nano-engineered material that requires energy-intensive production, which has prompted researchers to reconsider the ecological costs and to advocate for sustainability practices in digital fabrication [13, 21, 78]. There have been successful demonstrations of biodegradable electronics, such as energy storage [79] or heating devices [77]. Bio-based material are generally generally degradable, accessible, and DIY-friendly [63], such as fungi [27, 83], wood [67], algae [8, 96], bacterial cellulose [9, 52], and slime mold [46, 56]. However, while many of these bio-based materials have shown promising potential for sensing or actuation, they often require specific cultivation, post-processing, or embedded infrastructure to support interactive functionalities. Soil, when used in the form of SMFCs, exhibits electrochemical activity that can be harnessed to detect pressure-based input. This property allows it to serve as a sensing interface within an interactive system, without requiring additional sensing components or complex fabrication.

Biodesign. Over the decade, bringing living organisms into interactive systems has been an emerging field in HCI, such as Microbe-HCI [37] and the Human-plant Interaction [14]. These applications have encompassed diverse contexts such as sensing and display [28, 51], direct interaction [42, 57], and interactive public art [39], which not only highlight the sustainability of materials but also expand the design space for embedding biological processes into interactive systems. Soil, as intimately connected with plants and microorganisms, also holds a potentially significant role in biodesign. For instance, in [14], the state of the soil is used to indirectly reflect the well-being of plants. Similarly, in Electric Life [58], the principle of SMFC is harnessed to create an illuminating installation, blending ecological processes with artistic expression. In this paper, we explore how the voltage response of SMFCs can support tactile input, enabling soil to function as a sensing interface in potential biodesign contexts. This approach complements existing bio-based systems by offering a low-cost, materially integrated method for interaction within natural environments.

3 SoilSense

This section introduces how SMFCs can be appropriated as an active component in tangible interfaces. This section discusses the foundation of the sensing principle, particularly the physical and electrochemical mechanisms behind the induced voltage changes.

3.1 Voltage Variation

A central insight in our work is that applying pressure to the cathode of an SMFC results in a measurable increase in output voltage. This behavior differs fundamentally from conventional touch interfaces, which typically rely on changes in capacitance or material resistance [26, 50, 95]. In SMFCs, the carbon felt electrodes are highly conductive (0.87 Ω/m), and their electrical resistance does not change significantly under compression [55], which makes the resistance-based sensing can hardly explain the observed voltage variation. Instead, the voltage variation can be attributed to the unique physical and electrochemical structure of SMFCs, where pressure influences both the electrode–soil interface and the properties of the soil itself.

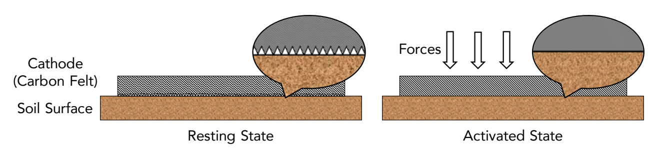


Figure 3: A schematic showing the contact condition between the carbon felt and soil changes under applied pressure.

From the perspective of the electrode–soil interface, vertical force improves the contact between the cathode and the surrounding soil (Figure 3). When carbon felt is placed on the soil in an uncompressed state, its soft and porous structure, combined with its lightweight nature, tends to create interfacial gaps and dry spots. These discontinuities may hinder ionic conduction and reduce the efficiency of oxygen reduction reactions [80, 88]. Applying pressure compresses the felt, reduces these interfacial discontinuities, and enhances local reaction kinetics, which contributes to an increase in output voltage. Within the soil matrix, pressure induces compaction, decreasing porosity and increasing bulk density [7, 24]. These structural changes affect the distribution of water and oxygen, both critical to sustaining electrochemical performance [49]. Furthermore, the associated reduction in oxygen diffusion rate (ODR) may promote more anaerobic conditions favorable to microbial activity at the anode [68]. While these internal changes evolve more gradually, they are presumably contributing to longer-term voltage variation after the force is applied. In contrast, the immediate voltage response observed in our experiments is primarily attributed to the enhanced contact conditions between the cathode and the soil interface.

3.2 Design Patterns

We explore three design patterns derived from soil characteristics and the basic structure of an SMFC: adaptive form factors, expandable input channel, and ecological compatibility, as illustrated in Figure 4.

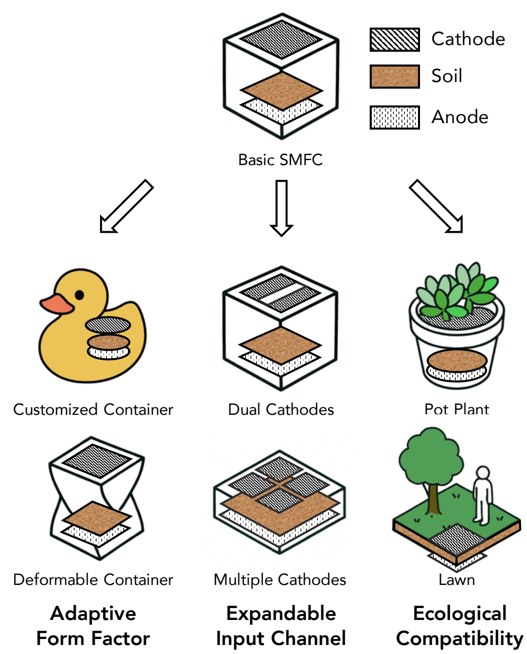


Figure 4: Design patterns for appropriating SMFCs to create tangible interfaces.

Adaptive Form Factors. Soil's malleability allows it to conform to a wide range of customized container shapes and structures, enabling designers to explore unconventional geometries and interactions. Designers can simply use diverse containers to imbue interaction with specific meanings. Furthermore, by embedding the SMFC within flexible or deformable containers, we can extend interaction modes to diverse input modes while simultaneously leveraging visual cues from material deformation. These form factors make the interface both expressive and functionally rich, allowing the shape and material behavior of the device to naturally suggest or afford particular interactions.

Expandable Input Channel. A single SMFC container can support multiple cathodes connected to a shared anode, each capable of independently detecting localized pressure. For example, by embedding two cathodes on opposite sides of a container and comparing their respective voltage signals, we can distinguish whether the left or right side has been pressed. As the number of cathodes increases, more sophisticated spatial sensing becomes possible, forming a low-resolution electrode matrix. While the signal resolution remains limited compared to capacitive sensors, it enables coarse force mapping with minimal hardware. In such setups, each cathode must be electrically isolated with separate traces and protected from crosstalk, either through physical spacing or differential referencing techniques.

Ecological Compatibility. Soil is a naturally occurring, bio-based material that is widely present in outdoor and plant-integrated environments. SMFC-based interfaces have the potential be deployed in contexts where soil is already part of the setting, such as potted plants or garden beds [24], providing a tangible input channel without introducing foreign substrates. This design pattern offers a practical approach to embedding interactive systems into ecologically situated settings, particularly where minimal material intrusion is desired.

In the following section, we focus on characterizing the core sensing behavior of SMFCs under different environmental conditions and configurations, laying the groundwork for the use of SoilSense in interaction design.

4 Evaluation

To characterize the sensing capability of SMFCs, we conducted a series of experiments that examined how they respond to mechanical input. In this section, we first investigate the relationship between increasing pressure and voltage output to understand the dynamic range and responsiveness of the system. Second, we study how the voltage changes over time under a sustained force, as SMFC behavior could potentially exhibit transient or decaying responses due to electrochemical stabilization. Finally, we examine the role of soil moisture, a known environmental factor for SMFC performance, to evaluate how VWC modulates the sensitivity of the sensing signal.

4.1 Experiment Setup

Experiments were conducted at room temperature (around 25°C) in the laboratory environment. The soil used in the experiments was collected from gardens on a university campus in Asia. The soil was sieved through a 2 mm mesh to remove large particles, insects, and debris. Before being placed into the containers, the soil was moistened with water and stirred thoroughly to form a uniform mixture. Before starting the experiments, we prepared three SMFCs with VWC around 90%, 70%, and 50%, each placed in a cubic container with a side length of 100 mm. To ensure the anaerobic environment inside the soil, the SMFCs were prepared 48 hours in advance to reach a stable voltage output level by the time the experiments commenced.

(a) SMFC Container (b) Electrodes (c) Moisture Sensor (d) Digital Multimeter (e) Force Gauge

Figure 5: Instruments and items during the experiments.

Figure 5 shows the instruments used during the experiments. The soil is contained within a cubic vessel, with a side length of 100 mm. We used LOKIH 5 mm thick carbon felt [76]. The distance between the electrodes was approximately 70 mm, with two types of electrodes in size: squares with edge lengths of 45 mm and 90 mm. Copper wires with an insulated diameter of approximately 1 mm and stainless clips were used to form the external circuit. A 2 kΩ resistor was included in the external circuit to maximize the power output of the device according to the empirical results determined by Lin et al. [45, 89]. We used a digital multimeter to keep track of the output voltage and current, with an accuracy of one millivolt and one milliampere, respectively. Four moisture sensors (DiyStudio A3012656JP) are inserted at different positions within the soil, and the VWC is estimated by averaging their values. We used an IMADA DST Series digital force gauge along with an MX2 Series vertical motorized test stand to generate specific forces. A 3D-printed attachment was created for the force gauge's probe to control the pressure applied to the cathode so that it is distributed evenly.

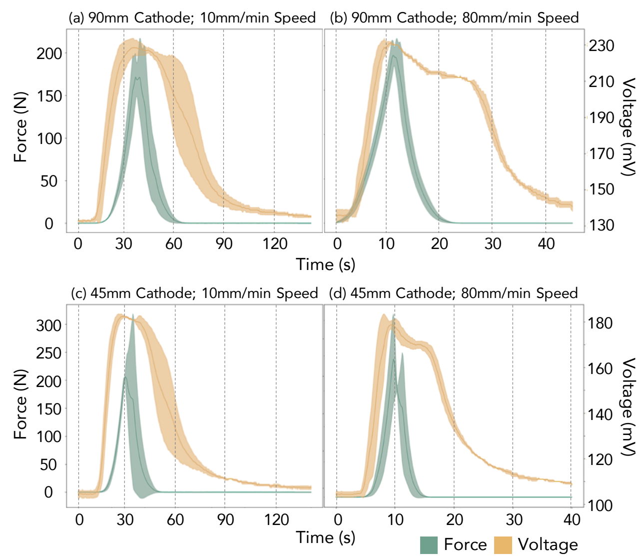


Figure 6: Relationship between the voltage and the force applied on the cathode of two SMFC with different cathode sizes of 45 mm and 90 mm, and different force gauge speeds of 10 mm/min and 80 mm/min. The curves show the mean value, and the colored area represents the range of fluctuations after aligning the time axis.

4.2 Effects of Increasing Force

We explored the relationship between the output voltage and the pressure applied onto the cathode under the VWC around 90%. We conducted tests on two different electrodes to inspect the potential effect of the size as a factor in this relationship. We used a force gauge in combination with a motorized test stand with adjustable speed to record the applied force. Since the downward motion of the test stand occurs at a fixed speed, the resulting pressure change is inherently nonlinear. To avoid rapid spikes in pressure within a short time frame as much as possible, we set the descent speed to a slower 10 mm/min and a faster 80 mm/min. The slower speed allowed for careful observation of gradual changes, while the faster speed simulated the rapid pressure variations typical of real-world interactions. The test stand was reversed and moved upward at the same speed once the force gauge's reading reached around 200 N, allowing us to capture the voltage response during the recovery phase of the device.

We conducted three trials for each configuration, and the results are plotted in Figure 6. Larger cathodes exhibited higher peak voltages during compression but also required more time to return to a resting state. When the force gauge descended at a faster speed, the voltage response (both rise and fall) became notably quicker. Compared to typical gesture-based interactions, which often involve faster exertion rates and lower force ranges (< 50 N) [20, 53], our experimental setup was designed to characterize the relationship between applied force and voltage output across a wide range of pressures in controlled speeds. By comparing responses at two speeds, we observed that the voltage dynamics remained consistent across a broad temporal window. The faster speed (80 mm/min) produced quicker voltage transitions without fundamentally altering the signal profile. In particular, the initial rising edge of the voltage curve showed comparable sensitivity under both speeds, indicating that the system responds promptly under different force application rates. These support the feasibility of using the sensing technique in gesture-speed interactions.

4.3 Effects of Sustained Force

In the previous section, we explored how the output voltage of the SMFC responded to varying levels of pressure applied to the cathode. We conducted experiments using cathodes with side lengths of 90 mm and 45 mm under sustained pressure. The motorized test stand was adjusted to apply forces ranging from 10 N up to 300 N. Voltage readings were collected within the first minute of five trials of each force level and are presented in Figure 7. Across all configurations, the output voltage declines over time irrespective of cathode size or the magnitude of applied force. In most cases, the voltage decreases to between 80% and 90% of its initial value within one minute. Furthermore, larger voltage reductions are likely associated with trials that begin with higher initial voltages.

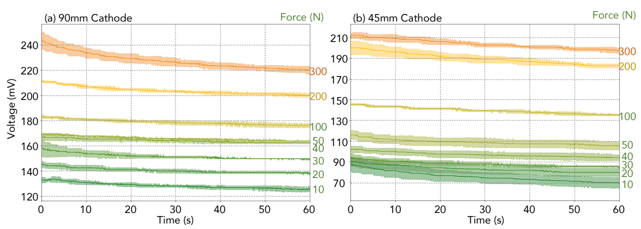


Figure 7: Voltage change of two SMFC with different cathode sizes when applying a sustained force. The colored curves and shaded areas indicate different force levels, with the corresponding force values annotated at the end of each curve.

In SMFCs, a potential difference exists between the cathode and the soil surface [81]. As discussed in Section 3, applied pressure enhances cathode-soil contact, leading to reduced resistance and facilitating the release of charges between the interface via the external circuit, similar to a discharge process. This causes a temporary surge in output voltage. In 60 seconds, the interfacial potential difference dissipates, and the system stabilizes at a new equilibrium, leading to a gradual voltage decline. This phenomenon highlights the need to consider such transient instabilities when employing SMFCs as input interfaces for sustained interactions. Despite the moderate and slow nature of the decline, it might still influence threshold-based input interpretations.

4.4 Effects of Levels of VWC

We conducted the same tests using a 90 mm cathode setup at three different VWC levels of 90%, 70%, and 50%. For forces ranging from 0 to 200 N, we recorded a measurement every 10 N and repeated the measurements five times for each, shown in Figure 8. At higher VWC, both the peak voltage and the rate of voltage increase are elevated. The slope within the 0 N to 20 N force range is notably steeper. As the VWC decreases, a downward trend is observed in both the voltage peak and its rate of change. This is because SMFCs inherently operate more effectively under higher VWC conditions, which ensure smoother ionic pathways. This characteristic also contributes to enhanced responsiveness when the system is employed as an input interface.

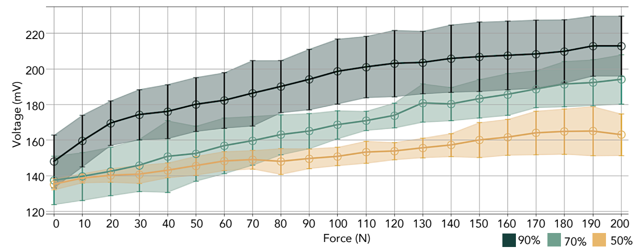


Figure 8: Relationship between the output voltage and the force applied on the cathode for SMFCs with fixed cathode area under three different VWC.

5 Interface Prototypes

Building upon the design pattern outlined earlier in Section 3, we developed a series of 3D-printed Thermoplastic Polyurethane (TPU) containers to explore how SMFC can support tactile interaction. These artifacts aim to transform applied gestures into the pressure on the cathode-soil interface. We draw inspiration from various soft interfaces [50], by fitting soil into soft containers that provide deformation feedback and allow hand-held interaction, with a rigid lid to transmit forces effectively and enable multi-cathode installation.

As shown in Figure 9, we created two types of containers and two types of lids to accommodate different ways of interaction: (a) a basic container suited for pressing and bending, (b) a twisted container to guide rotational input, (c) a lid supporting both squeezing and twisting, and (d) a dual-cathode lid with a middle divider to prevent contact. The container walls are 1 mm thick to maintain flexibility, and each lid includes a 1 mm groove underneath for secure attachment.

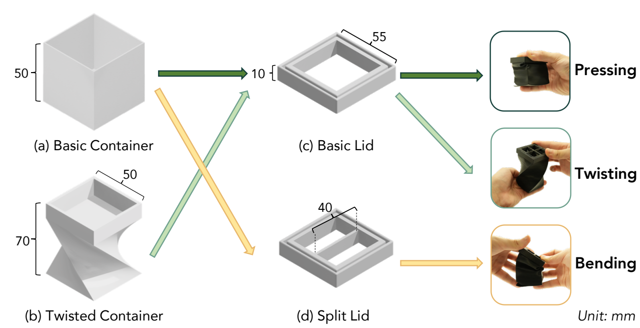


Figure 9: Two types of containers, (a) Basic Container and (b) Twisted Container, can be combined with two types of lids (c) Basic Lid and (d) Split Lid to support interactions including pressing, twisting, and bending.

5.1 Interaction Modes

5.1.1 Pressing. We used the same force measurement device as in Section 4. Given that the 50 mm container is suitable for hand-held interaction, we tested up to 30 N of pressure. As previous studies indicate, pinch and poke forces are unlikely to exceed 50 N as easily as grip strength, making it a more appropriate threshold for typical

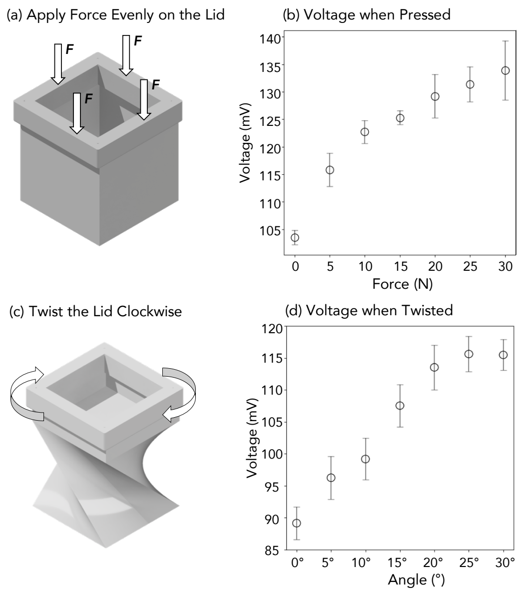


Figure 10: Relationships between (b) voltage and pressure, as well as between (d) voltage and rotation angle when (a) force is applied evenly onto, or (c) twist the lid (white arrows indicating force).

interaction forces [20, 53]. The results of three rounds of measurement are recorded and shown in Figure 10 (b). For small containers and minor force variations, the voltage increase is relatively gradual, but it exhibits responsive feedback within the initial range up to 5 N.

5.1.2 Twisting. To measure the twisting angle of the lid, we used a camera positioned directly above the device to capture the rotational displacement of a marker placed on the edge. We synchronized the timestamps of the video recording with the voltage data to obtain voltage values at specific twisting angles. Figure 10 (d) shows the averaged results of three trials. Due to the rotation, the torque does not directly act on the cathode as vertical pressure does. Instead, it indirectly compresses the cathode through the downward displacement of the lid caused by the deformation of the container. During this process, the deformation of the container structure is not significant at smaller angles but becomes gradually noticeable, leading to a more apparent voltage change.

5.1.3 Bending. We can achieve directional force detection by installing multiple cathodes sharing a common anode in the container. As shown in Figure 11 (a), a partitioned lid separates the cathodes and the soil, which otherwise would cause a short circuit. We applied pressure to one side of the lid and recorded the voltage readings from both cathodes, repeating the measurement three times and recording the results in Figure 11. When pressure is applied to a single side, the opposite cathode is not at the center of the force, leading to a corresponding voltage difference between.

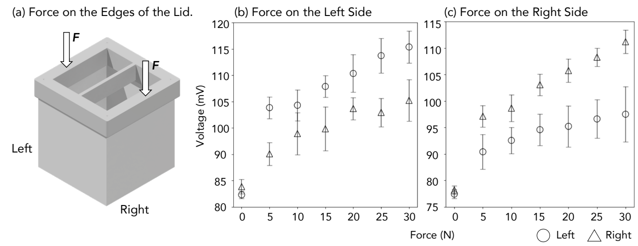


Figure 11: When pressure is applied to the left and right sides of a lid with a central partition (white arrows indicating force). The voltage readings from the electrodes on the left and right sides are represented with circles and triangles, respectively.

5.2 Interaction Over Time

The long-term reliability of SMFC-based interactions is strongly influenced by moisture retention, as evaporation disrupts the electrochemical stability of the system. As VWC decreases, ionic conductivity within the soil weakens, causing a noticeable drop in output voltage [89]. We conducted an experiment under the same setup as described in Section 5.1.1 over 10 consecutive days at room temperature, at around 20°C. It is worth mentioning that the evaporation rate is highly dependent on environmental conditions such as temperature, moisture, wind, soil composition, and the thickness of the soil layer [40]. The results shown here are intended for preliminary reference.

As shown in Figure 12, the VWC was reduced by nearly half, alongside a 49.6 mV decrease in the idle state voltage. This reduction in VWC notably affected the voltage response during the initial pressure application (between 0 N and 5 N). When the soil moisture was higher, the voltage rise was steep and immediate; however, beginning on day 8, the voltage response became considerably flatter. Several factors contribute to this effect. While pressure can enhance the contact between the electrode and the soil surface, it is insufficient to overcome the performance limitations imposed by poor ion conductivity in drier soil. Dehydrated surfaces are also prone to air gaps rather than forming conductive water films at the contact interface. This highlights a key difference between SMFC-based inputs and conventional electronic or mechanical interfaces: unlike conventional electronic interfaces that remain stable post-fabrication, SMFC-based inputs demand continued user attention to maintain moisture and ensure functionality, blurring the boundary between interaction and care.

6 Example Applications

SoilSense enables a range of tangible interaction possibilities by leveraging the unique sensing mechanism of SMFCs. To demonstrate its versatility, we present four example applications that explore different use cases, form factors, and deployment contexts. These prototypes illustrate how SMFC-based sensing can be adapted for customized tangible interfaces, spatial sensing surfaces, ecologically compatible installations, and ambient systems.

Adaptive Form Factor (Figure 13 a): The fabrication of SMFCs is accessible, for which well-established commercial toolkits already exist [48] and numerous DIY tutorials have been available online

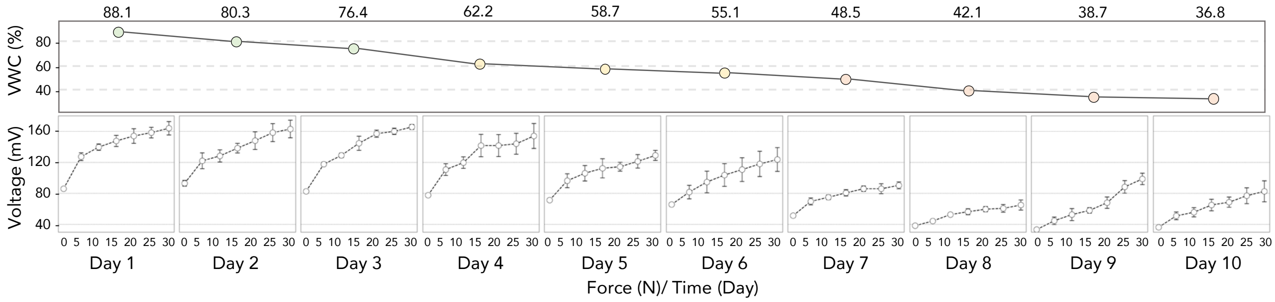


Figure 12: Measurements of VWC across 10 days, with corresponding voltage changes when force is applied to the cathode.

Figure 13: (a) Tactile animal models that display corresponding images when pressed; (b) Tile composed by electrode matrix enables the spatial mapping of pressure distribution; (c) Potted plant that reports soil moisture when touched; (d) Lawn that keeps track of the number of people passing by.

[17, 54, 84]. This allows users to easily create, customize, and upgrade soil-based interfaces. The timely response of voltage change enables the controllers to perform similarly to keyboard buttons, capable of detecting taps and long presses, that can be modular and combined into a larger interactive system. Additionally, the malleability of soil opens up extensive possibilities for container design, enabling interactions to convey an extra layer of meaning depending on the form. In Figure 13 (a), we made a series of educational toys inspired by MudWatt [48], where duck, turtle, and dog models were created with hollow interiors containing SMFCs. When users press the electrodes embedded on the surface, a small LED embedded in the model illuminates, with a visual representation of the corresponding animal appearing on the display.

Expandable Input Channel (Figure 13 b): Section 11 illustrated that embedding multiple cathodes within a single SMFC allows for independent voltage readings, enabling the system to capture richer information, such as detecting bending directions. Pushing this concept further, we created a matrix made up of electrodes similar to a capacitive sensing tile. As shown in Figure 13 (b), 16 cathodes arranged in a 4 × 4 grid were fixed onto a cork sheet with sufficient spacing to ensure electrical isolation between cathodes. Voltages from the cathodes were captured with an Arduino Mega 2560. As a preliminary exploration, this prototype is not yet optimized for precision or resolution because of the wide electrode spacing and lack of signal calibration. However, it can localize coarse input events, such as identifying which quadrant a hand was pressed or where a stack of books was placed. This demonstrates the feasibility of spatially distributed sensing with SMFCs and suggests potential for future development.

Ecological Compatibility (Figure 13 c, d): Interactions with natural environments often lack suitable tangible mediums, making it difficult to establish direct and expressive input channels. For instance, engaging with plants or microbes is challenged by their slow or imperceptible responses to human stimuli [14] and microscopic scale [38]. SoilSense explores one possible way to bridge this gap by leveraging soil as a native input medium. In Figure 13 (c), we embed an SMFC into a potted plant to demonstrate a tangible input channel that responds to user touch. When the cathode is pressed, the system detects the voltage change and reports the moisture level. While previous work has enabled touch input with plants through conductive sensing[1], this approach shifts the sensing focus to the soil, a naturally coexisting layer with plants, avoiding invasive techniques like inserting electrodes into plant tissue [74]. In Figure 13 (d), we created a prototype where electrodes were embedded underneath a patch of lawn. When someone walks across the surface, the pressure applied to the cathode produces a voltage spike, which can be used to estimate traffic. While current SMFC implementations include non-biodegradable components such as carbon felt and copper wires, they demonstrate how soil can function as a sensing layer in ecologically compatible interface deployments.

7 Discussion

SoilSense introduces a novel way of using SMFCs not just as energy sources, but as a sensing mechanism. Beyond validating this behavior through voltage response experiments and functional prototypes, this section reflects on its broader design implications. We discuss how fabrication choices align with DIY and sustainable values, how the dual nature of the voltage signal influences interaction design, and how different power supply strategies shape possible deployment scenarios. Together, these perspectives help position our contribution within the growing space of ecologically grounded interaction technologies.

7.1 Design and Fabrication Considerations

7.1.1 Supporting DIY Practices and Accessibility. Although DIY fabrication could be more laborious and time-consuming compared to the commercial-off-the-shelf (COTS) products, crafting with accessible material and technology has been widely promoted as democratizing technology, empowering communities, encouraging self-expression, and aligning with ecological values [25, 43, 64, 71]. As discussed in Section 6 *a* on *DIY-friendly interfaces*, SMFCs are highly accessible and accompanied by numerous tutorials. Their core material, soil, is readily available and can be returned to the environment after disassembly; The carbon felt electrodes are inexpensive (approximately \$0.1/cm^2) and reusable; Microcontrollers used for voltage measurement are typically included in basic electronics kits, often found in educational or maker spaces. However, certain considerations must still be taken into account during fabrication. While the adaptive form factor of soil allows SMFCs to be embedded into a wide variety of containers, this flexibility does not come without constraints — the basic structural and operational requirements of SMFCs must still be respected. For example, when embedding SMFCs into objects, the volume should not be too small (e.g., less than one cubic centimeter); or, when placed inside a soft container, care must be taken to ensure that deformation does not expose the anode to air. These design decisions require designers to have a fundamental understanding of SMFC properties. Additionally, efforts to build fully self-powered systems or optimize energy output introduce added complexity [86]. Such developments shift SMFCs beyond the beginner-friendly DIY domain, increasingly relying on specialized toolkits and power management techniques to support intermittent computing [30, 41, 60].

7.1.2 Sustainability and Alternative Materials. There has been a well-established connection between sustainable design and DIY practices, as both frequently leverage accessible, non-industrial materials. In our current prototypes, several key components, including carbon felt electrodes and copper wires, which are not biodegradable or toxic to plants, and thus the SMFC cannot be considered fully sustainable in its present form. Biodegradable solutions promoted in sustainable design often introduce a trade-off with durability. For instance, carbon felt electrodes, critical for SMFC stability and electrochemical performance [32], are highly resistant to degradation. Most current biodegradable electronics are intended for above-ground use and designed to safely decompose into non-toxic compounds within the soil environment [77, 79], precisely the environment where SMFCs are expected to operate reliably. Nevertheless, for electronics operating outside the soil, there have been degradable substitutes of conductors [31, 77] and capacitors [1].

Regarding SMFC containers, the 3D-printed TPU materials used in Section 5 offer convenience in prototyping, but are not ideal for a fully biodegradable design. Alternatives, including soil-derived ceramics or organic materials such as mycelium [27, 83] or food waste [10, 70], could better align with biodesign principles in future practice. We see material sustainability as a key area for future development, particularly for deploying SoilSense in long-term or environmentally integrated contexts.

7.2 Interpretation of the Voltage Signal

The voltage variations in SMFCs exhibit dual-layered information: a baseline drift due to environmental factors, and rapid transients in response to applied pressure. While the former has been characterized [23, 45], our investigation focuses on the dynamic voltage signal under force input. As described in Section 5, container geometry modulates how user-applied gestures are translated into pressure on the cathode. However, the system can not distinguish between different forms of force transmission (e.g., pressing or twisting) based on the resulting signal alone. This limitation is addressed through the mechanical encoding of interaction types, similar to prior work in mechanically augmented sensing systems [26, 73, 95]. These designs emphasize customization and adaptability, enabling quick modifications through components like springs, threads, or sliders to create buttons or knobs. Furthermore, we demonstrated the scalability of the sensing architecture using a 4 x 4 cathode grid, analogous to capacitive matrices [90], enabling coarse spatial sensing. As such, while the sensing mechanism is versatile and structurally reconfigurable, its signal interpretation is tightly coupled with the physical design, making it highly adaptable yet context-bound, limiting abstraction across designs.

In addition to immediate pressure-induced voltage changes, SMFC-based sensing is influenced by slower environmental processes such as soil moisture variation. As demonstrated in Sections 4.4 and 5.2,

[1] https://makeymakey.com/

VWC affects both the baseline voltage and the system's responsiveness to mechanical input—higher VWC results in stronger and faster signal changes, while drier soil leads to weaker and delayed responses. This temporal layering introduces both a short-term interaction channel and a slower environmental modulation, which designers may leverage to create systems that respond to both user input and ambient conditions.

7.3 Implications Under Different Power Modes

As a type of long-standing energy harvesting device, SMFCs have been extensively studied across disciplines on their power generation [12, 22, 33, 34, 65, 89, 93]. While this paper does not aim to improve SMFCs as energy harvesters, energy availability remains a practical constraint for deploying SoilSense in real-world settings. In many cases, power limitations directly shape how interactions can be designed, affecting their frequency, duration, and feedback mechanisms [19, 75, 94]. Therefore, we briefly examine how different energy configurations impact the viability of SMFCs as an input method and reflect on the trade-offs between system expressiveness and self-sustainability. Therefore, we limit ourselves to a brief discussion and a preliminary simulation to examine the feasibility of self-sustainability using SMFCs as the interaction method across varying energy budgets.

However, evaluating whether a system can be self-sustained cannot be separated from its operational patterns and the interaction modes it supports. The energy harvesting efficiency, the frequency of interaction events, and the energy consumption per event are the key determining factors. Ideally, when the harvested power is sufficient to meet the energy demand of individual interaction events, the system can achieve self-sustained operation without external power. However, as the available power decreases, either the frequency of interactions must be reduced, or each interaction should be redesigned to require less energy. If the energy required by a single interaction exceeds the capacitor's storage capacity, the system will inevitably depend on an additional battery or a stable power source.

The power generation of SMFCs is subject to a wide range of factors, including microbial composition, electrode surface area, and environmental variables, making it difficult to draw definitive conclusions from existing literature [89]. In this section, we conducted a charging efficiency test using the Basic Container described in Section 5, aiming to reflect the performance in small-scale, uncontrolled DIY settings. The connection schematic is shown in Figure 15. We connected a 2 kΩ resistor to maximize the output power following Lin et al. [45]. We used an ADP5090-2-EVALZ energy harvester with a built-in 0.1 F capacitor. A button cell battery was added to bypass the cold start. The voltage across the load was monitored using an MSP-EXP430FR4133 microcontroller [6, 18], which was externally powered via USB and not supplied by the SMFC, through its ADC. The program running on the microcontroller was adapted from an official Texas Instruments example project[2], and its energy consumption was monitored using the EnergyTrace[3].

Based on an estimation approach similar to that used by Yen and Jaliff et al. [89], we found that the power generated around 30 μW of power when using three containers, which is notably lower than the results of several hundred μW indicated by previous works [33, 34]. The discrepancy may be attributed to the limited size of the containers and the absence of a custom-designed energy harvester tailored for SMFCs. On the microcontroller side, we measured an average power consumption of 0.96 mW of ADC at a sampling rate of 30 Hz, over the course of an hour. Together with this information, we discuss the aspect of interaction design under three power modes: *Fully Self-powered*, *Partially Self-powered*, and *Plugged* (Figure 14).

7.3.1 Minimal Interaction in Fully Self-powered Mode. When aiming for fully self-powered operation, trade-offs must be made in interaction frequency and duration to allocate sufficient time for the SMFC to recharge. For instance, as the example shown in Section 6 *d*, based on our earlier estimation, even for a minimal system that disregards wireless transmission, approximately 16 hours of charging would be required to sustain a single interaction lasting 3 seconds. If the interaction duration is reduced to 1 second, approximately 7 hours of charging time would be needed. This type of infrequent interaction is suitable for scenarios with minimal human intervention.

While powering sophisticated interfaces solely with SMFCs is challenging, there are still methods that we can use to increase the interaction frequency by maximizing the charging power and minimizing the energy consumption for the system operation. For instance, the empirical power density of SMFCs is approximately 3 mW/m^2 [65]. By deploying larger-scale SMFCs or connecting multiple cells in series, it is theoretically possible to harvest significantly more energy than demonstrated in our charging example discussed above. Prior studies have demonstrated that, with techniques such as supplementing with organic substrates, SMFCs have successfully powered devices like e-ink displays consuming tens of mWs [3, 47], or enabled LoRa-based wireless sensor data transmission [59]. Likewise, in terms of reducing consumption, developers can incorporate ultra-low power technologies, such as using RF backscatter for data transmission [35, 36] or analog computing systems [4, 29].

7.3.2 Extending Lifetime Through Partially Self-powered Mode. This configuration reflects a practical middle ground. While full autonomy may not always be feasible, partial harvesting can meaningfully reduce maintenance and extend deployment lifetime in moderate-use settings. We describe the partially self-powered mode as a system that mainly relies on external power sources while incorporating an energy harvester as a supplementary power supply. In this situation, while the system design could surpass the energy budget of the SMFC, the harvested energy serves to prolong battery life and reduce the frequency of replacements. It serves as a transitional stage, aiming to strike a balance between energy independence and operational flexibility, making it suitable for scenarios where moderate interaction frequency is required, yet access to stable power sources is limited.

7.3.3 Maximizing Interactivity with Plugged Power. The plugged mode abandons the SMFC's role as an energy harvesting device, simplifying system implementation by removing the energy harvester module. A stable power source allows us to design systems with energy consumption that is much higher than SMFCs can

[2] https://dev.ti.com/tirex/explore
[3] https://www.ti.com/tool/ENERGYTRACE

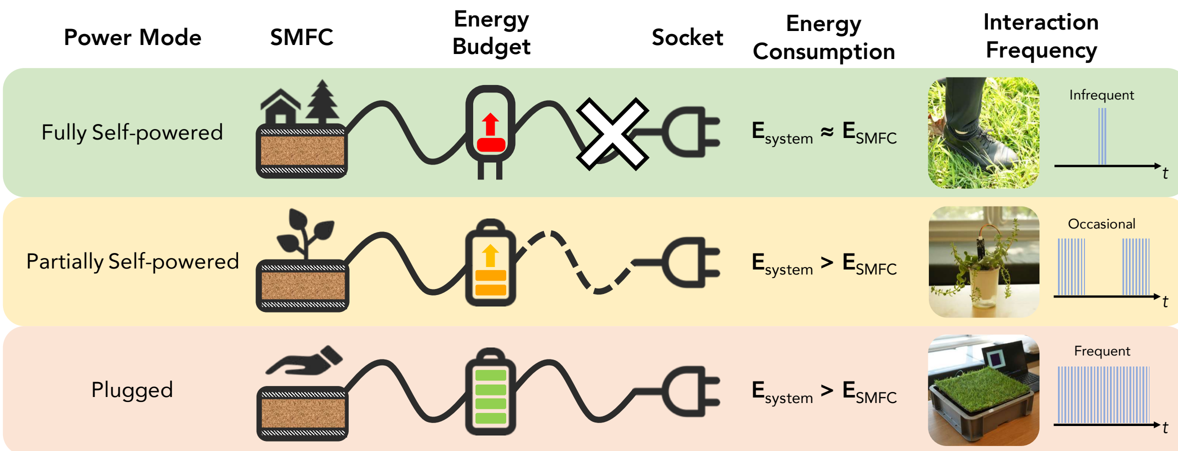


Figure 14: Three types of power mode: *Fully Self-powered, Partially Self-powered* and *Plugged* shaping their corresponding scenarios and ways of interaction. Energy budget refers to the expected amount of energy available for the system under the mode; Socket indicates whether the device requires connection to a stable power source; Energy consumption shows the relationship between the whole system's energy demand (E_{system}) and the SMFC could afford (E_{SMFC}); Interaction frequency use the time axis (t) and blue bars to indicate interaction intensity the system intended to support within a period of time.

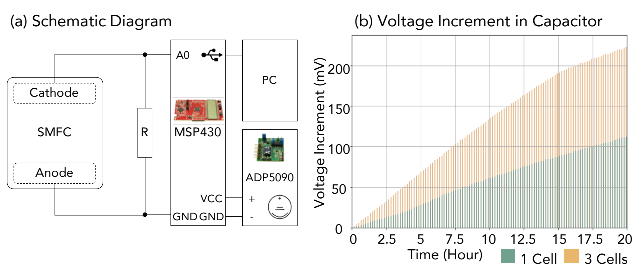


Figure 15: (a) Connection schematic of measuring SMFC output voltage with microcontroller. An external USB powers the MSP430 to enable sampling during operation.; (b) Voltage across the built-in capacitor in ADP5090 over 20 hours with a single cell and 3 cells, respectively.

afford. Although this mode sacrifices energy autonomy, it unlocks richer interaction possibilities, aligning with scenarios where responsiveness and complexity are prioritized over sustainability, such as educational or biodesign artifacts [2, 16, 74]. These systems usually place more emphasis on sensory experience and user engagement through multimedia approaches, such as LED displays, actuators, and speakers.

8 Limitations & Future Work

Firstly, while SMFCs are intrinsically energy-harvesting devices, our focus is not on optimizing their power output or enabling fully self-powered systems. This choice was intentional: focusing on the sensing potential of SMFCs allows us to explore a new interaction paradigm before addressing the more complex challenge of achieving energy autonomy. Instead, we discuss energy only in the context of interaction design. Future work could further investigate more sophisticated energy-aware interaction strategies and system-level sustainability under different power constraints.

Secondly, another important direction lies in advancing the interpretation and processing of SMFC voltage signals. While we can establish a relationship between the force applied to the cathode and the resulting voltage changes, it remains challenging for us to perform precise regression, such as predicting the exact magnitude of pressure based on the voltage variations. This limitation stems from the variability in the SMFC fabrication process, which trades off measurement precision for accessibility and ease of making. In this study, we used a threshold-based calibration approach similar to other sensors influenced by fabrication variability and environmental drift when developing example applications [50, 62, 97]. However, a more systematic methodology for signal interpretation, such as integrating machine learning or multi-SMFC fusion, could help translate voltage changes into more precise or expressive input semantics.

Thirdly, while we showcased example applications that demonstrate how SoilSense could integrate into everyday contexts, we have not conducted formal user studies to evaluate the usability, intuitiveness, or acceptance of soil-based interfaces. As SoilSense operates through a novel tactile paradigm and material substrate, future work could examine how users perceive soil as a medium for input, and how interaction ergonomics, feedback latency, or visual cues influence user experience.

Lastly, although we demonstrated the potential of embedding SMFCs into plant pots and lawn environments in Section 6, these prototypes serve as conceptual explorations rather than systematically validated deployments. We did not evaluate how well SMFCs co-exist with actual vegetation over extended periods, nor how outdoor environmental factors, such as sunlight, temperature fluctuation, and weather, affect sensing performance. While prior work suggests SMFC's compatibility with plant ecosystems [6, 59], future implementation is needed to assess how the dual role of soil as both substrate for living organisms and sensing medium influences real-world robustness and applicability.

9 Conclusion

In this paper, we presented *SoilSense*, a novel approach that appropriates Soil-based Microbial Fuel Cells (SMFCs) as tangible interfaces. By characterizing the voltage response to pressure across different electrode configurations and environmental conditions, we demonstrated how soil can support rich interactions. Building on this mechanism, we proposed a set of design patterns, such as adaptive form factors, expandable input channels, and ecological compatibility, that outline new interaction possibilities with soil-based interfaces. Our prototypes explored applications that cover a wide range of applicable scenarios, supported by a discussion of energy-aware interaction under different power modes. While future challenges remain in signal processing, fabrication consistency, or real-world deployment, this work positions soil as both a sensing and structural medium, contributing to the broader vision of nature-integrated computing. We believe this opens new design opportunities for interactive systems that are not only functional but ecologically situated and materially expressive.

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References

[1] Xavier Aeby, Alexandre Poulin, Gilberto Siqueira, Michael K Hausmann, and Gustav Nyström. 2021. Fully 3D printed and disposable paper supercapacitors. *Advanced Materials* 33, 26 (2021), 2101328. doi:10.1002/adma.202101328

[2] Leonardo Angelini, Maurizio Caon, Stefania Caparrotta, Omar Abou Khaled, and Elena Mugellini. 2016. Multi-sensory EmotiPlant: multimodal interaction with augmented plants. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct* (Heidelberg, Germany) *(UbiComp '16)*. Association for Computing Machinery, New York, NY, USA, 1001–1009. doi:10.1145/2968219.2968266

[3] Wilgince Apollon, Sathish-Kumar Kamaraj, Héctor Silos-Espino, Catarino Perales-Segovia, Luis L. Valera-Montero, Víctor A. Maldonado-Ruelas, Marco A. Vázquez-Gutiérrez, Raúl A. Ortiz-Medina, Silvia Flores-Benítez, and Juan F. Gómez-Leyva. 2020. Impact of Opuntia species plant bio-battery in a semi-arid environment: Demonstration of their applications. *Applied Energy* 279 (2020), 115788. doi:10.1016/j.apenergy.2020.115788

[4] Nivedita Arora, Ali Mirzazadeh, Injoo Moon, Charles Ramey, Yuhui Zhao, Daniela C. Rodriguez, Gregory D. Abowd, and Thad Starner. 2021. MARS: Nano-Power Battery-free Wireless Interfaces for Touch, Swipe and Speech Input. In *The 34th Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '21)*. Association for Computing Machinery, New York, NY, USA, 1305–1325. doi:10.1145/3472749.3474823

[5] Nivedita Arora, Steven L. Zhang, Fereshteh Shahmiri, Diego Osorio, Yi-Cheng Wang, Mohit Gupta, Zhengjun Wang, Thad Starner, Zhong Lin Wang, and Gregory D. Abowd. 2018. SATURN: A Thin and Flexible Self-powered Microphone Leveraging Triboelectric Nanogenerator. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 2, 2, Article 60 (July 2018), 28 pages. doi:10.1145/3214263

[6] Daniel Ayala-Ruiz, Alejandro Castillo Atoche, Erica Ruiz-Ibarra, Edith Osorio de la Rosa, Javier Vázquez Castillo, and Zoran Stamenkovic. 2019. A Self-Powered PMFC-Based Wireless Sensor Node for Smart City Applications. *Wirel. Commun. Mob. Comput.* 2019 (jan 2019), 10 pages. doi:10.1155/2019/8986302

[7] Amr S. Azzouz, Raymond J. Krizek, and Ross B. Corotis. 1976. Regression Analysis of Soil Compressibility. *Soils and Foundations* 16, 2 (1976), 19–29. doi:10.3208/sandf1972.16.2_19

[8] Fiona Bell, Latifa Al Naimi, Ella McQuaid, and Mirela Alistar. 2022. Designing with Alganyl. In *Proceedings of the Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Daejeon, Republic of Korea) *(TEI '22)*. Association for Computing Machinery, New York, NY, USA, Article 2, 14 pages. doi:10.1145/3490149.3501308

[9] Fiona Bell, Joshua Coffie, and Mirela Alistar. 2024. Bio-Digital Calendar: Attuning to Nonhuman Temporalities for Multispecies Understanding. In *Proceedings of the Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Cork, Ireland) *(TEI '24)*. Association for Computing Machinery, New York, NY, USA, Article 38, 15 pages. doi:10.1145/3623509.3633386

[10] Fiona Bell, Camila Friedman-Gerlicz, Lauren Urenda, and Leah Buechley. 2025. 3D Printing Eggshells: Exploring Eco-Socio-Technical Relations through Biomaterial Design. In *Proceedings of the 2025 CHI Conference on Human Factors in Computing Systems (CHI '25)*. Association for Computing Machinery, New York, NY, USA, Article 299, 19 pages. doi:10.1145/3706598.3714290

[11] Fiona Bell, Netta Ofer, and Mirela Alistar. 2022. ReClaym our Compost: Biodegradable Clay for Intimate Making. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 454, 15 pages. doi:10.1145/3491102.3517711

[12] Chen Boneng, Weiling Cai, and A. Garg. 2023. Relationship between bioelectricity and soil-water characteristics of biochar-aided plant microbial fuel cell. *Acta Geotechnica* 18 (01 2023), 3529–3542. doi:10.1007/s11440-022-01787-z

[13] Hronn Brynjarsdottir, Maria Håkansson, James Pierce, Eric Baumer, Carl DiSalvo, and Phoebe Sengers. 2012. Sustainably unpersuaded: how persuasion narrows our vision of sustainability. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Austin, Texas, USA) *(CHI '12)*. Association for Computing Machinery, New York, NY, USA, 947–956. doi:10.1145/2207676.2208539

[14] Michelle Chang, Chenyi Shen, Aditi Maheshwari, Andreea Danielescu, and Lining Yao. 2022. Patterns and Opportunities for the Design of Human-Plant Interaction. In *Proceedings of the 2022 ACM Designing Interactive Systems Conference* (Virtual Event, Australia) *(DIS '22)*. Association for Computing Machinery, New York, NY, USA, 925–948. doi:10.1145/3532106.3533555

[15] Zhaoxin Chang, Fusang Zhang, Jie Xiong, Junqi Ma, Beihong Jin, and Daqing Zhang. 2022. Sensor-free Soil Moisture Sensing Using LoRa Signals. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 6, 2, Article 45 (jul 2022), 27 pages. doi:10.1145/3534608

[16] Dominique Chen, Young ah Seong, Hiraku Ogura, Yuto Mitani, Naoto Sekiya, and Kiichi Moriya. 2021. Nukabot: Design of Care for Human-Microbe Relationships. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI EA '21)*. Association for Computing Machinery, New York, NY, USA, Article 291, 7 pages. doi:10.1145/3411763.3451605

[17] Cindy Collins. 2015. *Creating a Microbial Fuel Cell.* https://www.youtube.com/watch?v=-cPvp3_WYPg

[18] Pierangela Cristiani, Iwona Gajda, John Greenman, Francesca Pizza, Paolo Bonelli, and Ioannis Ieropoulos. 2019. Long Term Feasibility Study of In-field Floating Microbial Fuel Cells for Monitoring Anoxic Wastewater and Energy Harvesting. *Frontiers in Energy Research* 7 (2019). doi:10.3389/fenrg.2019.00119

[19] Jasper de Winkel, Vito Kortbeek, Josiah Hester, and Przemysław Pawełczak. 2020. Battery-Free Game Boy. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 4, 3, Article 111 (Sept. 2020), 34 pages. doi:10.1145/3411839

[20] Angela DiDomenico and Maury Nussbaum. 2008. Estimation of forces exerted by the fingers using standardised surface electromyography from the forearm. *Ergonomics* 51 (07 2008), 858–871. doi:10.1080/00140130801915980

[21] Carl DiSalvo, Phoebe Sengers, and Hrönn Brynjarsdóttir. 2010. Mapping the landscape of sustainable HCI. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Atlanta, Georgia, USA) *(CHI '10)*. Association for Computing Machinery, New York, NY, USA, 1975–1984. doi:10.1145/1753326.1753625

[22] Sara J. Dunaj, Joseph J. Vallino, Mark E. Hines, Marcus Gay, Christine Kobyljanec, and Juliette N. Rooney-Varga. 2012. Relationships between Soil Organic Matter, Nutrients, Bacterial Community Structure, And the Performance of Microbial Fuel Cells. *Environmental Science & Technology* 46, 3 (07 Feb 2012), 1914–1922. doi:10.1021/es2032532

[23] Jakub Dziegielowski, Benjamin Metcalfe, Paola Villegas-Guzman, Carlos A. Martínez-Huitle, Adryane Gorayeb, Jannis Wenk, and Mirella Di Lorenzo. 2020. Development of a functional stack of soil microbial fuel cells to power a water treatment reactor: From the lab to field trials in North East Brazil. *Applied Energy* 278 (2020), 115680. doi:10.1016/j.apenergy.2020.115680

[24] Jaydel Marge Francisco, Janelle Macariola, and Kristopher Ray Pamintuan. 2023. Effect of Soil Properties on the Power Output Performance of Plant-Microbial Fuel Cells and Growth of Pechay (Brassica Rapa Subsp. Chinensis). In *2023 11th International Conference on Smart Grid and Clean Energy Technologies (ICSGCE)*. IEEE, 72–78.

[25] William Gaver, Andy Boucher, Michail Vanis, Andy Sheen, Dean Brown, Liliana Ovalle, Naho Matsuda, Amina Abbas-Nazari, and Robert Phillips. 2019. My Naturewatch Camera: Disseminating Practice Research with a Cheap and Easy DIY Design. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–13. doi:10.1145/3290605.3300532

[26] Jun Gong, Olivia Seow, Cedric Honnet, Jack Forman, and Stefanie Mueller. 2021. MetaSense: Integrating Sensing Capabilities into Mechanical Metamaterial. In *The 34th Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '21)*. Association for Computing Machinery, New York, NY, USA, 1063–1073. doi:10.1145/3472749.3474806

[27] Phillip Gough, Praneeth Bimsara Perera, Michael A. Kertesz, and Anusha Withana. 2023. Design, Mould, Grow!: A Fabrication Pipeline for Growing 3D Designs Using Myco-Materials. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 851, 15 pages. doi:10.1145/3544548.3580958

[28] Eduard Georges Groutars, Carmen Clarice Risseeuw, Colin Ingham, Raditijo Hamidjaja, Willemijn S. Elkhuizen, Sylvia C. Pont, and Elvin Karana. 2022. Flavorium: An Exploration of Flavobacteria's Living Aesthetics for Living Color Interfaces. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 99, 19 pages. doi:10.1145/3491102.3517713

[29] Cihan Berk Güngör, Patrick P. Mercier, and Hakan Töreyin. 2021. A 3.75 nW Analog Electrocardiogram Processor Facilitating Stochastic Resonance for Real-Time R-wave Detection. In *2021 IEEE Biomedical Circuits and Systems Conference (BioCAS)*. 1–6. doi:10.1109/BioCAS49922.2021.9645028

[30] Josiah Hester and Jacob Sorber. 2017. Flicker: Rapid Prototyping for the Batteryless Internet-of-Things. In *Proceedings of the 15th ACM Conference on Embedded Network Sensor Systems* (Delft, Netherlands) *(SenSys '17)*. Association for Computing Machinery, New York, NY, USA, Article 19, 13 pages. doi:10.1145/3131672.3131674

[31] Liangbing Hu, Jang Wook Choi, Yuan Yang, Sangmoo Jeong, Fabio La Mantia, Li-Feng Cui, and Yi Cui. 2009. Highly conductive paper for energy-storage devices. *Proceedings of the National Academy of Sciences* 106, 51 (2009), 21490–21494. arXiv:https://www.pnas.org/doi/pdf/10.1073/pnas.0908858106 doi:10.1073/pnas.0908858106

[32] Thi Xuan Huong Le, Mikhael Bechelany, and Marc Cretin. 2017. Carbon felt based-electrodes for energy and environmental applications: A review. *Carbon* 122 (2017), 564–591. doi:10.1016/j.carbon.2017.06.078

[33] Simeon Imologie, Agidi Gbabo, and Okoro Shekwaga. 2016. Performance of a Single Chamber Soil Microbial Fuel Cell at Varied External Resistances for Electric Power Generation. *Journal of Renewable Energy and Environment* 3 (08 2016), 53–58. doi:10.30501/jree.2016.70092

[34] Yun-Bin Jiang, Wen-Hui Zhong, Cheng Han, and Huan Deng. 2016. Characterization of Electricity Generated by Soil in Microbial Fuel Cells and the Isolation of Soil Source Exoelectrogenic Bacteria. *Frontiers in Microbiology* 7 (2016). doi:10.3389/fmicb.2016.01776

[35] Colleen Josephson, Manikanta Kotaru, Keith Winstein, Sachin Katti, and Ranveer Chandra. 2021. Low-cost In-ground Soil Moisture Sensing with Radar Backscatter Tags. In *Proceedings of the 4th ACM SIGCAS Conference on Computing and Sustainable Societies* (Virtual Event, Australia) *(COMPASS '21)*. Association for Computing Machinery, New York, NY, USA, 299–311. doi:10.1145/3460112.3472326

[36] Colleen Josephson, Weitao Shuai, Gabriel Marcano, Pat Pannuto, Josiah Hester, and George Wells. 2022. The Future of Clean Computing May Be Dirty. *GetMobile: Mobile Comp. and Comm.* 26, 3 (oct 2022), 9–15. doi:10.1145/3568113.3568117

[37] Raphael Kim, Pat Pataranutaporn, Jack Forman, Seung Ah Lee, Ingmar H. Riedel-Kruse, Mirela Alistar, Eldy S. Lazaro Vasquez, Katia Vega, Roland van Dierendonck, Gilad Gome, Oren Zuckerman, Angela Vujic, David S. Kong, Pattie Maes, Hiroshi Ishii, Misha Sra, and Stefan Poslad. 2021. Microbe-HCI: Introduction and Directions for Growth. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI EA '21)*. Association for Computing Machinery, New York, NY, USA, Article 155, 4 pages. doi:10.1145/3411763.3450408

[38] Raphael Kim, Clarice Risseeuw, Eduard Georges Groutars, and Elvin Karana. 2023. Surfacing Livingness in Microbial Displays: A Design Taxonomy for HCI. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 156, 21 pages. doi:10.1145/3544548.3581417

[39] Takaki Kimura and Yasuaki Kakehi. 2014. MOSS-xels: slow changing pixels using the shape of racomitrium canescens. In *ACM SIGGRAPH 2014 Posters* (Vancouver, Canada) *(SIGGRAPH '14)*. Association for Computing Machinery, New York, NY, USA, Article 20, 1 pages. doi:10.1145/2614217.2630572

[40] Junsei Kondo and Nobuko Saigusa. 1994. Modelling the evaporation from bare soil with a formula for vaporization in the soil pores. *Journal of the Meteorological Society of Japan. Ser. II* 72, 3 (1994), 413–421.

[41] Vito Kortbeek, Abu Bakar, Stefany Cruz, Kasim Sinan Yildirim, Przemysław Pawełczak, and Josiah Hester. 2020. BFree: Enabling Battery-free Sensor Prototyping with Python. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 4, 4, Article 135 (Dec. 2020), 39 pages. doi:10.1145/3432191

[42] Satoshi Kuribayashi, Yusuke Sakamoto, and Hiroya Tanaka. 2007. I/O plant: a tool kit for designing augmented human-plant interactions. In *CHI '07 Extended Abstracts on Human Factors in Computing Systems* (San Jose, CA, USA) *(CHI EA '07)*. Association for Computing Machinery, New York, NY, USA, 2537–2542. doi:10.1145/1240866.1241037

[43] Stacey Kuznetsov and Eric Paulos. 2010. Rise of the expert amateur: DIY projects, communities, and cultures. In *Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries* (Reykjavik, Iceland) *(NordiCHI '10)*. Association for Computing Machinery, New York, NY, USA, 295–304. doi:10.1145/1868914.1868950

[44] Kathryn Lawson, Ruggero Rossi, John M. Regan, and Bruce E. Logan. 2020. Impact of cathodic electron acceptor on microbial fuel cell internal resistance. *Bioresource Technology* 316 (2020), 123919. doi:10.1016/j.biortech.2020.123919

[45] Fu-To Lin, Yu-Chun Kuo, Jen-Chien Hsieh, Hsi-Yuan Tsai, Yu-Te Liao, and Huang Chen Lee. 2015. A Self-Powering Wireless Environment Monitoring System Using Soil Energy. *IEEE Sensors Journal* 15 (07 2015), 3751–3758. doi:10.1109/JSEN.2015.2398845

[46] Jasmine Lu and Pedro Lopes. 2022. Integrating Living Organisms in Devices to Implement Care-based Interactions. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology* (Bend, OR, USA) *(UIST '22)*. Association for Computing Machinery, New York, NY, USA, Article 28, 13 pages. doi:10.1145/3526113.3545629

[47] Gabriel Marcano and Pat Pannuto. 2021. Soil Power? Can Microbial Fuel Cells Power Non-Trivial Sensors?. In *Proceedings of the 1st ACM Workshop on No Power and Low Power Internet-of-Things* (New Orleans, LA, USA) *(LP-IoT'21)*. Association for Computing Machinery, New York, NY, USA, 8–13. doi:10.1145/3477085.3478989

[48] Magical Microbes. 2024. *MudWatt: Grow a Living Fuel Cell.* https://www.magicalmicrobes.com/products/mudwatt-clean-energy-from-mud

[49] Ana Iris Correa Muler. 2016. *Effect of experimental parameters on the voltage output of a sediment microbial fuel cell.* Ph. D. Dissertation. Reykjavik University.

[50] Satoshi Nakamaru, Ryosuke Nakayama, Ryuma Niiyama, and Yasuaki Kakehi. 2017. FoamSense: Design of Three Dimensional Soft Sensors with Porous Materials. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology* (Québec City, QC, Canada) *(UIST '17)*. Association for Computing Machinery, New York, NY, USA, 437–447. doi:10.1145/3126594.3126666

[51] Hye Yeon Nam, JaNiece Campbell, Andrew M. Webb, and Brendan Harmon. 2023. FloraWear: Wearable Living Interface. In *Proceedings of the Seventeenth International Conference on Tangible, Embedded, and Embodied Interaction* (Warsaw, Poland) *(TEI '23)*. Association for Computing Machinery, New York, NY, USA, Article 30, 15 pages. doi:10.1145/3569009.3572801

[52] Madalina Nicolae, Vivien Roussel, Marion Koelle, Samuel Huron, Jürgen Steimle, and Marc Teyssier. 2023. Biohybrid Devices: Prototyping Interactive Devices with Growable Materials. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (San Francisco, CA, USA) *(UIST '23)*. Association for Computing Machinery, New York, NY, USA, Article 31, 15 pages. doi:10.1145/3586183.3606774

[53] Tove Nilsen, Merete Hermann, Camilla Eriksen, Hanne Dagfinrud, Petter Mowinckel, and Ingvild Kjeken. 2011. Grip force and pinch grip in an adult population: Reference values and factors associated with grip force. *Scandinavian journal of occupational therapy* 19 (02 2011), 288–296. doi:10.3109/11038128.2011.553687

[54] Paul Nylund. 2013. *DIY Microbial Fuel Cell (easy).* https://www.youtube.com/watch?v=yDarDR4vi1A

[55] Eudesio O. Vilar, Freitas de, Lirio de, and Sousa de. 1998. Study of the electrical conductivity of graphite felt employed as a porous electrode. *Brazilian Journal of Chemical Engineering* 15 (09 1998). doi:10.1590/S0104-66321998000300007

[56] Netta Ofer and Mirela Alistar. 2024. Tracing as a Strategy for Orienting to Nonhuman Perspectives. In *Proceedings of the 2024 ACM Designing Interactive Systems Conference* (Copenhagen, Denmark) *(DIS '24)*. Association for Computing Machinery, New York, NY, USA, 1087–1100. doi:10.1145/3643834.3661621

[57] Netta Ofer, Fiona Bell, and Mirela Alistar. 2021. Designing Direct Interactions with Bioluminescent Algae. In *Proceedings of the 2021 ACM Designing Interactive Systems Conference* (Virtual Event, USA) *(DIS '21)*. Association for Computing Machinery, New York, NY, USA, 1230–1241. doi:10.1145/3461778.3462090

[58] Daniëlle Ooms, Bahareh Barati, Miguel Bruns, and Teresa van Dongen. 2022. From Concern to Care: A Transformative Reflection on Designing-with the Living. In *Nordic Human-Computer Interaction Conference* (Aarhus, Denmark) *(NordiCHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 96, 15 pages. doi:10.1145/3546155.3547285

[59] Edith Osorio-de-la Rosa, Javier Vázquez-Castillo, Alejandro Castillo-Atoche, Julio Heredia-Lozano, Andrea Castillo-Atoche, Guillermo Becerra-Nuñez, and Romeli Barbosa. 2021. Arrays of Plant Microbial Fuel Cells for Implementing Self-Sustainable Wireless Sensor Networks. *IEEE Sensors Journal* 21, 2 (2021), 1965–1974. doi:10.1109/JSEN.2020.3019986

[60] Jung Wook Park, Sienna Xin Sun, Tingyu Cheng, Dong Whi Yoo, Jiawei Zhou, Youngwook Do, Gregory D. Abowd, and Rosa I. Arriaga. 2023. Exergy: A Toolkit to Simplify Creative Applications of Wind Energy Harvesting. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 7, 1, Article 25 (March 2023), 28 pages. doi:10.1145/3580814

[61] Pat Pataranutaporn, Angela Vujic, David S. Kong, Pattie Maes, and Misha Sra. 2020. Living Bits: Opportunities and Challenges for Integrating Living Microorganisms in Human-Computer Interaction. In *Proceedings of the Augmented Humans International Conference* (Kaiserslautern, Germany) *(AHs '20)*. Association for Computing Machinery, New York, NY, USA, Article 30, 12 pages. doi:10.1145/3384657.3384783

[62] Yuecheng Peng, Danchang Yan, Haotian Chen, Yue Yang, Ye Tao, Weitao Song, Lingyun Sun, and Guanyun Wang. 2024. IntelliTex: Fabricating Low-cost and Washable Functional Textiles using A Double-coating Process. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 859, 18 pages. doi:10.1145/3613904.3642759

[63] Birgit Penzenstadler, Jason Plojo, Marinela Sanchez, Ruben Marin, Lam Tran, and Jayden Khakurel. 2018. The afordable DIY resilient smart garden kit. In *Proceedings of the 2018 Workshop on Computing within Limits* (Toronto, Ontario, Canada) *(LIMITS '18)*. Association for Computing Machinery, New York, NY, USA, Article 4, 10 pages. doi:10.1145/3232617.3232619

[64] James Pierce and Eric Paulos. 2015. Making Multiple Uses of the Obscura 1C Digital Camera: Reflecting on the Design, Production, Packaging and Distribution of a Counterfunctional Device. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 2103–2112. doi:10.1145/2702123.2702405

[65] Andrea Pietrelli, Andrea Micangeli, Vincenzo Ferrara, and Alessandro Raffi. 2014. Wireless sensor network powered by a terrestrial microbial fuel cell as a sustainable land monitoring energy system. *Sustainability* 6, 10 (2014), 7263–7275. doi:10.3390/su6107263

[66] M. C. Potter. 1911. Electrical effects accompanying the decomposition of organic compounds. *Proc. R. Soc.* 84 (1911), 260–276. doi:10.1098/rspb.1911.0073

[67] Tucker Rae-Grant, Shuhong Wang, and Lining Yao. 2024. ExCell: High Expansion Ratio Moisture-Responsive Wooden Actuators for DIY Shape-Changing and Deployable Structures. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 516, 14 pages. doi:10.1145/3613904.3642565

[68] R Rickman, J Letey, and L Stolzy. 1965. Soil compaction effects on oxygen diffusion rates and plant growth. *California Agriculture* 19, 3 (1965), 4–6.

[69] Hamid Rismani-Yazdi, Sarah M. Carver, Ann D. Christy, and Olli H. Tuovinen. 2008. Cathodic limitations in microbial fuel cells: An overview. *Journal of Power Sources* 180, 2 (2008), 683–694. doi:10.1016/j.jpowsour.2008.02.074

[70] Michael L. Rivera, S. Sandra Bae, and Scott E. Hudson. 2023. Designing a Sustainable Material for 3D Printing with Spent Coffee Grounds. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference* (Pittsburgh, PA, USA) *(DIS '23)*. Association for Computing Machinery, New York, NY, USA, 294–311. doi:10.1145/3563657.3595983

[71] Daniela Rosner and Jonathan Bean. 2009. Learning from IKEA hacking: i'm not one to decoupage a tabletop and call it a day.. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Boston, MA, USA) *(CHI '09)*. Association for Computing Machinery, New York, NY, USA, 419–422. doi:10.1145/1518701.1518768

[72] Kimiko Ryokai, Peiqi Su, Eungchan Kim, and Bob Rollins. 2014. EnergyBugs: energy harvesting wearables for children. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Toronto, Ontario, Canada) *(CHI '14)*. Association for Computing Machinery, New York, NY, USA, 1039–1048. doi:10.1145/2556288.2557225

[73] Valkyrie Savage, Ryan Schmidt, Tovi Grossman, George Fitzmaurice, and Björn Hartmann. 2014. A series of tubes: adding interactivity to 3D prints using internal pipes. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology* (Honolulu, Hawaii, USA) *(UIST '14)*. Association for Computing Machinery, New York, NY, USA, 3–12. doi:10.1145/2642918.2647374

[74] Jinsil Hwaryoung Seo, Annie Sungkajun, and Jinkyo Suh. 2015. Touchology: Towards Interactive Plant Design for Children with Autism and Older Adults in Senior Housing. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI EA '15)*. Association for Computing Machinery, New York, NY, USA, 893–898. doi:10.1145/2702613.2732883

[75] Fereshteh Shahmiri, Chaoyu Chen, Anandghan Waghmare, Dingtian Zhang, Shivan Mittal, Steven L. Zhang, Yi-Cheng Wang, Zhong Lin Wang, Thad E. Starner, and Gregory D. Abowd. 2019. Serpentine: A Self-Powered Reversibly Deformable Cord Sensor for Human Input. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–14. doi:10.1145/3290605.3300775

[76] Imologie Meshack Simeon, Alfons Weig, and Ruth Freitag. 2022. Optimization of soil microbial fuel cell for sustainable bio-electricity production: combined effects of electrode material, electrode spacing, and substrate feeding frequency on power generation and microbial community diversity. *Biotechnology for Biofuels and Bioproducts* 15, 1 (16 Nov 2022), 124. doi:10.1186/s13068-022-02224-9

[77] Katherine W Song, Aditi Maheshwari, Eric M Gallo, Andreea Danielescu, and Eric Paulos. 2022. Towards Decomposable Interactive Systems: Design of a Backyard-Degradable Wireless Heating Interface. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 100, 12 pages. doi:10.1145/3491102.3502007

[78] Katherine W Song and Eric Paulos. 2021. Unmaking: Enabling and Celebrating the Creative Material of Failure, Destruction, Decay, and Deformation. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 429, 12 pages. doi:10.1145/3411764.3445529

[79] Katherine Wei Song and Eric Paulos. 2023. Vim: Customizable, Decomposable Electrical Energy Storage. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 180, 18 pages. doi:10.1145/3544548.3581110

[80] Tian Song, Yan Zaisheng, Zhi-Wei Zhao, and Helong Jiang. 2011. Construction and operation of freshwater sediment microbial fuel cell for electricity generation. *Bioprocess and biosystems engineering* 34 (06 2011), 621–627. doi:10.1007/s00449-010-0511-x

[81] Carlos Sánchez, Paolo Dessì, Maeve Duffy, and Piet N.L. Lens. 2022. Corrigendum to "Gauging sediment microbial fuel cells using open-circuit auxiliary electrodes" [J. Power Sources 527 (15 April 2022) 231216]. *Journal of Power Sources* 535 (2022), 231474. doi:10.1016/j.jpowsour.2022.231474

[82] Matteo Tucci, Carolina Cruz Viggi, Abraham Esteve Núñez, Andrea Schievano, Korneel Rabaey, and Federico Aulenta. 2021. Empowering electroactive microorganisms for soil remediation: Challenges in the bioelectrochemical removal of petroleum hydrocarbons. *Chemical Engineering Journal* 419 (2021), 130008. doi:10.1016/j.cej.2021.130008

[83] Eldy S. Lazaro Vasquez and Katia Vega. 2019. From plastic to biomaterials: prototyping DIY electronics with mycelium. In *Adjunct Proceedings of the 2019 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2019 ACM International Symposium on Wearable Computers* (London, United Kingdom) *(UbiComp/ISWC '19 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 308–311. doi:10.1145/3341162.3343808

[84] Amphora Video. 2018. *How to Make a Microbial Fuel Cell.* https://www.youtube.com/watch?v=-NIzK91ISdo

[85] Ju Wang, Liqiong Chang, Shourya Aggarwal, Omid Abari, and Srinivasan Keshav. 2020. Soil moisture sensing with commodity RFID systems. In *Proceedings of the 18th International Conference on Mobile Systems, Applications, and Services* (Toronto, Ontario, Canada) *(MobiSys '20)*. Association for Computing Machinery, New York, NY, USA, 273—-285. doi:10.1145/3386901.3388940

[86] Chengshuo Xia, Tian Min, Daxing Zhang, and Congsi Wang. 2024. Understanding the Needs of Novice Developers in Creating Self-Powered IoT. In *Proceedings of the CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 932, 17 pages. doi:10.1145/3613904.3642576

[87] Xiaoying Yang, Jacob Sayono, Jess Xu, Jiahao Nick Li, Josiah Hester, and Yang Zhang. 2022. MiniKers: Interaction-Powered Smart Environment Automation. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 6, 3, Article 149 (Sept. 2022), 22 pages. doi:10.1145/3550287

[88] Yonggang Yang, Lei Yan, Jianhua Song, and Meiying Xu. 2018. Optimizing the electrode surface area of sediment microbial fuel cells. *RSC Advances* 8 (07 2018), 25319–25324. doi:10.1039/C8RA05069D

[89] Bill Yen, Laura Jaliff, Louis Gutierrez, Philothei Sahinidis, Sadie Bernstein, John Madden, Stephen Taylor, Colleen Josephson, Pat Pannuto, Weitao Shuai, George Wells, Nivedita Arora, and Josiah Hester. 2024. Soil-Powered Computing: The Engineer's Guide to Practical Soil Microbial Fuel Cell Design. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 7, 4, Article 196 (jan 2024), 40 pages. doi:10.1145/3631410

[90] Takatoshi Yoshida, Narin Okazaki, Ken Takaki, Masaharu Hirose, Shingo Kitagawa, and Masahiko Inami. 2022. Flexel: A Modular Floor Interface for Room-Scale Tactile Sensing. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology* (Bend, OR, USA) *(UIST '22)*. Association for Computing Machinery, New York, NY, USA, Article 24, 12 pages. doi:10.1145/3526113.3545699

[91] Bao Yu, Liu Feng, Yali He, Lei Yang, and Yu Xun. 2021. Effects of anode materials on the performance and anode microbial community of soil microbial fuel cell. *Journal of Hazardous Materials* 401 (2021), 123394. doi:10.1016/j.jhazmat.2020.123394

[92] Tianhong Catherine Yu, Nancy Wang, Sarah Ellenbogen, and Cindy Hsin-Liu Kao. 2023. Skinergy: Machine-Embroidered Silicone-Textile Composites as On-Skin Self-Powered Input Sensors. In *Proceedings of the 36th Annual ACM Symposium*

on User Interface Software and Technology (San Francisco, CA, USA) *(UIST '23)*. Association for Computing Machinery, New York, NY, USA, Article 33, 15 pages. doi:10.1145/3586183.3606729

[93] Daxing Zhang, Yubing Ge, and Weidong Wang. 2013. Study of a terrestrial microbial fuel cell and the effects of its power generation performance by environmental factors. In *Proceedings of the 2013 International Conference on Advanced Mechatronic Systems*. 445–448. doi:10.1109/ICAMechS.2013.6681825

[94] Dingtian Zhang, Jung Wook Park, Yang Zhang, Yuhui Zhao, Yiyang Wang, Yunzhi Li, Tanvi Bhagwat, Wen-Fang Chou, Xiaojia Jia, Bernard Kippelen, Canek Fuentes-Hernandez, Thad Starner, and Gregory D. Abowd. 2020. OptoSense: Towards Ubiquitous Self-Powered Ambient Light Sensing Surfaces. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 4, 3, Article 103 (Sept. 2020), 27 pages. doi:10.1145/3411826

[95] Yang Zhang, Gierad Laput, and Chris Harrison. 2017. Electrick: Low-Cost Touch Sensing Using Electric Field Tomography. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 1–14. doi:10.1145/3025453.3025842

[96] Jiwei Zhou, Raphael Kim, Zjenja Doubrovski, Joana Martins, Elisa Giaccardi, and Elvin Karana. 2023. Cyano-chromic Interface: Aligning Human-Microbe Temporalities Towards Noticing and Attending to Living Artefacts. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference* (Pittsburgh, PA, USA) *(DIS '23)*. Association for Computing Machinery, New York, NY, USA, 820–838. doi:10.1145/3563657.3596132

[97] Nianmei Zhou, Steven Devleminck, and Luc Geurts. 2024. Contact Resistance Sensing for Touch and Squeeze Interactions. *Multimodal Technologies and Interaction* 8, 2 (2024). doi:10.3390/mti8020014

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