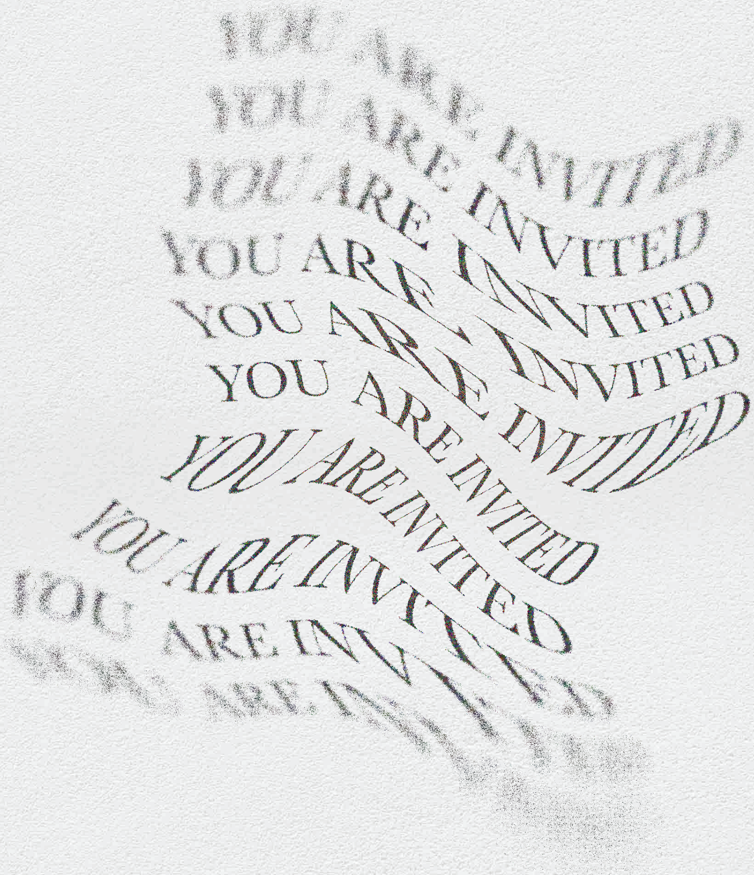
Electric Skin



a kit for the community

An invitation to join the open documentation, and collection of resources that enables you to learn more about Electric Skin research.

funded
&
mentored
by

WORTH
PARTNERSHIP
PROJECT

Crafting a new, self-powering biomaterial:
Beautiful, Growable, Compostable

#bioelectricity, #Electromicrobiology, #Nano Electronics

Content Page

We are Nada Elkharashi, Catherine Euale, Sequoia Fischer, and Paige Perillat- Piratoine. We met at the intersection of Biosummit and Biodesign Challenge communities, all fascinated by the possibilities of Biodesign.We're deeply motivated by care, materiality, and ancestry.

In October 2021, we participated in the *Biodesign x Google* Sprint and decided to explore how we could make our devices more sustainable but also meaningful. We felt if our phones felt different to the touch and told a different story, then disposing of them would be less of an option.

We stumbled across a Science article titled *"The Mud is Electric"* during the Biodesign Sprint. It told the story of the scientists who first documented electrically active bacteria and started playing with their possibilities. It turns out these bacteria are found everywhere in oxygen-starved soils, from salt marshes to backyard ponds and deep sea trenches. And their capabilities can be harnessed to generate power.

For us, this was very intriguing. Is there a way to generate electricity by growing bacteria? What if we could create a material that could power our devices and go back to the soil at the end of its use?

That's the idea behind Electric Skin. A Self-Powering Material. Beautiful, growable, compostable.

But as time went on, and the more we researched, we realized that not only is this possible, but there are likely many more applications, <u>ones that are not obvious to us but will be to others.</u>

This toolkit is an open documentation of our process and an invitation to join the research. We want to gather a community of researchers, designers, and artists working with bacteria and steering our world to a **regenerative energy future.**

The energy industry underlies everything we do. It's what makes global communication, transport, and production viable. From our most menial tasks like having light at night to space travel, there is a lot to be thankful for.

But it has its flaws.

The environmental impact of the energy industry is considerable. Producing, transporting and consuming energy all negatively impact our ecosystems. Oil leaks, nuclear disasters and climate change are just a few of the challenges in a system we are deeply dependant on. The same goes for the intersecting electronics industry. From mining precious metals to programmed obsolescence; we have many things to solve as a society.

The issue compounds when even our market ready renewable energies have deep environmental costs for an example: biofuels drive deforestation, solar panels still end up in e-waste piles.

There is a way to build on this global system and plug it back into planetary boundaries.

we think our energy future is grown

not extracted

It starts with bacteria and an emerging trend in research — still in its infancy, still mostly hidden in labs, industry and obscure biohacker forums:

Hygroelectricity is “a type of static electricity that forms on water droplets and can be transferred from droplets to small dust particles”[1]

But the focus of **th__is** toolkit is a soil dwelling bacteria called *Geobacter Sulfureducens*[2] and its hairlike protein nanowires called pili that harness this phenomenon.[3]

Zoom in on Geobacter

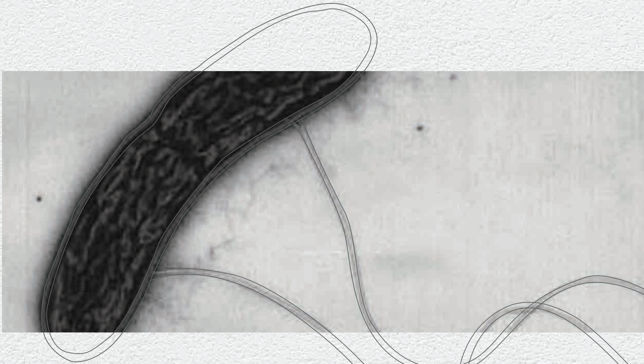


Figure 1:
Geobacter sulfurreducens Bacteria

Geobacter sulfurreducens in figure 1, is a bacterium that has been extensively studied by researchers due to its ability to transfer electrons outside its cell membrane. Geobacter sulfurreducens uses its pili, ie their microscopic electrically conductive hairs to transport electrons to nearby metals like iron.

Research on Geobacter sulfurreducens began in the late 1980s, when Derek Lovley, a microbiologist at the University of Massachusetts, discovered the bacterium in sediment samples from the Potomac River. Over the years, researchers have made significant progress in understanding the mechanisms of extracellular electron transfer in Geobacter sulfurreducens.

They have identified the proteins and genes involved in this process, including the conductive pili and cytochromes that enable the bacterium to exchange electrons with its environment.

Geobacter Sulfurreducens creates microscopic protein nanowires called pili which have power generation abilities. by means of electron transport chains.

Electroactive microorganisms (EAM) evolved from a new tactic of energy recovery via respiration through extracellular electron transfer (EET), through the interaction with ambient humidity.

Electroactive microorganisms (EAM), capable of (EET) can be used in bioelectronics for harnessing electricity from humidity in the air.

Key research done on the applications of Geobacter sulfurreducens:

1.Bioremediation:
Geobacter sulfurreducens has been studied for its potential use in bioremediation, particularly for the cleanup of contaminated groundwater. The bacterium can use pollutants such as uranium and perchlorate as electron acceptors, converting them into less harmful substances.

2.Bioenergy:
Geobacter sulfurreducens has also been investigated for its potential use in bioenergy production. The bacterium can be used in microbial fuel cells to generate electricity by transferring electrons from organic matter to an electrode.

3.Biosensing:
Geobacter sulfurreducens has been used as a biosensor for detecting environmental pollutants. The bacterium can be engineered to produce an electric signal when it encounters a specific chemical or toxin, allowing for rapid and sensitive detection.

Today, Geobacter sulfurreducens **continue** to be a subject of intense study, with researchers exploring **new** applications and uncovering new insights into its unique properties and capabilities.

There are also wonderful low-tech applications and art explorations, and startups rallied around this type of energy generation:

- The MudWatt is a science kit designed for kids to learn about the power of microorganisms and electricity. It consists of a small container filled with mud and two electrodes placed inside the mud. The microorganisms in the mud generate electricity by transferring electrons to the electrodes. This process, known as microbial fuel cell technology, is used to power a small LED light or a digital clock that comes with the kit. As the microorganisms in the mud produce more electricity, the LED light or clock becomes brighter or runs for a longer time...

- Geo LLum is an art installation and "a proposal for public lighting in urban spaces based on a bacterium that produces electricity while decontaminating the soil."

- Bioo's main product is a plant-based biological battery that generates electricity from the organic matter in the soil. The battery consists of two electrodes placed in soil and a plant that serves as a biological catalyst to facilitate the transfer of electrons between the electrodes. As the plant undergoes photosynthesis, it releases organic compounds into the soil, which are then broken down by microorganisms to produce electrons. These electrons are then captured by the electrodes and converted into electricity.

To start experimenting yourself with some low tech applications, we recommend The Ars Electronica Material Workshop that explains various ways to build Microbial Fuel Cells.

We're collaborating with Derek Lovely's Lab at the University of Massachusetts (UMASS), pioneering this research.

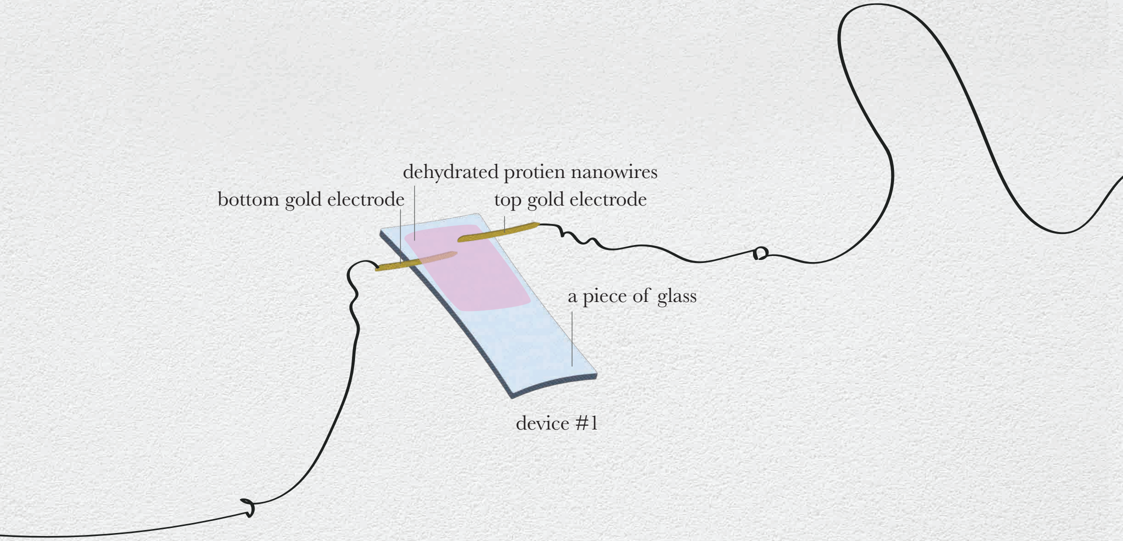
<u>Figure 2:</u>
Umass Experiment

Over the years, they have contributed immensely to the research on the potential of Geobacter sulfurreducens for bioremediation, bioenergy, and biosensing. They have shown that the bacterium can be used to clean up contaminated groundwater, generate electricity in microbial fuel cells, and detect environmental pollutants.

On top of this, they have uncovered the complex lab processes to cultivate the bacterium as well as engineered e.coli to express Geobacter pili (this allows for the lab processes to be more industry standard).

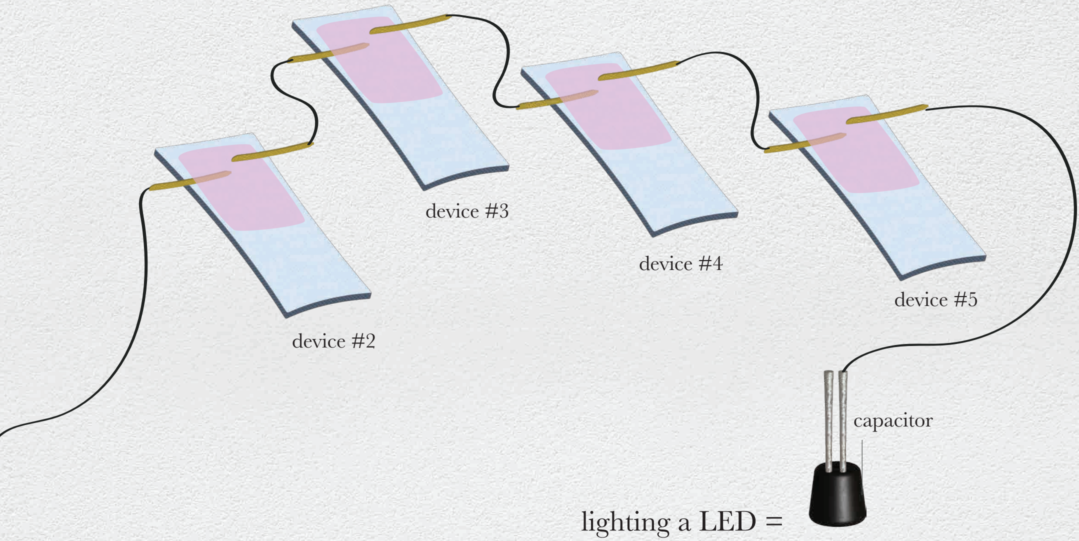
But the piece that rea___lly filled our minds with visions of the future is the Air Gen. The Air Gen device consists of a thin film of these pili that are deposited on an electrode. Moisture in the air is absorbed by the pili or protein nanowires, which generate a small electric current that can be harnessed to power electronic devices.

To simplify, the Airgen is essentially a piece of glass on which they put a gold electrode. On top of this gold electrode, they drop the protein nanowires. They then allowed the protein nanowires to dehydrate and then put a gold electrode on top. This itself created a measurable current. To actually light an LED, they connected five of these devices in series as well as a capacitor to even out the current.



Airgen Device

UMASS's Experiment



The Lovley Lab has several patents related to this research:

US Patent 9,017,720:
"Methods for improved production of electricity in microbial fuel cells using conductive pili and genetically modified microorganisms." This patent covers the use of conductive pili and genetically modified microorganisms to improve the efficiency of microbial fuel cells.

US Patent 8,569,443:
"Bacteria and methods for production of electricity." This patent covers the use of specific types of bacteria to generate electricity in microbial fuel cells.

US Patent 9,981,918:
"Methods for the treatment of hydrocarbon-contaminated soils using Geobacteraceae bacteria." This patent covers the use of Geobacteraceae bacteria to clean up soils contaminated with hydrocarbons.

US Patent 10,469,775:
titled "Electricity-Generating Protein Nanowires for the Direct Extraction of Energy from Air". This patent was filed on August 21, 2018, and was granted on November 5, 2019. The patent describes the use of Geobacter bacteria to produce electrically conductive protein nanowires that can be used to generate electricity from moisture in the air.

Why is this research amazing?

The possibility of making disposable (compostable) electronics

Power generation without the need for batteries and heavy extraction of metals such as lithium-ion

Offer a continuous energy-harvesting strategy that is less restricted by location or environmental conditions.

Power can be generated in almost any environment on earth.

The power comes from water vapour that is recycled.

The human body does not reject this form of electricity, and therefore this technology could be used to make thin films for medical biosensors

These pili are robust! Stable in a diversity of solvents (water, chloroform, DMSO, THF, hexane), under vacuum, at high temperature, and over wide pH ranges

Readily mass-produced from inexpensive, renewable feedstocks.

Derek Lovley's lab at the University of Massachusetts grows Geobacter sulfurreducens using standard microbiology techniques. The bacteria are typically grown in a culture medium containing nutrients such as carbon, nitrogen, and sulfur sources.

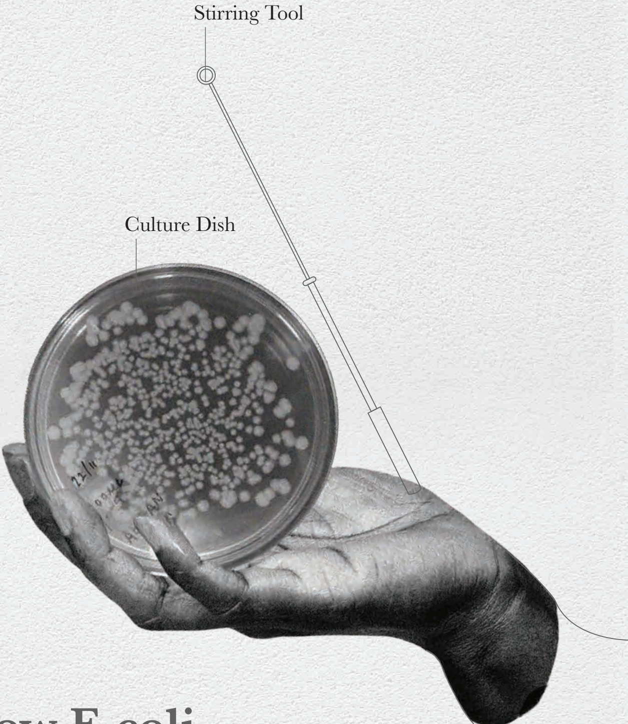
To extract the pili from Geobacter sulfurreducens, the lab uses a process called *sonication*. In this process, the bacterial cells are subjected to high-frequency sound waves, which disrupt the cell membranes and release the pili into the surrounding liquid.

The extracted pili are then purified using a series of biochemical techniques, such as chromatography and gel electrophoresis. This allows the lab to isolate the *electrically conductive pili* and study their properties in more detail.

But these processes are **not** quite feasible at an industrial scale.

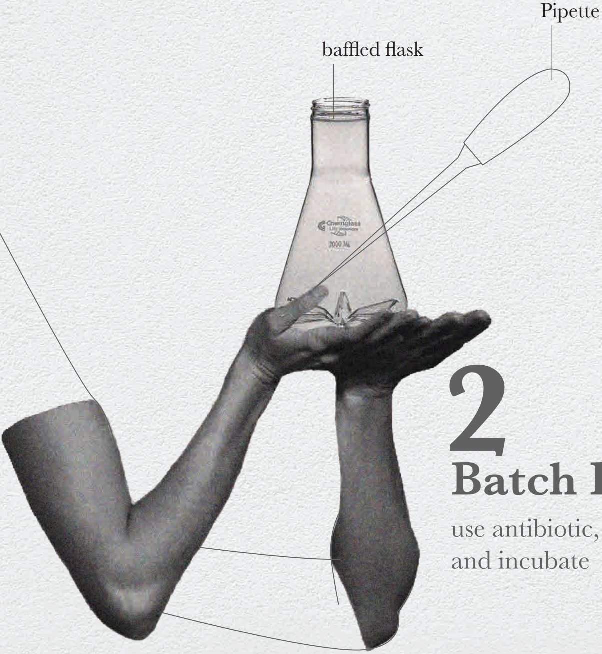
So our first step at Electric Skin has been uncovering the steps to scale up the production of pili to make it more affordable and accessible.

This is where we have invested most of our Worth funding so far. Thanks to the engineered e.coli strain we received from UMASS, we are able to produce pili from liquid batches.



1
Grow E.coli starter Culture

Using a tested broth as a sample into a culture tube or dish, then into the shaker.



2
Batch Production

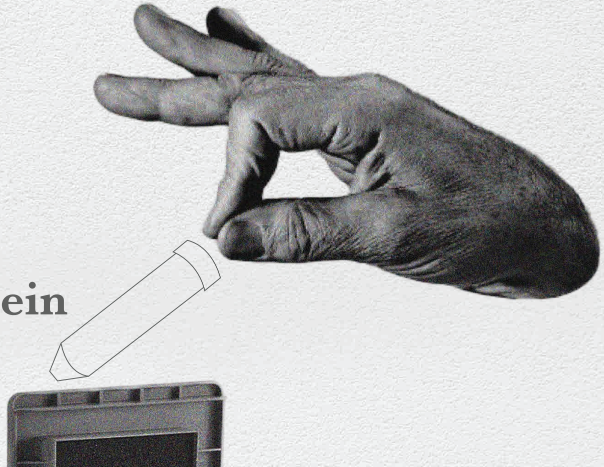
use antibiotic, Shake overnight and incubate

3
Protein extraction

Collect the E. coli cells from media, and shake at at room temperature

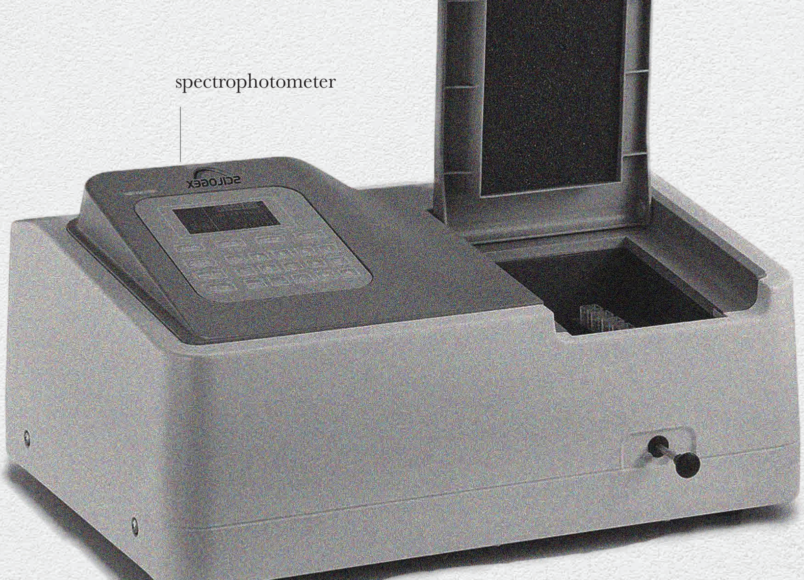
4
Protein purification

Set up the stirred filter system and collect the pili protein from the filter



5
Calculate protein concentration

Collect absorbance at 280nm using spectrophotometer



Our Twist
Electric Skin

Since the beginning of our journey into electrically conductive biomaterials, we had a vision of a **skin** for our devices. This skin would serve as a flexible battery adaptable to many forms of technology.

Why skin? We envisioned a **biophilic future** where our devices are cared for as we would care for a plant, pet or companion. The addition of a textured membrane that could charge our devices with ambient air gives our design **an inherent living or biomimetic property**, which we think can help us connect better with our devices and their material bodies, making them less disposable and therefore reduce e-waste.

So far, the small devices created at Lovley's lab at UMASS have been created using polyamide or glass as the substrates, or base on which we cast our nanowires.

We wanted to take the technology a step further into complete circularity by making our material from soil — bacteria to skin — user interface and back to the soil— compost.

With all of the parameters* needed for working with the protein nanowires, we are **developing** a biodegradable material based on calcium alginate composites with silk fibroin, chitosan and glycerin as a plasticizer.

This material is made into flexible sheets on which we drop the protein nanowires (pili) using a laboratory pipette.

Calcium alginate sheets have tunable hydrophobicity. meaning they absorb ambient humidity and expand, without degrading. Once ambient humidity lessens, they release the absorbed liquid. In this way they "perspire" with changes in environmental humidity. We are testing if this helps maintain a more stable current.

The choice of calcium alginate as a first test substrate is exactly due to this ability as a “bioplastic” to absorb and release humidity without melting or degrading.

Calcium alginate is created through a chemical reaction between calcium chloride (used for fermentation of wines and cheeses) and alginate which is present in the cell walls of brown algae, as the calcium, magnesium and sodium salts of alginic acid. The product of this chemical reaction is calcium alginate and simple table salt (sodium chloride).

Current uses of calcium alginate are:

in plant tissue culture to produce insoluble artificial seeds

for immobilizing enzymes by entrapment

to produce an gelants for food

incorporated into wound dressings (alginate dressings) as a hemostatic

as a alginate hydrogel, can be used for a controlled-release drug delivery system

used in molecular gastronomy in spherification.

To create Electric Skin, our material parameters are:

Porosity & Hydrophobicity:
The material itself does not have to be porous, but it does help capture moisture, which amplifies the current output of the nanowires.

Material surface porosity can also cause a bit of current resistance, and so we are also testing our alginate polymers with a **plasma process** to improve their tensile strength (decreases their porosity and helps with adhesion properties).

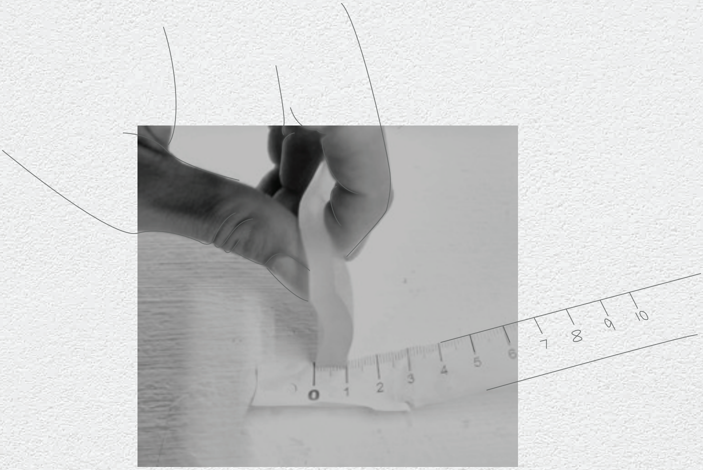
Adherence:
Plasma etching also has the potential to tune the bioploymer's surface adherence, since the fluctuating hydrophobicity of our material makes it difficult for the nanowires and conductive electrode materials to stay adhered over time.

Surface tension:
Plasma etching might help our alginate substrate by tuning the porosity and therefore better the surface tensions to increase surface conductivity (as it lowers surface resistance).

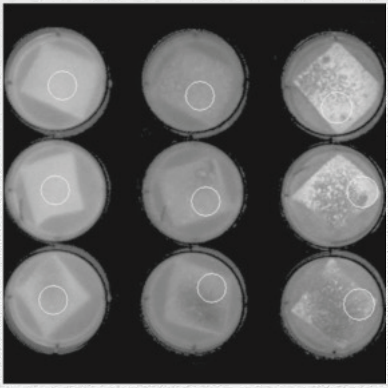
We are still waiting to test this process.

Flexibility:
Calcium alginate when plasticized makes a flexible material that can eventually be applied to different electronics (i,e, soft robotics or medical biosensors. There may be many interesting applications).

Electrode Conductivity:
Gold-based circuits are better suited for our material because they do not oxidise with moisture and also conduct better, since we have so little voltage production we need better materials to sustain, drive and amplify it.



<u>Figure 3:</u>
Calcium Alginate biopolymer sheet: absorption tests.



<u>Figure 4:</u>
Biodegradability in living environments test.

Figure 5:
Calcium Alginate biopolymer sheet: flexible substrate for nanowires

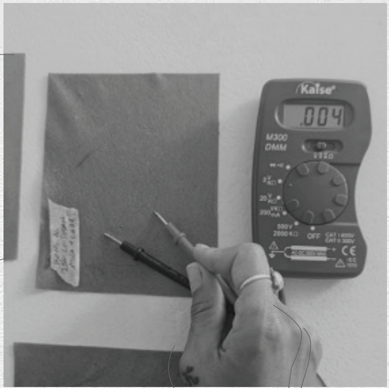


Figure 6:
Calcium Alginate embedded with activated charcoal and graphite to test conductivity of composite material.

Testing Circuits

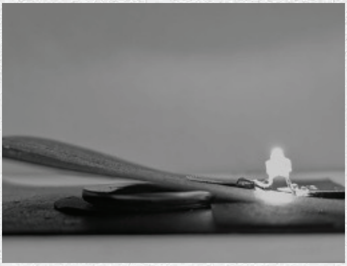


Figure 7.1:
Silver conductive fabric electrodes and LED circuit on bioplastic material.

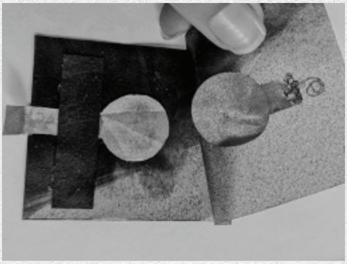


Figure 7.2:
Silver conductive fabric electrodes and LED circuit on bioplastic material.

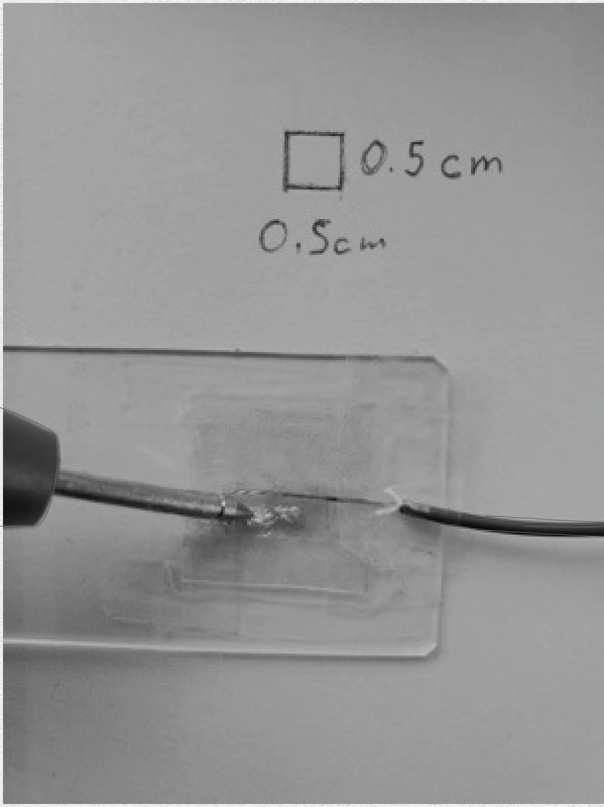


Figure 8:
Electrodes with gold conductive ink on bioplastic material. One 0.5cm x 0.5cm circuit

Figure 9:
5 electrodes connected in series

So from here where do we go ?

Our aim from the beginning is to gather a **community of researchers.** We're going to use our proof of concept to raise further **funds** and grow our own production of nanowire.

Our goal from there will be to create a physical toolkit so the community access these proteins and can progress this research together in a decentralised way.

WHAT WE WANT FROM YOU?

We want to make this research accessible: So far it's been stuck in university laboratories.

We want to simplify the jargon and give the physical tools to scientists

We want designers and artists start experimenting and telling stories of where this can go.

We want to lower the cost of entry.

We want to share our process and our mistakes, but create a community of research around protein based bioelectronics.

We are in touch with UMASS university and are working with them to scale the production of engineered e.coli to grow large quanitties of proteins.

We want to jumpstart a community of research: We think this idea needs to get out of the lab and into the hands of the biocommunity.

Electric Skin

Could reduce e-waste since our electronics could be powered by compostable skins.

Could potentially reduce the need to extract and process materials for electronics like silicon deposits, copper, lithium.

Could potentially bypass the use of harsh chemicals in processing materials and waste.

Bibliography

[1] "About: Hygroelectricity." Dbpedia.org, dbpedia.org/page/Hygroelectricity. Accessed 27 Feb. 2023.

[2] Pennisi, Elizabeth. "The Mud Is Electric." Science, vol. 369, no. 6506, 21 Aug. 2020, pp. 902–905, https://doi.org/10.1126/science.369.6506.902.

[3] "Geo-Llum" by Samira Benini Allaouat | Activities." CCCB, www.cccb.org/en/activities/file/geo-llum-by-samira-benini-allaouat/238293. Accessed 27 Feb. 2023.

Crafting a new self powering biomaterial

electric skin

made with bacteria

Beautiful . Growable . Compostable