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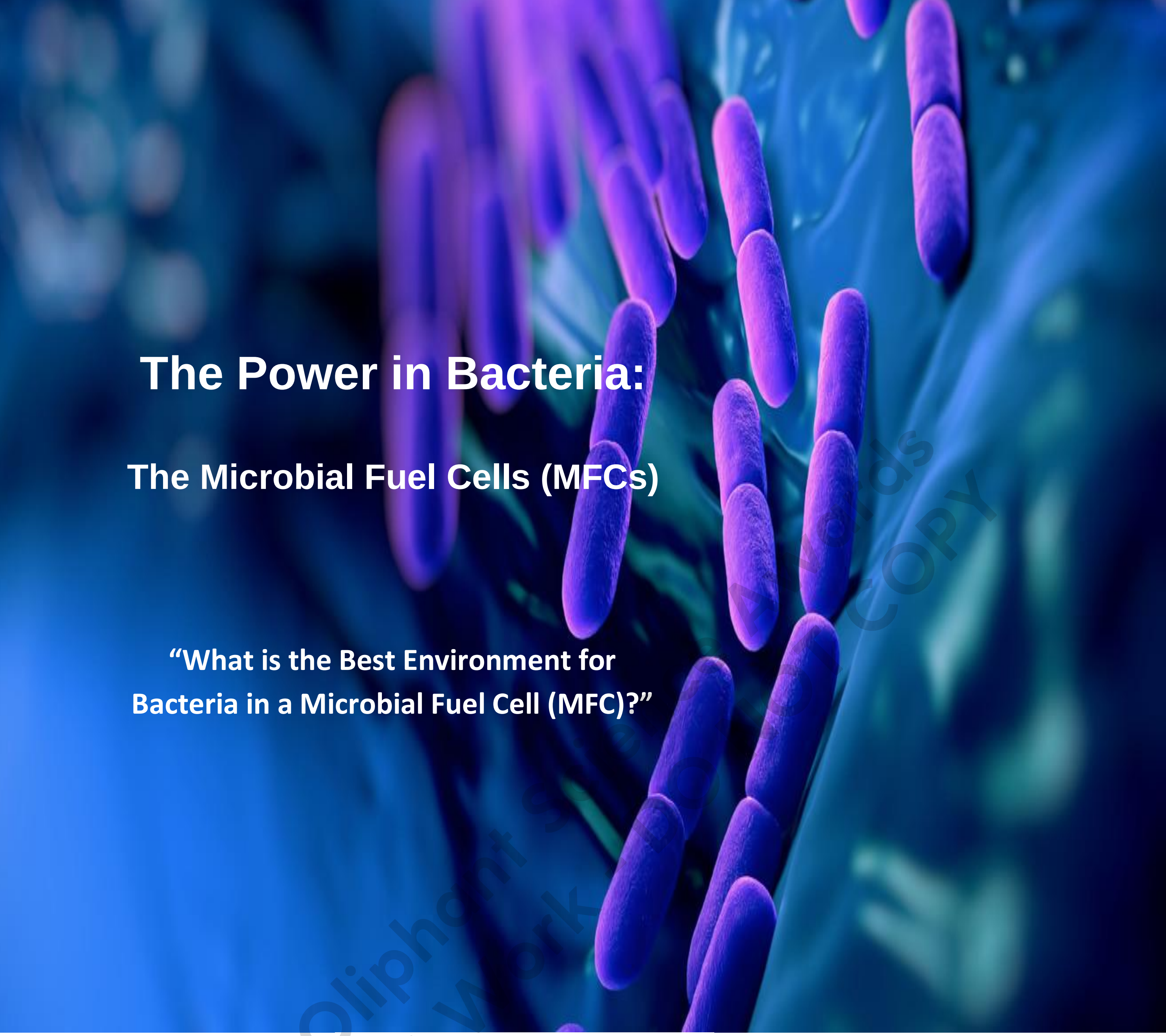


The Power in Bacteria:

The Microbial Fuel Cells (MFCs)

“What is the Best Environment for Bacteria in a Microbial Fuel Cell (MFC)?”

JULY 2021

Upload Code: XGD3UHQ8

Word Count: 1,985 words.
(Headings, titles, abstract, figure captions, tables, references and pictures/descriptions are excluded.)

Abstract

The purpose of this study is to understand how bacteria generate electricity and the impacts of various materials and factors on the power generation by Microbial Fuel Cells (MFCs). The aim of the experiments is to identify the comparison between different types of soils used in MFCs and to reflect on any discoveries made. The goal of this research is to provide a general overview of Microbial Fuel Cells and to provide a detailed methodology to represent procedures accurately.

Research Motivation

Microbes are often associated with disease or illness, but also the essential players in the recycling of nutrients and in providing key ingredients necessary to support life. There are three main types of microbes: bacteria, fungi and viruses; bacteria are the key layers in Microbial Fuel Cells (MFCs) and have dominated since life on Earth began and have been found in every imaginable type of environment, like acid pools, hot thermal vents and deep sea where thought to be uninhabitable.

The sewage generated by human activities has been discharged in large quantities, containing rich organic matter including bacteria and valuable substances, which cannot be recycled into effective energy resources. Instead, additional energy is required in the treatment, resulting in a lot of waste of resources. With the rise of the concept of modern circular economy and the breakthrough of microbial fuel cell (MFC) technology, many scientists began to consider the innovative sewage treatment system of circular economy, which can generate electricity and reduce the toxicity of heavy metals in water and soil.

In this topic, a simple mud-based battery (*Figure 1.*) will be created and explained how bacteria can convert chemical energy into electrical energy. Just as the food we eat contains a lot of energy, so does the waste we produce. If the waste had been dumped into rivers and oceans without removing the energy, the ecosystems may be damaged. For this reason, all the nutrient rich organics in wastewater must be removed, however, the process to remove these organics and treat the wastewater requires a lot of energy. Researchers are currently developing MFC as a method to simultaneously treat wastewater and convert the energy into electricity. If this can be done, it may be possible for wastewater treatment to go from a process that uses a lot of energy to one that could generate energy.

Introduction

What is a Microbial Fuel Cell?

A MFC is a bio-electrochemical system that can drive an electric current by using bacteria and a high-energy oxidant such as O_2, mimicking bacterial interactions found in nature. The MFCs are the devices which harness electrons given off naturally by bacteria within soil, sediment or wastewater, to create an electrical circuit. The first MFCs, demonstrated in the early 20th century by Michael Cressé Potter (1858-1948), used a mediator: a chemical that transfers electrons from the bacteria in the cell to the anode. In the 21st century MFCs have started to find commercial use in wastewater treatment (***Appendix 1***). The purpose of this study is to understand how bacteria generate electricity and the impacts of various materials and factors on the power (***Appendix 2***).

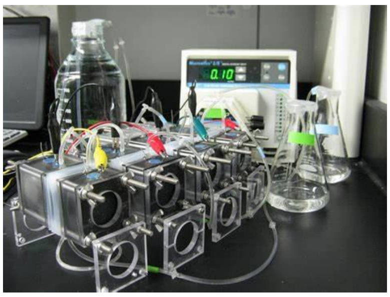
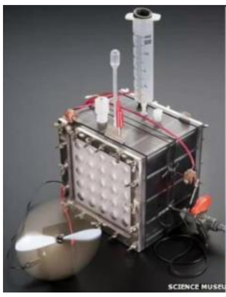
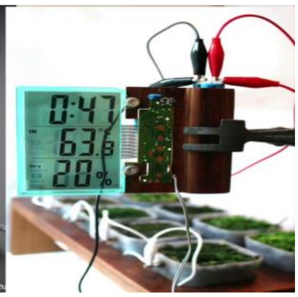





Figure 1. Single-Chamber MFC (SCMFC)

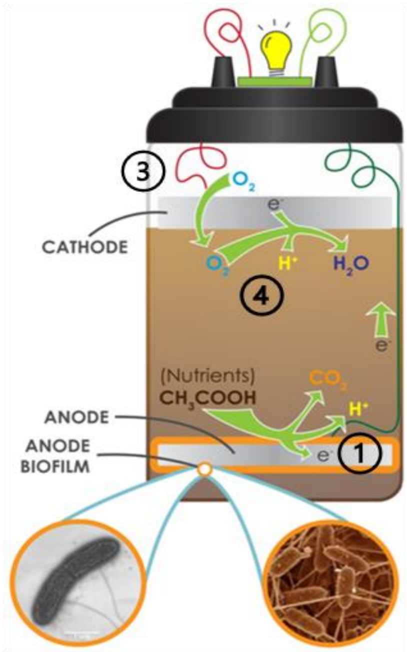


Figure 1. shows the flow of electrons through a single-chamber MFC.

https://en.wikipedia.org/wiki/Microbial_fuel_cell#/media/File:SoilMFC.png

① As the microbes around the anode munch up the nutrients in the mud, they deposit electrons onto the anode.
② These electrons travel through the wire to the Hacker board, where they power the electronics.
③ The electrons then travel back down through the wire to the cathode.
④ As the cathode, electrons interact with oxygen (from the air) and protons (from the anode) to form water.
Mechanism of Microbial Fuel Cells

Mechanism of Microbial Fuel Cells

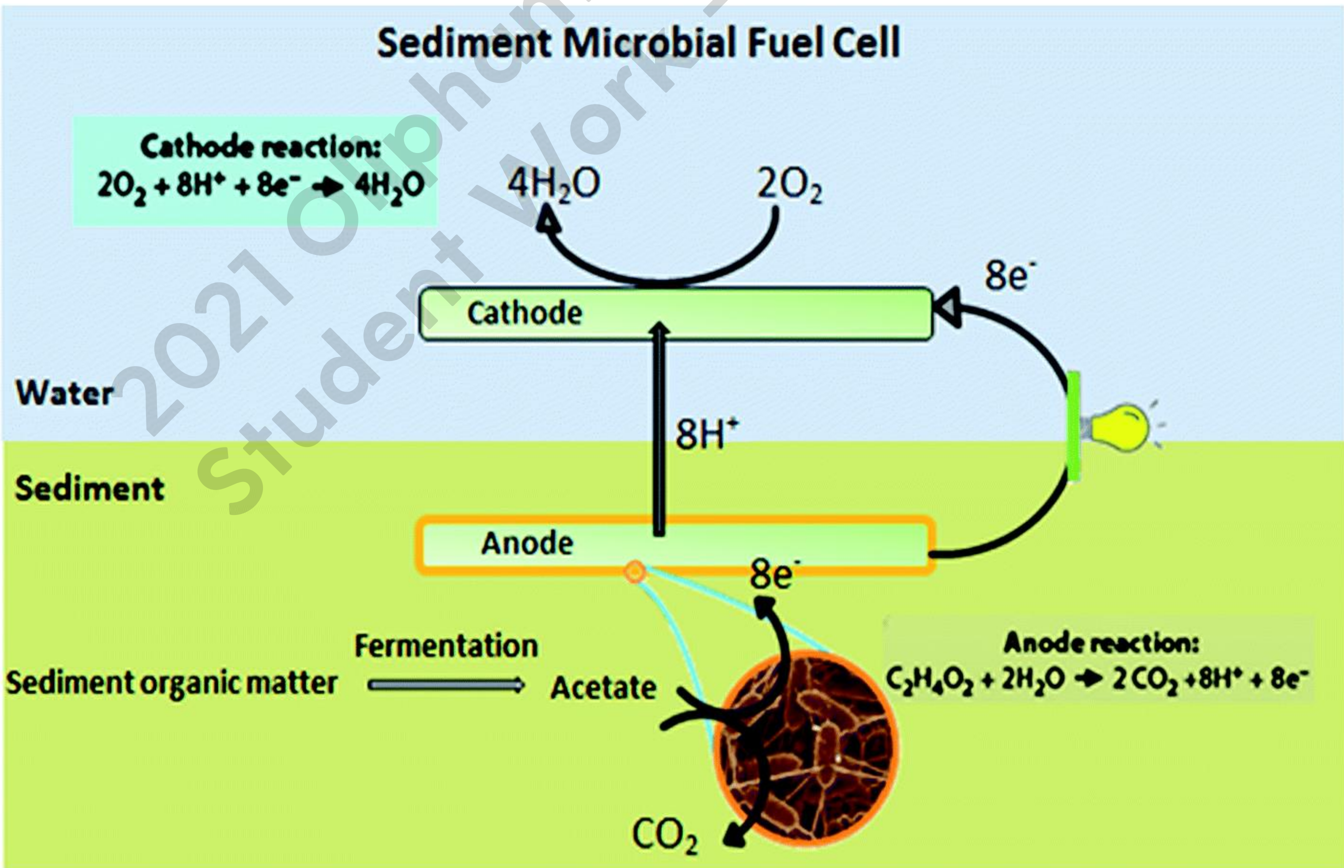
Anode:

$$C_6H_{12}O_6 + 6H_2O \xrightarrow{\text{Microbes}} 6CO_2 + 24H^+ + 24e^-$$

Cathode:

$$4H^+ + 4e^- + O_2 \rightarrow 2H_2O$$

$$C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 12H_2O$$



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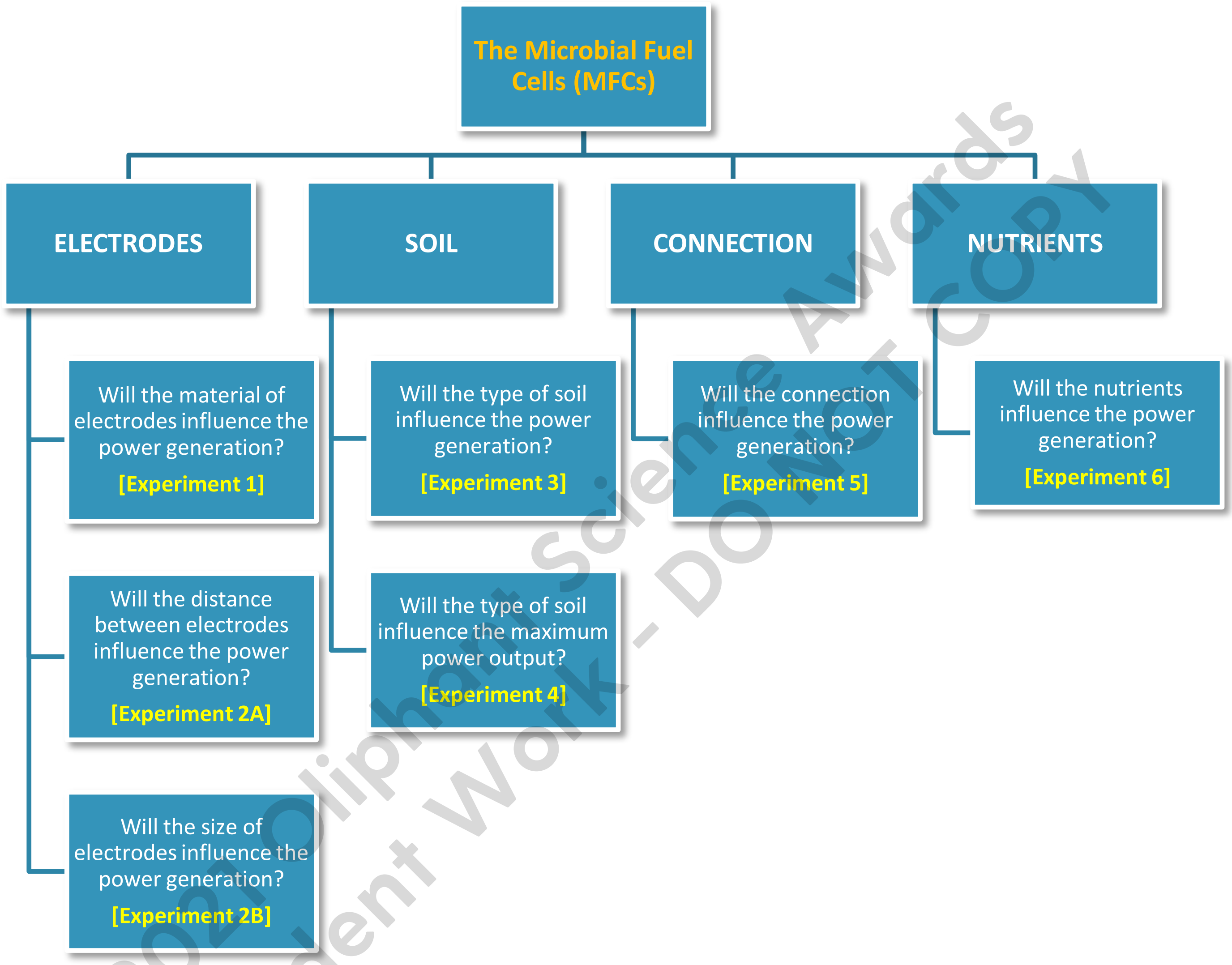
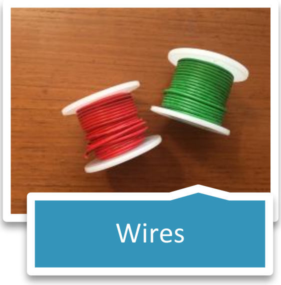
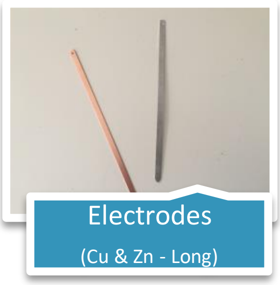
The Experimental Flow Chart



Materials & Equipment

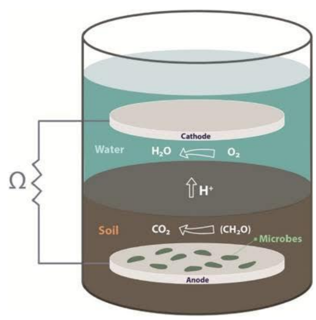




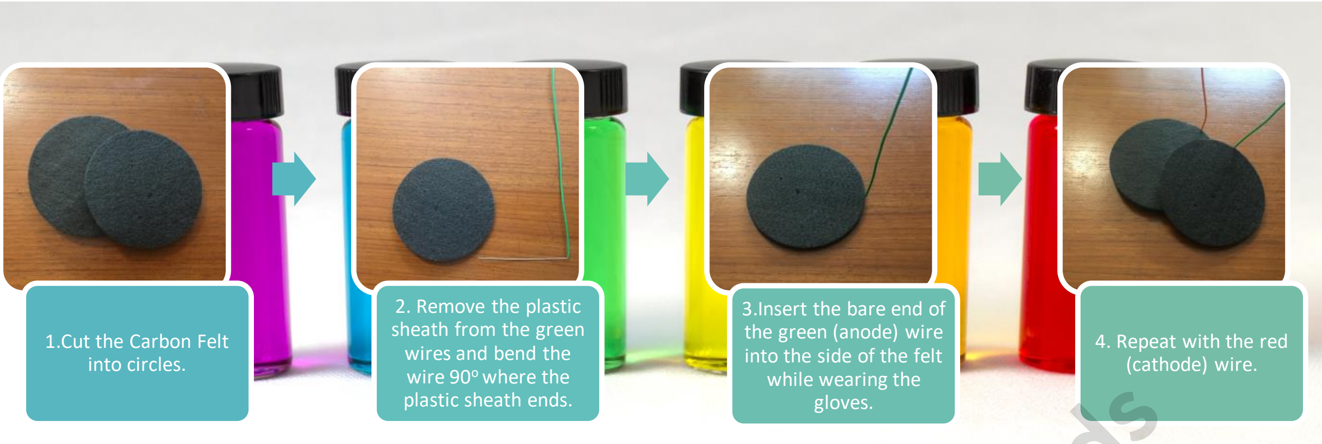
Equipment		Soil
8 × Plastic Vessels with Lids	6 × Capacitor (10ųF)	Benthic Mud
4 × Carbon Felts	1 × 10mL Glucose Solution	Forest Topsoil
1 × Red Wire for Cathode	6 × LED Light	Backyard Garden Soil
1 × Green Wire for Anode	1 × Cupper Sheets & 1 × Zinc Sheets	
1 × Multimeter	1 × 5g Sugar	
6 × Alligator Clips	1 × 5g Glucose	
6 × Gloves	1 × 5g Fructose	
8 × Resistors		

Method

Create a Single-chamber MFC Sample – Type 1A (Graphite Fiber).

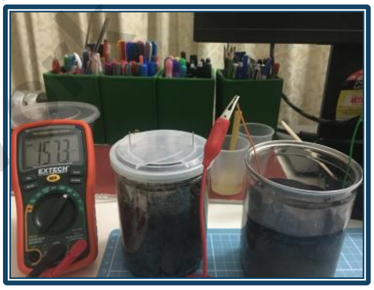


Step 1: Build the electrodes

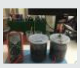
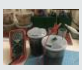


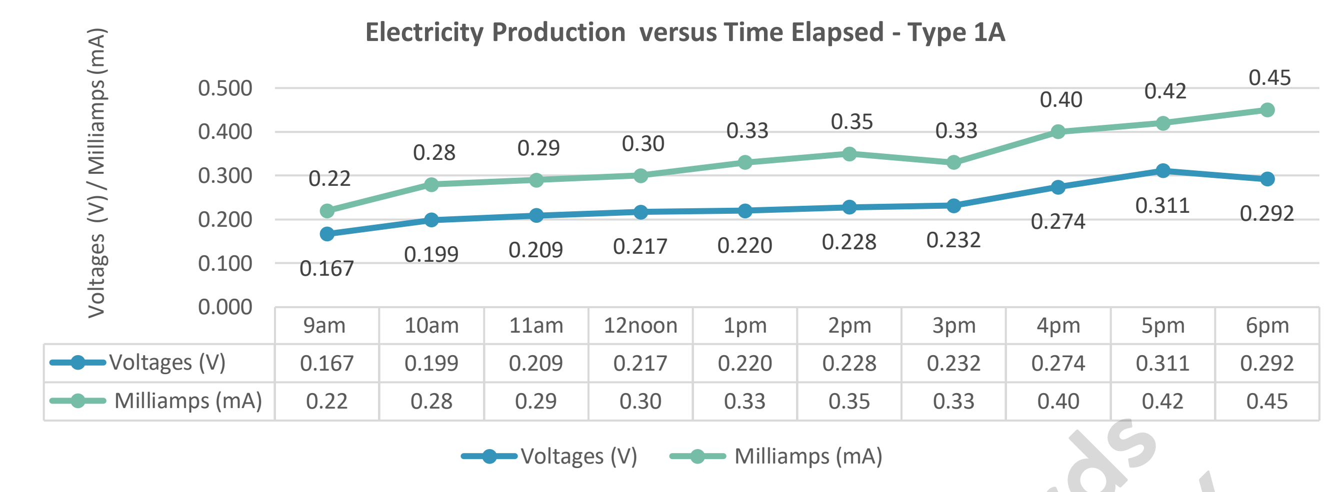
Step 2: Collect soil samples & attach the electrodes.

Step 3: Measure the Voltage and record the data (Result 1A).

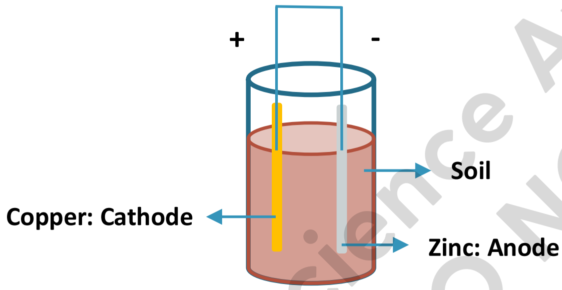

Result 1A (electrodes: Carbon Felt / Graphite Fiber)

Fixed Variable MFC Same Location, Temperature Multimeter, Alligator Clips, Soil (Garden Soil) (Created at 8am)	Independent Variables (Time Elapsed: Hourly) (01/05)									
	9am	10am	11am	12 noon	1pm	1pm	1pm	4pm	5pm	6pm
										
Dependent Variables Voltages (V)	V	V	V	V	V	V	V	V	V	V
	0.167	0.199	0.209	0.217	0.220	0.228	0.232	0.274	0.311	0.292
Milliamps (mA)	mA	mA	mA	mA	mA	mA	mA	mA	mA	mA
	0.22	0.28	0.29	0.30	0.33	0.35	0.33	0.40	0.42	0.45



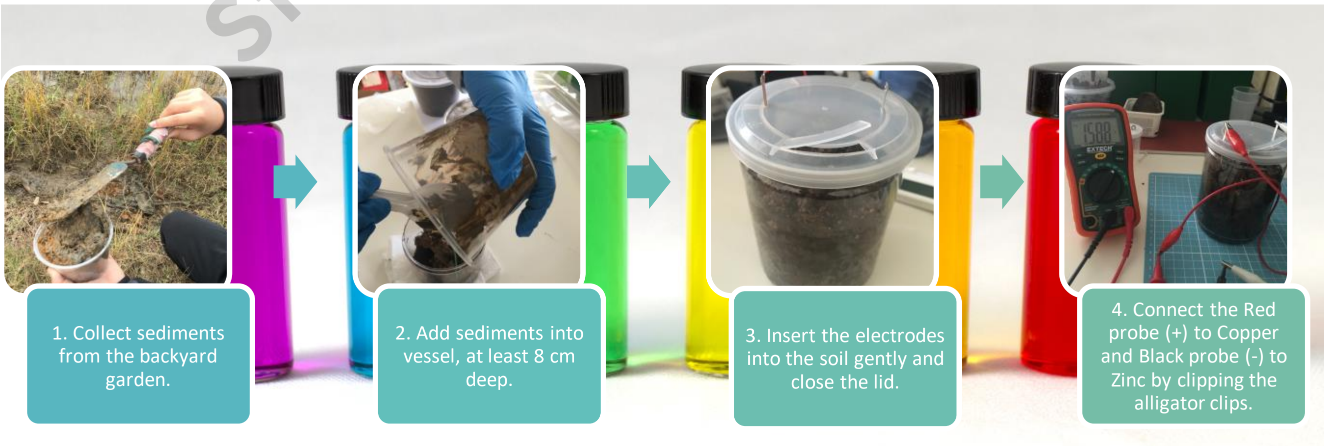
	9am	10am	11am	12noon	1pm	2pm	3pm	4pm	5pm	6pm
Voltages (V)	0.167	0.199	0.209	0.217	0.220	0.228	0.232	0.274	0.311	0.292
Milliamps (mA)	0.22	0.28	0.29	0.30	0.33	0.35	0.33	0.40	0.42	0.45

Create a Single-chamber MFC Sample – Type 1B (Metal Electrodes).

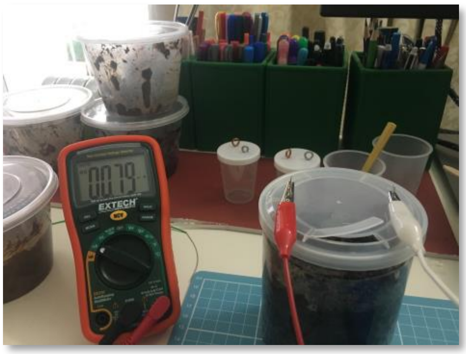


Step 1: Build the electrodes

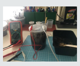
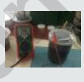
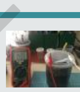
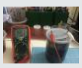
Step 2: Collect soil samples & attach the electrodes.

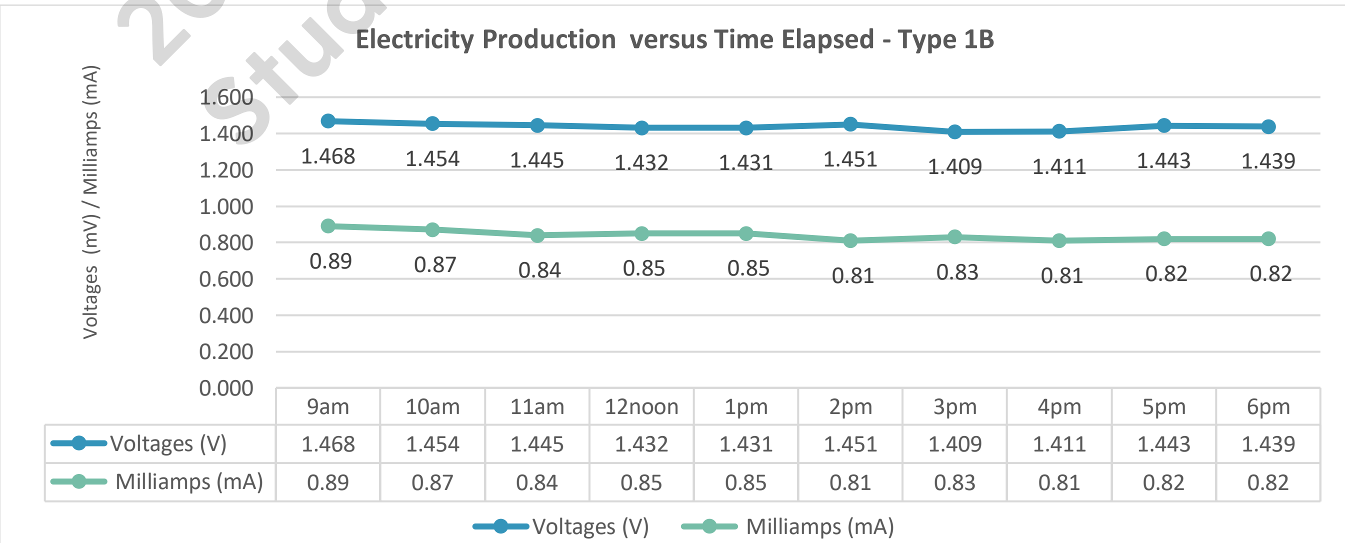


Step 3: Measure the Voltage and record the data.

Result 1B (Electrodes: Cu + An)

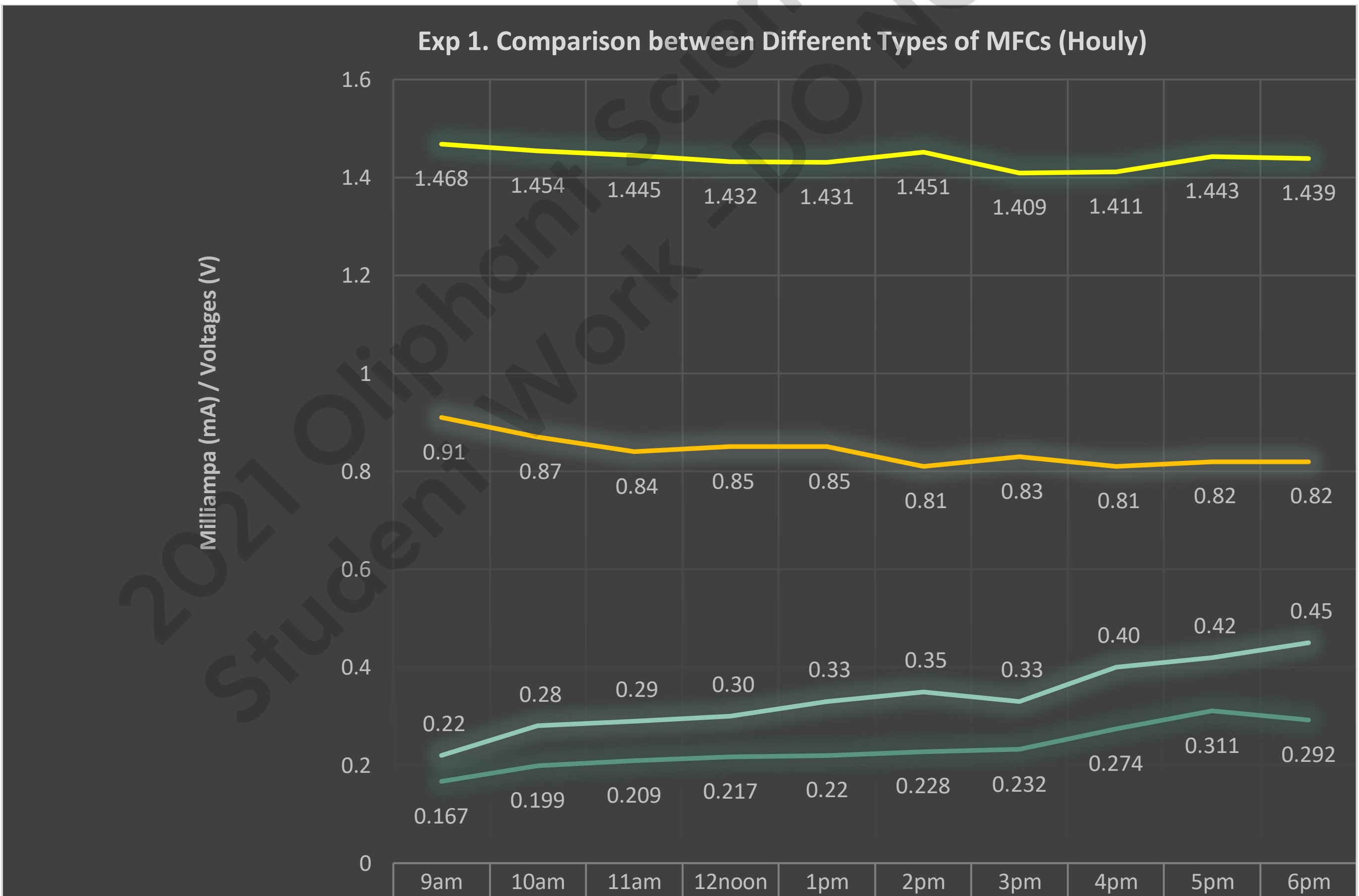
Fixed Variable MFC Same Location, Temperature Multimeter, Alligator Clips, Soil (Garden soil) (Created at 8am)	Independent Variables (Time Elapsed: Hourly) (01/05)									
	9am	10am	11am	12 noon	1pm	1pm	1pm	4pm	5pm	6pm
										
Dependent Variables	V	V	V	V	V	V	V	V	V	V
Voltages (V)	1.468	1.454	1.445	1.432	1.431	1.451	1.409	1.411	1.443	1.439
Milliamps (mA)	mA	mA	mA	mA	mA	mA	mA	mA	mA	mA
	0.89	0.87	0.84	0.85	0.85	0.81	0.83	0.81	0.82	0.82



Results of Experiment 1:

Two types of MFCs were created, one is used carbon felt as the electrodes (1A), and another one is used metal electrodes (1B), both are used garden soil as the sediment. From the figures above confirm that the potential can exist with the soil between electrodes. This is to investigate the voltage generated across the terminals, the electrodes were not connected to the pins on the Hacker board. The value of voltage was taken by connecting the multi-meter with alligator clips and the other end of the clips directly connected to the wires.

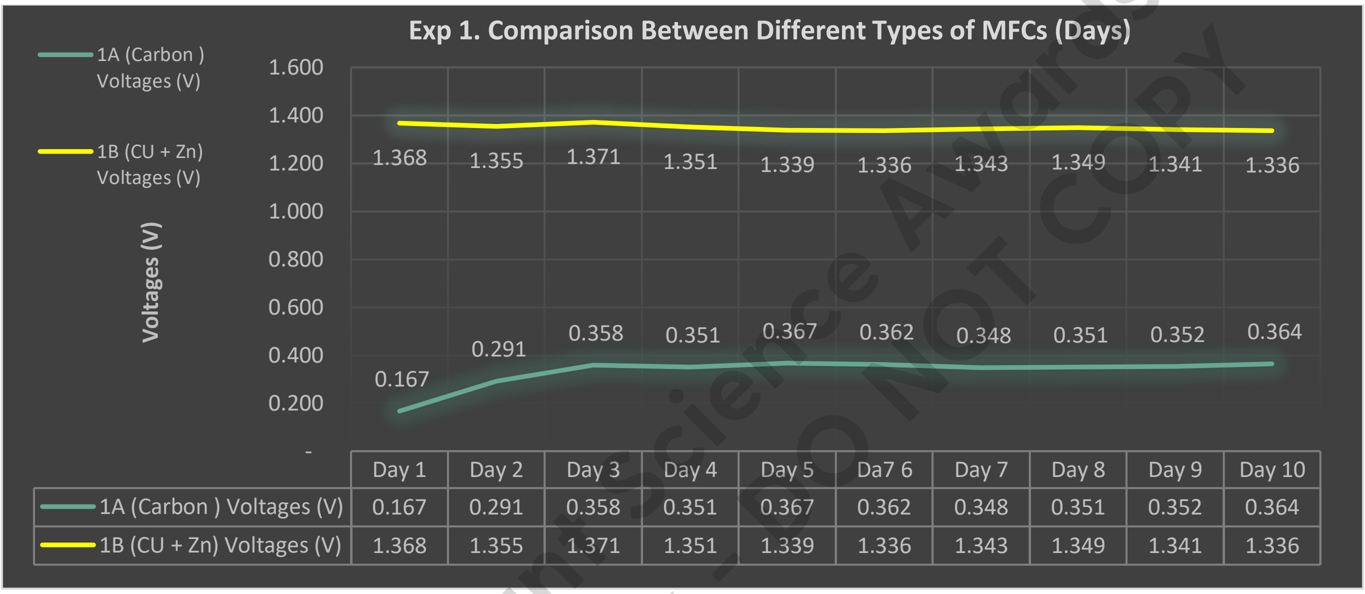
The MFC (1B) which is using the metal electrodes can reach stabler and higher power in a short time after creation, it can drive a small digital clock directly. Over time the voltage generated by the MFC increased and the peak voltages in the first 10 hours reached 0.311V in 1A and 1.468V in 1B. The MFC using graphite electrodes needs longer time to generate a small stable power which can only drive a LED light (at least 0.3V). But no matter which electrodes are used, the MFCs can generate different levels of electricity, proving that the bacteria in the soil can convert chemical energy into electrical energy.



	9am	10am	11am	12noon	1pm	2pm	3pm	4pm	5pm	6pm
1A (Carbon) Voltages (V)	0.167	0.199	0.209	0.217	0.22	0.228	0.232	0.274	0.311	0.292
1B(CU + Zn) Voltages (V)	1.468	1.454	1.445	1.432	1.431	1.451	1.409	1.411	1.443	1.439
1A (Carbon) Milliamps (mA)	0.22	0.28	0.29	0.30	0.33	0.35	0.33	0.40	0.42	0.45
1B (CU + Zn) Milliamps (mA)	0.91	0.87	0.84	0.85	0.85	0.81	0.83	0.81	0.82	0.82

1A (Carbon) Voltages (V)   1B(CU + Zn) Voltages (V)   1A (Carbon) Milliamps (mA)   1B (CU + Zn) Milliamps (mA)

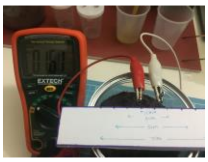
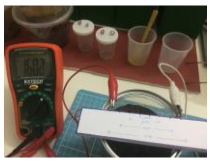
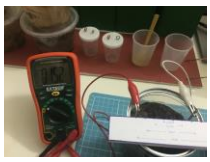
Fixed Variable Location, Temperature, Multimeter, Alligator Clips, Soil (Backyard Garden) (Created at 8am)	Independent Variables (Time Elapsed - Daily)									
	Day 1 (01/05)	Day 2 (02/05)	Day 3 (03/05)	Day 4 (04/05)	Day 5 (05/05)	Day 6 (06/05)	Day 7 (07/05)	Day 8 (08/05)	Day 9 (09/05)	Day 10 (10/05)
Dependent Variables	V	V	V	V	V	V	V	V	V	V
Voltages (V) Carbon Felt	0.167	0.291	0.358	0.351	0.367	0.362	0.348	0.351	0.352	0.364
	V	V	V	V	V	V	V	V	V	V
Voltages (V) Metal (Cu + Zn)	1.368	1.355	1.371	1.351	1.339	1.336	1.343	1.349	1.341	1.336

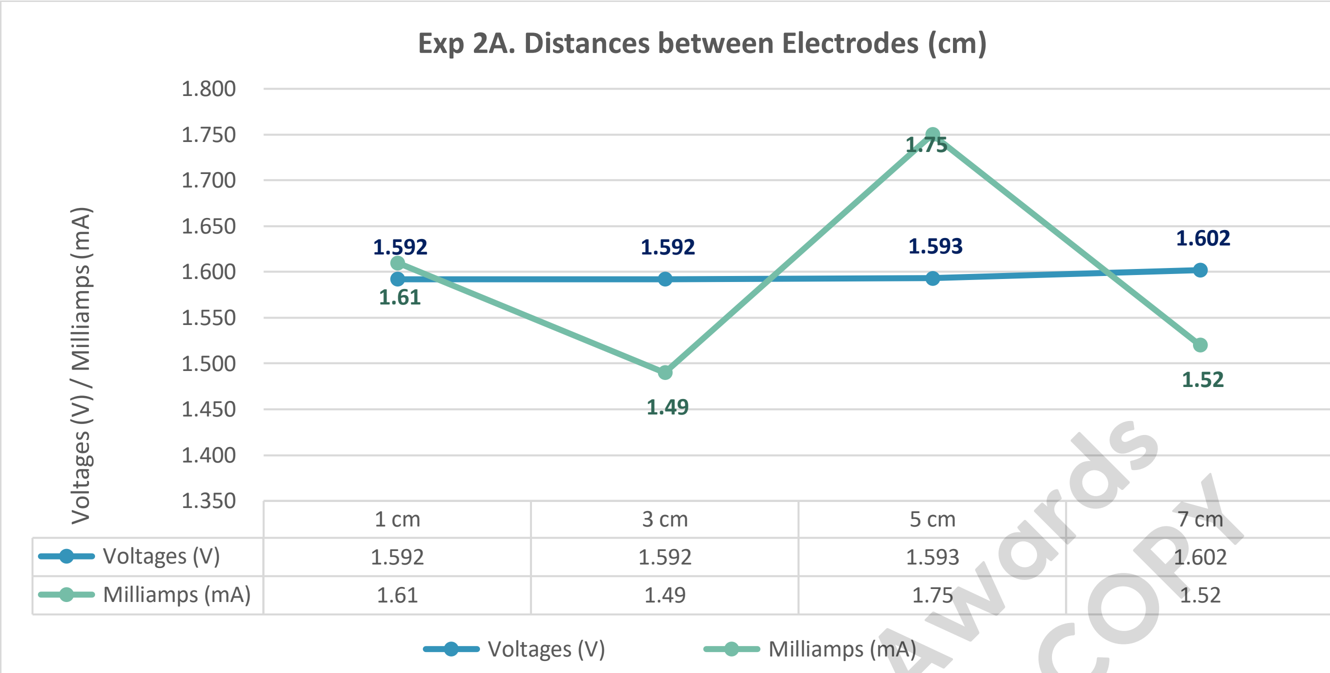


Experiment 2. Electrodes of the MFCs.

2A. The distances of the electrodes.

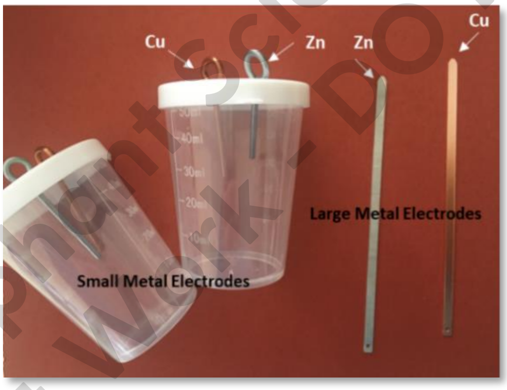
Type 1B (metal) is used to test whether the electrode distance influences the power generated because it's easier adjustment of the electrode distance than 1A type (Carbon).

Fixed Factors MFC	Independent Variable – Distances between Electrodes (15/05)			
	1 cm	3 cm	5 cm	7 cm
Same Location, Temperature Multimeter, Alligator Clips, Electrodes Materials.	 	 	 	 
Dependent Variables	V	V	V	V
Voltages (V)	1.592	1.592	1.593	1.602
	mA	mA	mA	mA
Milliamps (mA)	1.61	1.59	1.75	1.52



2B. The sizes of the electrodes.

Two sizes of metal electrodes were used to investigate the influence of size of electrodes (keep the electrode distance constant).



Fixed Factors MFC (15/05)	**Independent Variable – Distances between Electrodes (15/05)**	
	Large Metal Electrodes (10cm long)	Small Metal Electrodes (3cm long)
Same Location, Temperature Multimeter, Alligator Clips, Electrodes Materials, Electrode Distance (4cm).		
Dependent Variables	**V**	**V**
Voltages (V)	**1.521**	**0.735**

Results of Experiment 2:

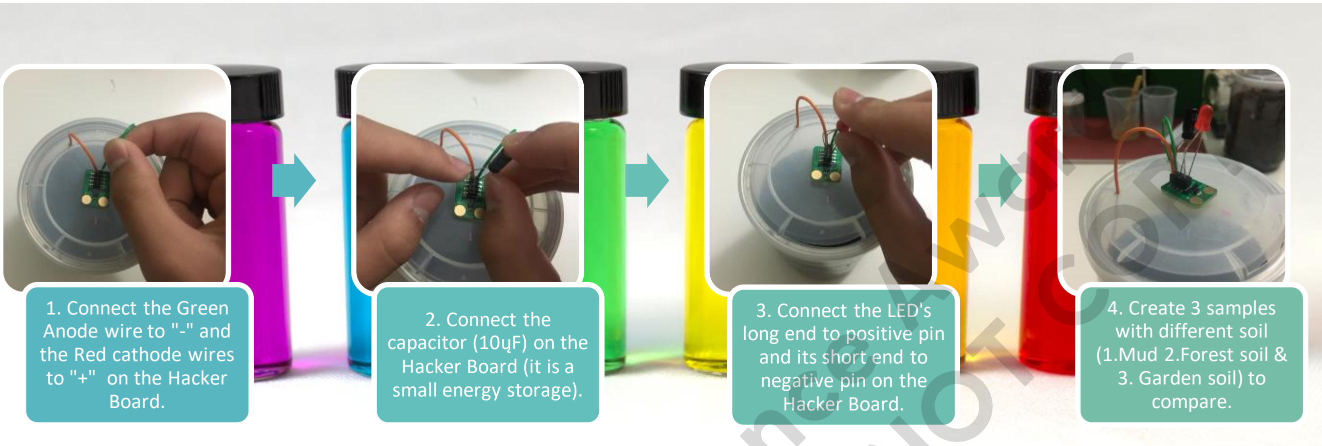
From the data above, it can be found that the electrode distance has no obvious correlation with the generated voltages, but the size of the electrodes affects the power generation.

Experiment 3 – Different Types of Soil (Mud/Forest Topsoil/Garden Soil).

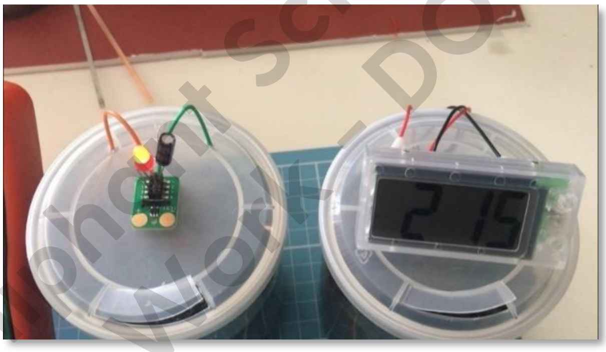
3A. Seconds between Two Blinks.

*(**Steps 1~3:** Install the electrodes and place the sediments as Steps 1-3 for 1A by using different soil).*

Step 4: Set up the Hacker Board.



Step 5: Measure the Time Duration between Two Blinks.

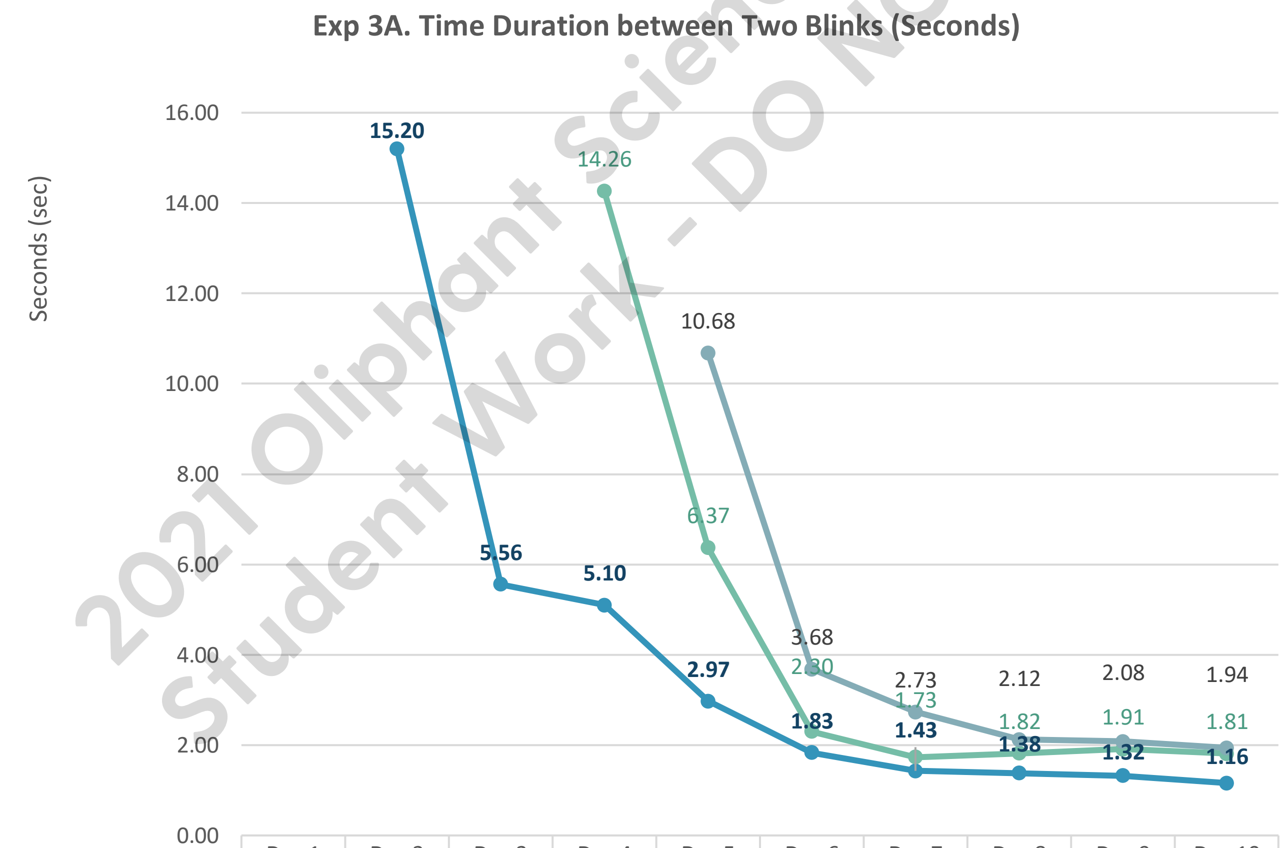


Fixed Variable MFC Same Location, Temperature Multimeter, Alligator Clips.	Independent Variables (Time between Two Blinks)									
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10
	16/05	17/05	18/05	19/05	20/05	21/05	22/05	23/05	24/05	25/05
Dependent Variables (Seconds)	Sec	Sec	Sec	Sec	Sec	Sec	Sec	Sec	Sec	Sec
Sample 1 Soil 1 – Benthic Mud	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Failed Experiment Suspended. (Check the connection and Recreated)		
Sample 2 Soil 2 – Forest Topsoil	Nil	Nil	Nil	14.26	6.37	2.30	1.73	1.82	1.91	1.81
Sample 3 Soil 3 – Backyard Garden	Nil	Nil	Nil	Nil	10.68	3.68	2.73	2.12	2.08	1.94
Sample 1 recreation.	Nil	15.20	5.56	5.10	2.97	1.83	1.43	1.38	1.32	1.16

Setup the Hacker board and the LED should start blinking after 3~7 days, the hacker board takes the low voltage and low current coming from the MFC and converts into short bursts of higher voltage and current to glow the LED light. Three MFC samples are created with different types of soil. The first sample of LED light did not glow, the experiment was terminated, and a new sample was recreated (blinks at Day 2). The MFC sample 2 took 3 days to drive LED light to blink, and the power output were still stable after a week, and sample 3 took a bit longer, which started blinking at Day 5. If the LED is blinking too fast, don't time the seconds between two blinks, the duration between 2 blinks can be obtained by measuring the time of 10 blinks. The chart in ***Appendix 3.*** helps the problem shooting, to achieve the goal of the experiment.

Results of Experiment 3A:

The MFC created by benthic mud first started to drive the LED to light, then the forest topsoil and the MFC created by backyard garden soil was the slowest one to light. The MFCs using different soil began to emit light within five days, and the interval of emission became shorter gradually, and the power remained stable after one week. The MFC using mud has the shortest interval between two blinks, followed by forest soil and finally the garden soil.

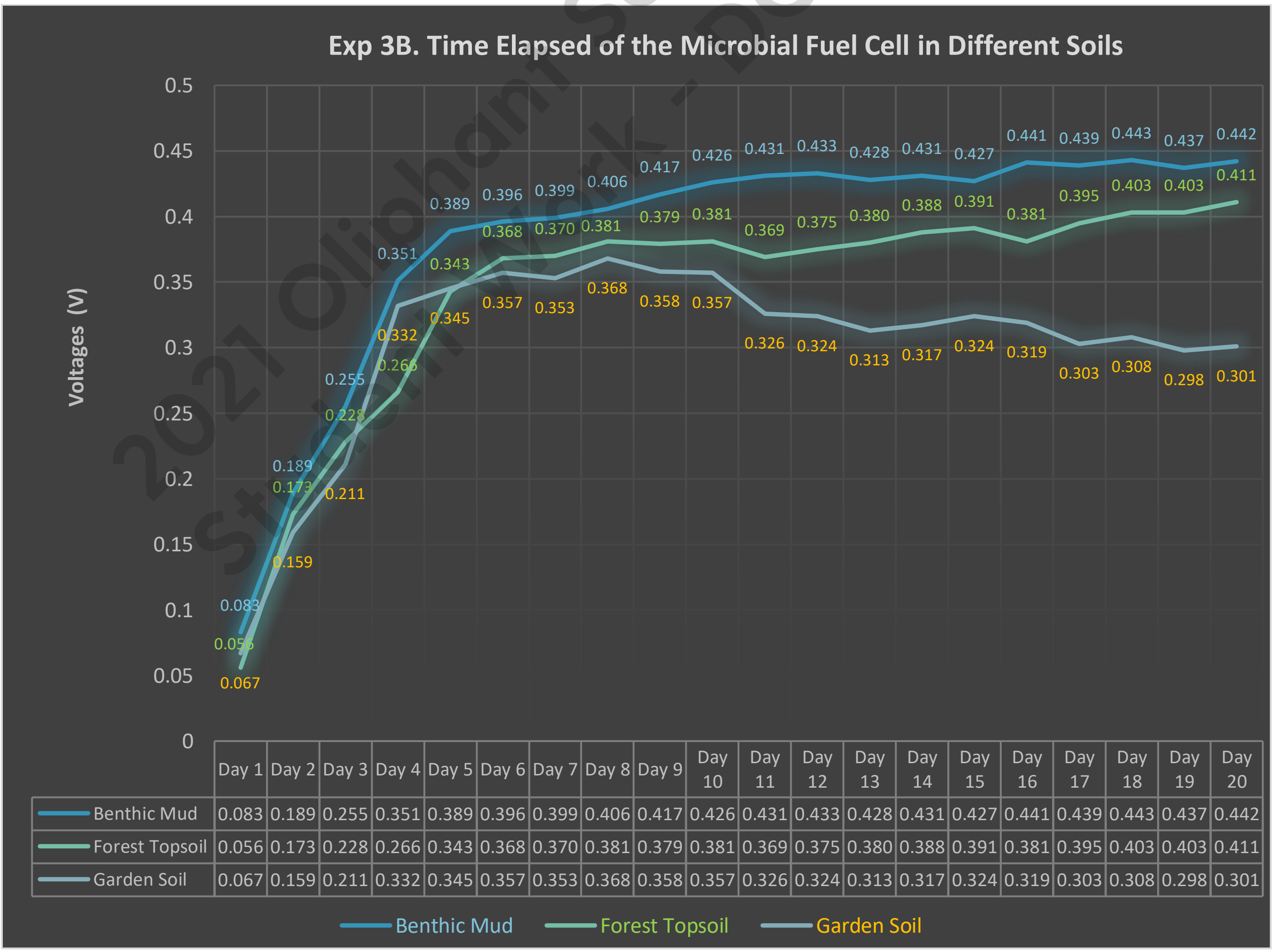


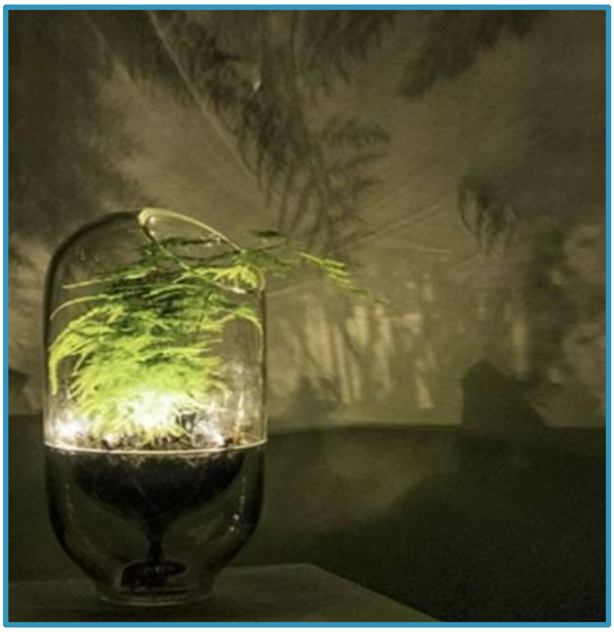
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10
Benthic Mud		15.20	5.56	5.10	2.97	1.83	1.43	1.38	1.32	1.16
Forest Topsoil				14.26	6.37	2.30	1.73	1.82	1.91	1.81
Backyard Garden					10.68	3.68	2.73	2.12	2.08	1.94

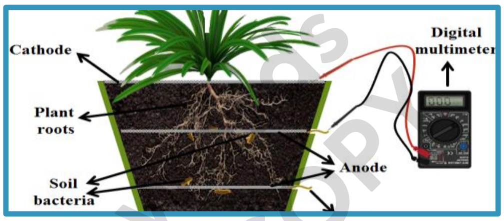
Benthic Mud Forest Topsoil Backyard Garden

Experiment 3B. Electricity Generation (Voltages) in Different Types of Sediments.

Fixed Variable Same Location, Temperature Multimeter, Alligator Clips, electrodes materials.	Independent Variables – Different Types of Soils									
	Day 1 (16/05)	Day 2 (17/05)	Day 3 (18/05)	Day 4 (19/05)	Day 5 (20/05)	Day 6 (21/05)	Day 7 (22/05)	Day 8 (23/05)	Day 9 (24/05)	Day 10 (25/05)
Dependent Variables Voltages (V)	V	V	V	V	V	V	V	V	V	V
Soil 1 (Benthic Mud)	0.083	0.189	0.255	0.351	0.389	0.396	0.399	0.406	0.417	0.426
Soil 2 (Forest Topsoil)	0.056	0.173	0.228	0.266	0.343	0.368	0.370	0.381	0.379	0.381
Soil 3 (Backyard Garden)	0.067	0.159	0.221	0.312	0.345	0.357	0.353	0.368	0.358	0.357
	Day 11 (26/05)	Day 12 (27/05)	Day 13 (28/05)	Day 14 (29/05)	Day 15 (30/05)	Day 16 (31/05)	Day 17 (01/06)	Day 18 (02/06)	Day 19 (03/06)	Day 20 (04/06)
	V	V	V	V	V	V	V	V	V	V
Soil 1 (Benthic Mud)	0.431	0.433	0.428	0.431	0.427	0.441	0.439	0.443	0.437	0.442
Soil 2 (Forest Topsoil)	0.369	0.375	0.380	0.388	0.391	0.381	0.395	0.403	0.403	0.411
Soil 3 (Backyard Garden)	0.326	0.324	0.313	0.317	0.324	0.319	0.303	0.308	0.298	0.301



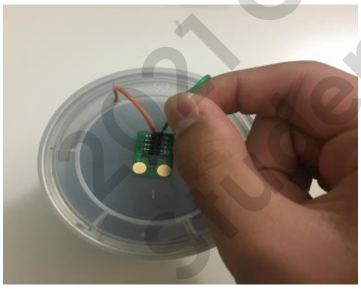




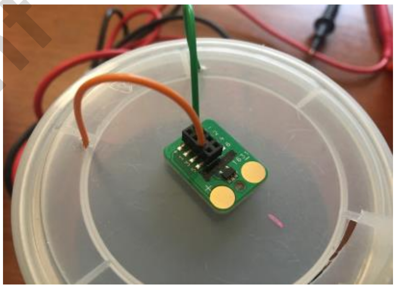
<u>Results of Experiment 3B</u>: All three MFCs generate different levels of electricity, meaning that the bacteria in the soil can convert chemical energy into electrical energy. Their trends are similar, they are low at the beginning, then gradually increase with time and reach a stable status after a few days. The MFC created by mud can drive LED light to emit light on the 2nd day, and presents a stable voltage after the 3rd day, which is still maintained at 0.426V on the 10th day and can still maintain at 0.44~0.48V without adding any nutrients after couple weeks. The other two MFCs produce slightly lower electricity and are relatively slower to make LEDs glow (forest soil: 4th day; garden soil: 5th day). The power of MFC1 (0.476V after 6 weeks) & MFC2 (0.431V after 6 weeks) is still rising steadily, but the MFC3 has begun to decline from the third week (nutrients are needed after Day 25 to keep 0.35V to light the LED in MFC3; refer to the logbook for long-term experimental data record).

Experiment 4. Resistors and the Maximum Power.

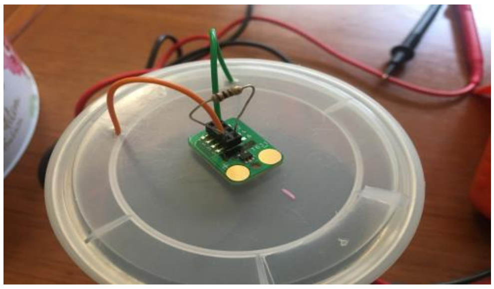
Measure the power output for three MFCs (different soil types) using the multimeter and resistors.



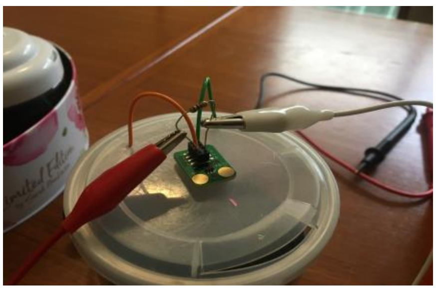
1. Remove the capacitor and LED from the Hacker Board.



2. Remove the red wire from the "+" pin and plug it into pin 3.



3. Place a resistor between pin 5 and 6, the orientation does not matter. Start with the largest-capacity resistor, which will be a 33 KΩ resistor.



4. Resistor's values are labeled using colour-coded bands (Use <u>Figure 2.</u> to determine the resistance for each resistor or using the multimeter by setting it to measure resistance).

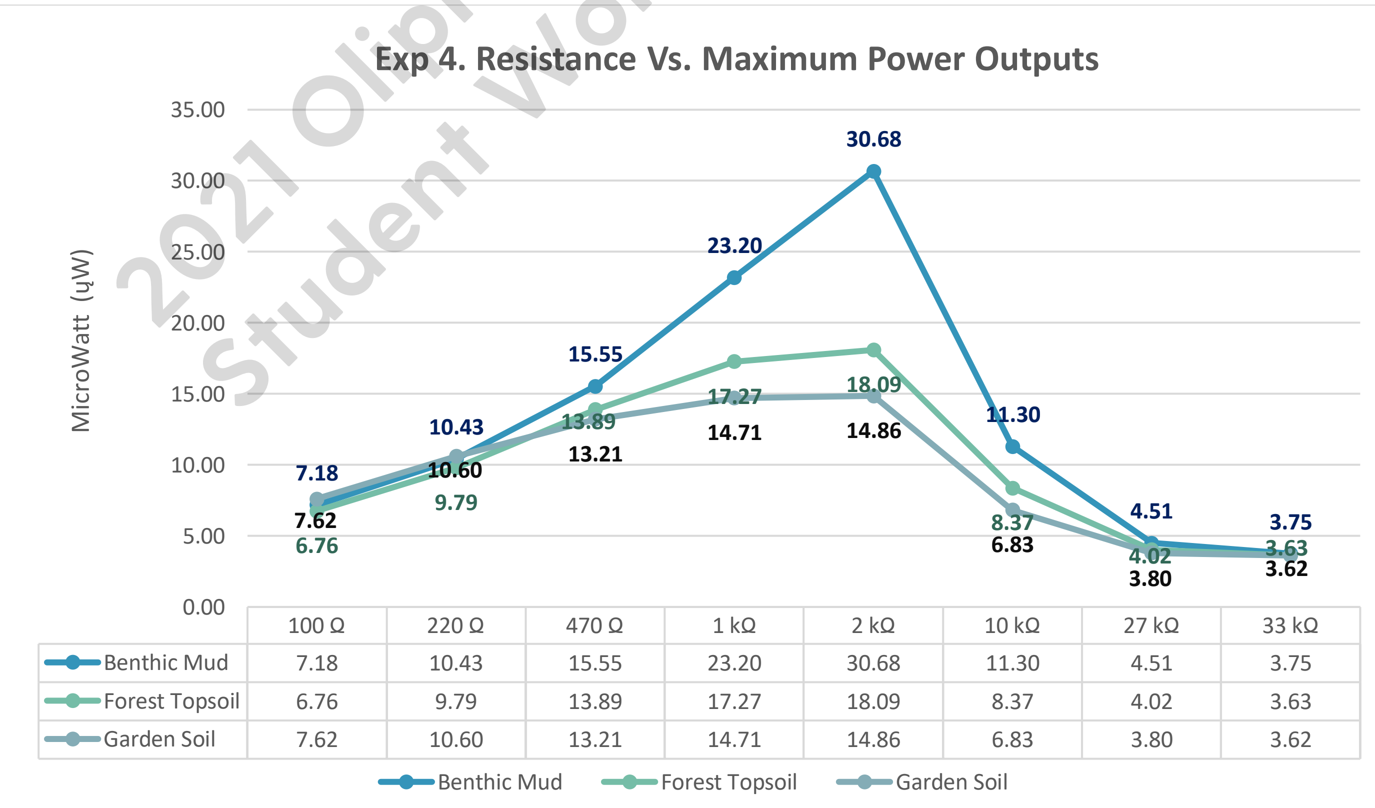
5. Connecting the multimeter's leads on the wire ends of the resistor (leave the resistor plugged in for 2 minutes).

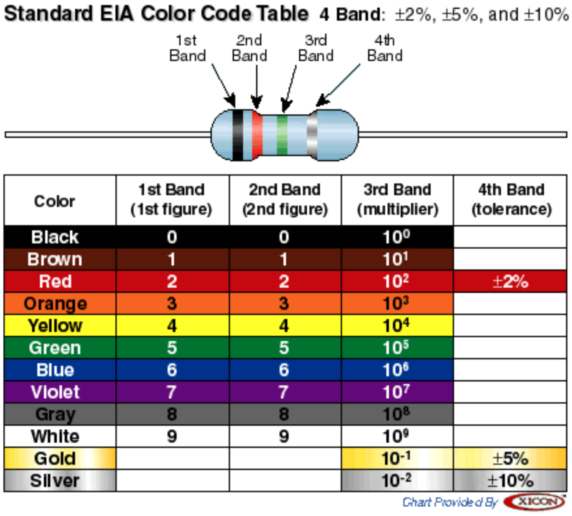
Fixed Variable Same Location, Temperature Multimeter, Alligator Clips, electrodes materials.	Independent Variables – Resistances (Ω)							
	100 Ω	220 Ω	470 Ω	1 KΩ	2 KΩ	10 KΩ	27 KΩ	33 KΩ
Dependent Variables Voltages (mV)	mV	mV	mV	mV	mV	mV	mV	mV
Soil 1 (Benthic Mud)	26.8	47.9	85.5	152.3	247.7	336.2	349.1	351.9
Soil 2 (Forest Soil)	26.0	46.4	80.8	131.4	190.2	289.3	329.6	345.9
Soil 3 (Backyard Garden Soil)	27.6	48.3	78.8	121.3	172.4	261.3	320.3	345.5

Power (Watt) = (Voltages)^2 / Resistances (ohms)

Power = (0.0276V)^2 / 100 ohms × 1,000,000 = 7.62 (Microwatt)
Means power out equal to 7.62 microwatt when using 100Ω resistor.

Fixed Variable Same Location, Temperature Multimeter, Alligator Clips, electrodes materials.	Independent Variables – Maximum Output (ųW)							
	100 Ω	220 Ω	470 Ω	1 KΩ	2 KΩ	10 KΩ	27 KΩ	33 KΩ
Dependent Variables Power (ųW)	ųW	ųW	ųW	ųW	ųW	ųW	ųW	ųW
Soil 1 (Benthic Mud)	7.18	10.43	15.55	23.20	30.68	11.30	4.51	3.75
Soil 2 (Forest Topsoil)	6.76	9.79	13.89	17.27	18.09	8.37	4.02	3.63
Soil 3 (Backyard Garden Soil)	7.62	10.60	13.21	14.71	14.86	6.83	3.80	3.62



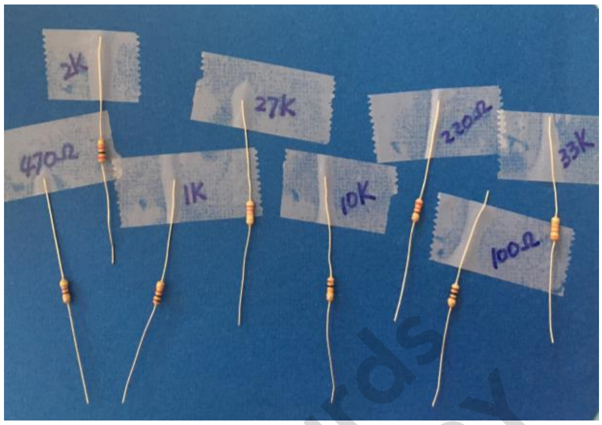


Standard EIA Color Code Table 4 Band: ±2%, ±5%, and ±10%

Color	1st Band (1st figure)	2nd Band (2nd figure)	3rd Band (multiplier)	4th Band (tolerance)
Black	0	0	10^0	
Brown	1	1	10^1	
Red	2	2	10^2	±2%
Orange	3	3	10^3	
Yellow	4	4	10^4	
Green	5	5	10^5	
Blue	6	6	10^6	
Violet	7	7	10^7	
Gray	8	8	10^8	
White	9	9	10^9	
Gold			10^{-1}	±5%
Silver			10^{-2}	±10%

Chart Provided By XICON

Figure 2. Resistor Colour Code Table



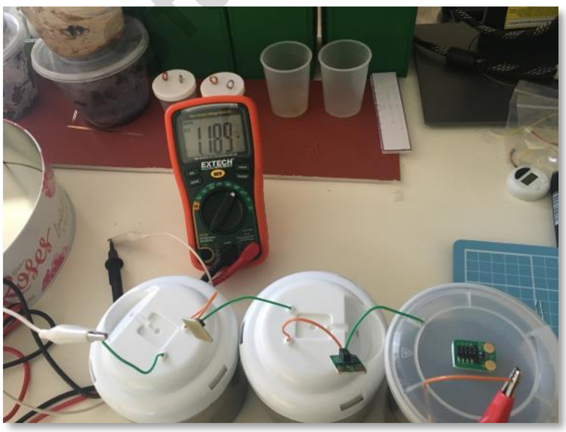
Results of Experiment 4:

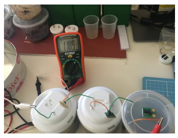
It is important to convert the voltage measurements into power output measurements. The power output depends on the resistors. The effectiveness of the MFC cannot be determined by just looking at the voltage generation alone because it is needed to convert into power for them to be more meaningful. The results show the peak powers of the MFCs were all found using a 2kΩ resistor and the peak powers are 30.68 ųW (Mud), 18.09 ųW (Forest) and 14.86 ųW (Garden) respectively. The sample with mud has the highest maximum power output and the garden soil has the lowest power output, meaning the benthic mud can generate more power than garden soil. Microbes like to eat something is bioavailable and easily broken down, therefore, forest or benthic mud will produce more electricity than the soil from the garden because it contains more decaying materials and organic matter in it.

To turn soil into a cell, the most important thing you need is lots of bacteria that help generate electricity when they break down organic or inorganic substrates in the soil. The soil bacterial eat the microscopic nutrients and sugars in the soil and produce electrons that are released back into the soil. Therefore, the soil that contains more organic matter generates higher voltages and power outputs.

Experiment 5. Connection in Series.

Multiple MFCs are connected in series respectively, to measure and compare the voltages with a single MFC.



Fixed Factors MFC	Independent Variable – Connections of the MFCs.				
	MFC ①	MFC ②	MFC ③	② & ③ connected in series.	①, ② & ③ connected in series.
Same Location, Temperature Multimeter, Alligator Clips, Electrodes Materials.					
Dependent Variables	V	V	V	V	V
Voltages (V)	0.421	0.403	0.396	0.773 < 0.799	1.189 < 1.220
		②+③ = 0.799			
	①+②+③ = 1.220				

Result of Experiment 5:

When the MFCs are connected in series, the voltage will increase (0.773V when two MFCs connected in series; 1.189V when three MFCs connected in series), but the voltages are getting slightly unstable due to the internal resistance (0.773V < 0.799V; 1.189V < 1.220V), so the generated voltage will be reduced slightly. Small electrical appliances like a digital clock can be driven if multiple MFCs connected in series.

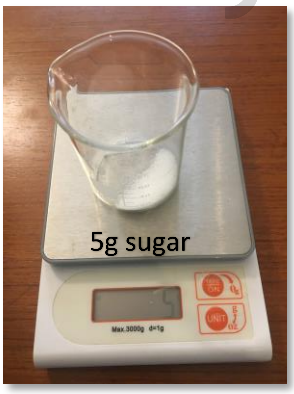
Experiment 6. Types of Nutrients

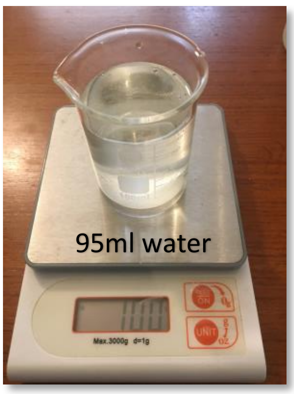
To explore the effect of added nutrients on power generation.

Nutrients:
(1) Sugar (2) Glucose (3) Fructose.

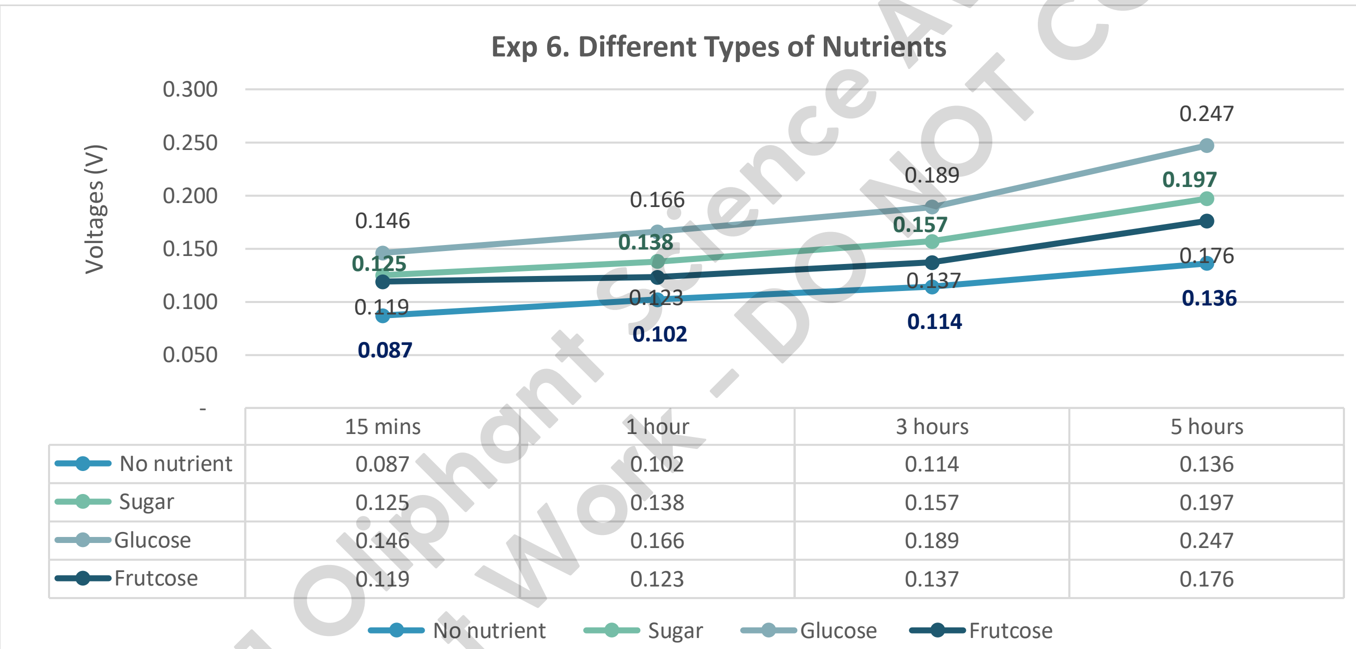
Step:

Add 5ml of different kinds of nutrients, and measure the voltages at the beginning, 1, 3 and 5 hours after adding the sugar water.





Fixed Factors MFC Same Location, Temperature Multimeter, Alligator Clips, Soil, Electrodes Materials.	Independent Variable – Nutrients Added on the Soil.			
	No nutrient Added	5ml (1) Sugar Water	5ml (2) Glucose Water	5ml (3) Fructose Water
Dependent Variables Voltages (V)	V	V	V	V
15 mins	0.087	0.125	0.146	0.119
1 hour	0.102	0.138	0.166	0.123
3 hours	0.114	0.167	0.189	0.137
5 hours	0.136	0.187	0.247	0.166



<u>Result of Experiment 6:</u>

From the data above, the power generations have been improved after adding nutrients. Compared with the control group without adding any nutrients, the MFC with glucose has the best power increase effect, followed by sugar and the MFC with fructose is the worst. The longer the standing time, the higher the power generated (within 5 hours). Bacteria can convert energy into electricity in the process of breaking down the raw materials for bacteria to generate electricity. The more the bacteria can make full use of nutrients, the power generation will be increased.

Conclusion

1. No matter what material of electrodes is used, the MFC generates electricity.
2. The MFC using metal electrodes generates faster, higher and stabler electricity than the one using carbon electrodes.

3. All samples can drive the LED to emit light, except the one that failed due to the damage of the LED component; the problem has been fixed after recreation (*Appendix 3*).
4. Benthic mud will produce more electricity than the soil from the garden because it contains more decaying materials and organic matter in it.
5. The peak powers were all found using a 2kΩ resistor which are 30.68 ųW (Mud), 18.09 ųW (Forest) and 14.86 ųW (Garden) respectively.
6. The electrode distance has no obvious correlation with the generated voltages, but the size of the electrodes will affect the power generation.
7. When multiple MFCs are connected in series, the voltage is added but the current stays the same.
8. The MFCs have been able to maintain stable power and kept the LED on for more than 8 weeks without adding any nutrients. It means if the nutrition can be added in time, the MFC can produce an endless stream of electricity.
9. Sugar, glucose and fructose can be used as the nutrients for bacteria to generate electricity.

Summary

Due to fossil fuels will not meet the future energy demand, it becomes necessary to develop sustainable and renewable energy resources and technologies. The organic matter stored in the natural environment and waste is a huge source of energy resources. Although the MFC technology has become a research hotspot, its power generation capacity has been continuously improved, but most of the results are carried out in a small laboratory, there are still many difficulties to overcome from the actual engineering application. The MFC can be used to support sustainable energy if it can be improved the efficiency and reduced the cost (***Appendix 4***). The MFC will be widely used and play an important role in reducing the waste and generate electricity in current pollution and energy shortage environment. The MFC synchronous pollution control and power generation catalytic wastewater treatment has great practical significance and potential. In the future, using bacteria and even viruses to generate electricity will no longer be the dream.

Appendix

1. The Developmental History of the Microbial Fuel Cells.
2. The Experimental Variables
3. Problem Solving Process
4. Advantages, Disadvantages of the MFCs.
5. Bibliography
6. Logbook

<u>Appendix 1.</u> **The Developmental History of the Microbial Fuel Cells**

Year	Author	Event
2015	The University of West England	Two mobile toilets with 8 MFC modules were driven by urine to generate electricity for LED lights.
1999	Kim, H. J., Hyun, M. S., Chang, I. S., Kim, & B. H.	Discovered firstly that certain electrochemically active bacterial species use no mediator molecules.
1993	Allen, R. M. & Bennetto, H. P.	Demonstrated improved biological fuel cells using various microbes to increase both the reaction rate and the efficiency of electron-transfer using mediator systems. Used sugar as food to let bacteria break down molecules and release electrons to drive the computers.
1966	Williams, K. R.	Showed that rice husk ins a potential source of lignocellulose as it can produce upon fermentation many useful enzymes and biofuels resulting in 40 mA at 6 V using biological fuel cells.
1962	Rohrback, G. H., Scott, W. R. & Canfield, J. H.	Designed the first biological fuel cell in which Clostridium butyricum was used as biomaterial to generate hydrogen by glucose fermentation.
1931	Cohen, B.	Voltage generation & current delivery by microorganisms. (Over 35 volts with only a current of 2 milliamps when connected in series.
1911	Potter, M.C.	Discovered electrical energy from cell cultures of Escherichia coli and Saccharomyces using platinum electrodes.
1910	Potter, M.C.	Voltage generation & current delivery by microorganisms.
1791	Luigi Galvani	Bioelectric phenomenon.

Appendix 2. Experimental Variables

<table>
<tr><th>Independent Variable</th><th colspan="3">How is it being changed?</th></tr>
<tr><td rowspan="2">The type of soil used in Microbial Fuel Cell.
</td><td colspan="3">Three different types of soils have been used in the experiment to investigate the power generated by Microbial Fuel Cells. Find out how the electricity generated by MFCs change if different types of soil have been used.</td></tr>
<tr><td>
Benthic Mud Topsoil from Forest</td><td>
Topsoil from Forest</td><td>
Backyard Garden Soil</td></tr>
</table>

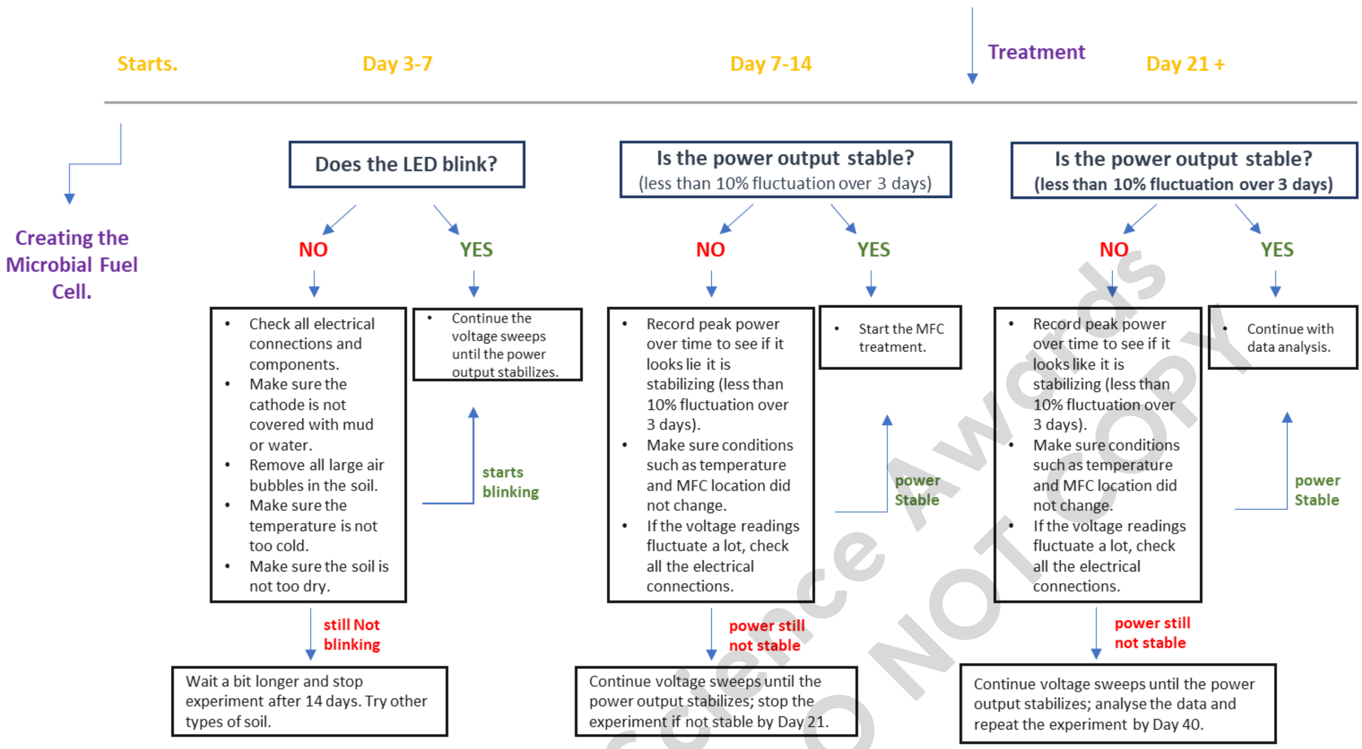
<table>
<tr><th>Dependent Variable</th><th colspan="3">How is it being measured? (Voltages)</th></tr>
<tr><td rowspan="2">The power generated by the Microbial Fuel Cells.</td><td colspan="3">Measuring the voltages and current generated by different Microbial Fuel Cells.</td></tr>
<tr><td>
[Soil 1]
Benthic Mud</td><td>
[Soil 2]
Forest Topsoil</td><td>
[Soil 3]
Backyard Garden Soil</td></tr>
</table>

Controlled Variables	**Make sure the variable cannot influence the results. This isolates the independent variable's effects on the experiment and can help rule out alternative explanations of the experimental results.**
Temperature	All MFCs will be kept in the same place to keep the temperature constant because it may influence the activity of bacteria. Different bacteria can survive in different temperature environments, maintaining the temperature can avoid the influence of the bacterial activity caused by temperature on the results.
Carbon Felts (Anode & Cathode)	Use the same carbon felts for anode and cathode for each MFC created and make sure the sizes of electrodes (carbon felts) are all the same.because the conductivity and electrode area may affect the accuracy of the experiment. The sizes of electrodes and the area of soil contact may affect the data.
Measuring Time	Make sure to measure the power generated by each MFC at the same time everyday.
Distance between electrode	Place the same amount of soil into each vessel (5 cm deep) or keep the electrodes at the same distance, making the distances between anode and cathode the same.
Vessel Size	Each vessel will be the same size and will hold the same amount of soil.
Soil Moisture	Make sure all kinds of soils are at the same level of moisture. The difference of moisture will also cause the difference of conductivity.
Nutrient content amount	Make sure to add the same volume of nutrient into soils.

<u>Appendix 3.</u> Problem Solving

The following chart can help solve the problems that may be encountered in the experiment.

Experiment Flow Chart



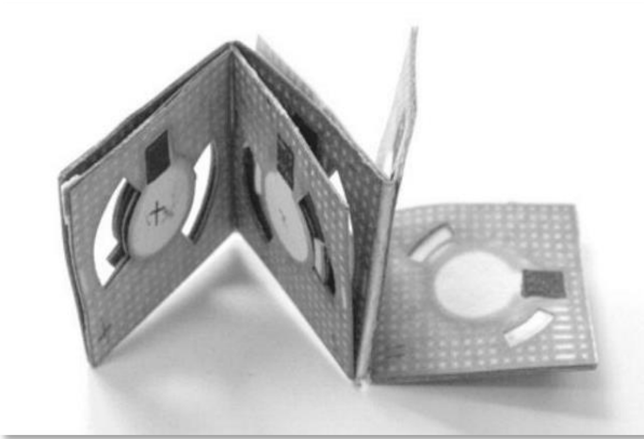
Problems	One LED doesn't emit light.	Unstable Temperature	Soil Sampling
	The experiment has to be suspended due to the LED not blinking after 7 days.	It's difficult to maintain the constant temperature in winter.	The samples were used several hours after collection.
Impacts	Unable to get comparative data, the sample has to be recreated, which might influence the experimental results.	The activity of bacteria varies with temperature. The results may be affected by the inconsistent temperature.	The bacterial colony might have already grown exponentially.
How to improve?	 Make sure the LED and capacitor are well connected to the Hacker Board, and that they are placed in the correct orientation. After rechecking the circuit, the reason of this failure was the damage of the LED. All equipment should be checked before use.	Use an apparatus that could keep constant temperature in an enclosed environment. In addition, the influences of temperature on the power output of an MFC can be the topic of further research.	Use the sample as soon as possible. 

<u>Appendix 4.</u> Advantages & Disadvantages of the MFCs.

Advantages and Disadvantages of the MFCs

MFC	Advantages	Disadvantages
	1. No burning is required to produce energy. 2. High energy conversion efficiency. 3. Wide range of raw materials. 4. Operating conditions are mild and can work in normal temperature, normal pressure and neutral environment. 5. Good biocompatibility and can be used as power supply for artificial organs. 6. Environment friendly. The only waste gas produced by the MFC is Co_2. 7. The solar cells made of bacteria can generate electricity normally in cloudy days (no effect of light intensity).	1. High power but low power density. 2. High initial Cost, especially the electrode materials (platinum catalysts for cathodes). 3. Bacterial metabolic losses.

Applications



Appendix 4. Bibliography

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- 2021. [online] Available at: https://www.researchgate.net/publication/276043847_An_Experimental_Study_of_Microbial_Fuel_Cells_for_Electricity_Generating_performance_characterization_and_capacity_improvement

Images

- resistor-color-codes.jpg (1024×1229) (build-electronic-circuits.com)
- https://en.wikipedia.org/wiki/Microbial_fuel_cell#/media/File:SoilMFC.png
- https://secureservercdn.net/198.71.233.68/97r.1fc.myftpupload.com/wp-content/uploads/2015/10/Fuel_cell.jpg

May

2021

Scientific Inquiry – The Power in Bacteria – The Microbial Fuel Cells (MFCs)

The MFCs Logbook

"What can affect the Microbial Fuel Cells? What is best environment for bacteria in the Microbial Fuel Cells?"

During April 2021, I searched several different topics and found out the topic I would like to do for Oliphant Science Competition 2021 and started to plan my experimental flow chart for my topic.

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
25 Topic confirmed. **The Microbial Fuel Cells (MFCs).**	26 Design experiments to support my argument and List all materials.	27 List where to get or buy materials where to collect the soil samples.	28 Search Information and References.	29 Set up the platform and methods.	30 Soil sampling.	May 1 **Experiment 1. (D1)** Electrode Materials. →
2 →	3 →	4 →	5 →	6 →	7 →	8 →
9 →	10 **Experiment 1.** **(Day 10)**	11	12	13	14 Soil sampling.	15 **Experiment 2A & 2B.** Distances & Sizes.
16 Experiment 3A & 3B. Soil Types.	17 →	18 →	19 →	20 →	21 →	22 →
23 →	24 →	25 Experiment 3A (Day 10)	26 →	27 →	28 →	29 →
30 →	31 →	June 1 →	2 →	3 →	4 **Experiment 3B** **(Day 20)**	5 →

2021.04.25 | **Experimental Record**

The Microbial Fuel Cells

- Confirmed the topic of the Oliphant Science Competition 2020:

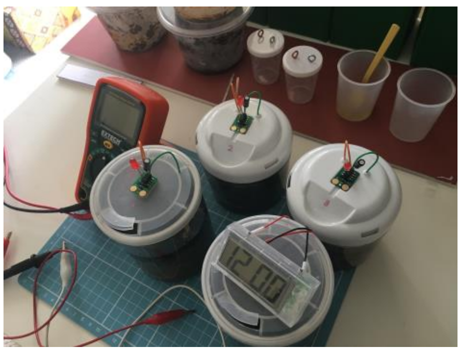
  "What can affect the Microbial Fuel Cells (MFCs)"
  "What is the best environment for bacteria in the MFCs?"

- Set up my hypothesis and experimental direction.

  One of the hypotheses:

  "The soil from benthic mud & forest topsoil will produce more electricity that the soil from the backyard garden because it contains more decaying material and organic matter in it."

2021.04.26 ~ 2021.04.27 | **Experimental Record**



- Designed different experiments to support the hypothesis.
  1. Electrode Materials (1A: Graphite Fiber; 1B: Metal).
  2. Electrodes: 2A: Distances between Electrodes (1 ~ 7cm).
     2B: Sizes of Electrodes (10cm vs 3cm).
  3. Different Types of Soil (Mud, Forest Topsoil, Garden Soil).
  4. Resistors & Maximum Power Outputs.
  5. Connection of multiple MFCs.
  6. Nutrients for Bacteria.
- Listed all materials and equipment for experiments (***Table 1***).

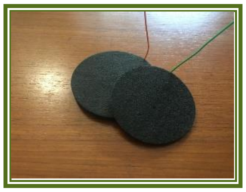
Table 1. Materials and Equipment

Equipment		Soils
8 × Plastic Vessels with Lids	6 × Capacitor (10ųF)	Benthic Mud
4 × Carbon Felts	1 × 10mL Glucose Solution	Forest Topsoil
1 × Red Wire for Cathode	6 × LED Light	Backyard Garden Soil
1 × Green Wire for Anode	1 × Cupper Sheets & 1 × Zinc Sheets	
1 × Multimeter	1 × 5g Sugar	
6 × Alligator Clips	1 × 5g Glucose	
6 × Gloves	1 × 5g Fructose	
8 × Resistors		

2021.04.28 | **Experimental Record**

- Searched the information and references for this project.
- Advantages and disadvantages of the MFCs.
- Lists all possible experimental variables (***Appendix 2***).
  - Dependent variables.
  - Independent variables.
  - Controlled variables.

2021.04.29	Experimental Record

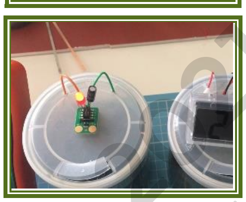


1. Build the Electrodes.

2. Collect soil samples & Add sediments into the vessels.

3. Set up the Multimeter & Measure the voltages generated.

4. Setup the Hacker Board.



5. Measure Blinking Intervals & Measure the Voltages.

6. Measure the Power Outputs.

- Set up the experimental platform and prepare to start the experiments.

- Designed the method steps of creating a MFC sample.

Step 1. Build the electrodes.

1. Cut the carbon felt into circles (one for anode and one for cathode) while wearing the gloves.
2. Remove the plastic sheath (8cm long) from the green wires and bend the wire 90° where the plastic sheath ends.
3. Insert the bare end of the green wire (anode) into the side of the felt while wearing the gloves.
4. Repeat with the red (cathode) wire.

Step 2. Collect soil samples & add sediments.

1. Collect soil from benthic mud, forest and backyard garden.
2. Add soil into the vessel, followed by the anode and fill with more mud (5 cm deep).
3. Place the cathode gently on the top of the mud, and make sure the top of the cathode is exposed to air.
4. Make sure the moisture of each kind of soil is constant, add some water if it is too dry.

Step 3. Measure the power generated by the Microbial Fuel Cell.

1. Plug the red probe (+) into the 'VΩmA' port and the black probe (-) into the "COM' port.
2. Connect the red probe and the red wire of the MFC with alligator clips.
3. Connect the black probe and the green wire of the MFC with alligator clips.
4. Turn the multimeter to V_{DC} and record the data each hour for first 10 hours.

Step 4. Hacker boards setup.

1. Bend and connect the cathode wire (Red) to '+' and the anode wire (Green) to '-' on the Hacker board.
2. Connect the long end of the capacitor (10µF) to Pin 1 and the short end to Pin2.
3. Connect the LED's long end to Pin 5 and its short end to Pin 6.
4. The LED should begin to blink after a few days. Measure the gap between blinks.

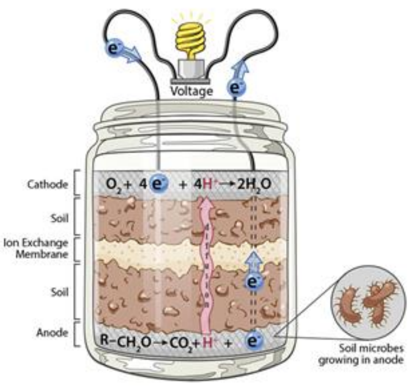
Step 5. Measure the duration of each blink.

1. Observe which MFC sample's LED starts to light first.
2. Measure the duration of 10 blinks in seconds.
3. Get the duration between two blinks in seconds and compare between three different MFCs.

Step 6. Measure the power outputs of each sample.

1. Remove all components from the Hacker Board except the anode wire (Green wire still in '-').
2. Remove the red wire from the "+" Pin and plug into Pin3.
3. Place a resistor between Pin 5 and 6, the orientation does not matter. Start with the largest-capacity resistor, which will be a 33 KΩ resistor.
4. Leave the resistor plugged in for 2 minutes and measure the voltages by using the multimeter & alligator clip.
5. Calculate the power output.
   Power (Watts) = (Voltages)² / Resistance $\text{Power (Watts)} = (\text{Voltages})^2 / \text{Resistance}$

2021.04.30	Experimental Record



Since the moisture will affect the conductivity, it is necessary to ensure that the humidity is consistent and use three-way meter to measure the humidity and PH value and control the humidity by adding water.

- Collected soil samples from the creek mud, forest topsoil and back yard garden soil.

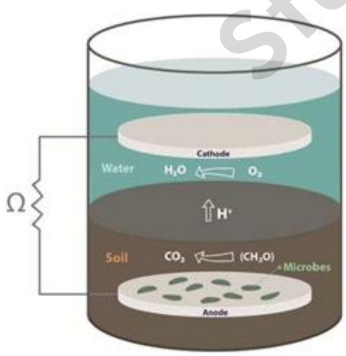

1. Mud


2. Forest Topsoil


3. Backyard Garden Soil

1. Mud: The colour is dark gray with very high moisture (Wet = 8) and stink smell (PH = 8).
2. Forest topsoil: The soil colour is brown with low moisture (Wet =1.5; PH = 8).
3. Backyard Garden Soil: The colours is dark brown with medium to low moisture (Wet = 2.5; PH = 8) .

2021.05.01 ~ 2021.05.10	Experimental Record

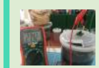


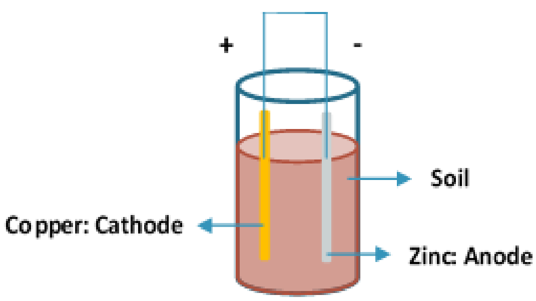
Create a Single-chamber MFC Sample – Type 1A (Graphite Fiber).

- Step 1: Build the electrodes
- Step 2: Collect soil samples & attach the electrodes.
- Step 3: Measure the Voltage and record the data (1A).

Result:
The MFC using graphite fiber electrodes produce smaller electricity.

Result 1A (Electrodes: Carbon Felt / Graphite Fiber)

Fixed Variable MFC Same Location, Temperature Multimeter, Alligator Clips, Soil (**Garden Soil**) (Created at 8am)	Independent Variables (Time Elapsed: Hourly) 2021.05.01									
	9am	10am	11am	12 noon	1pm	1pm	1pm	4pm	5pm	6pm
										
Dependent Variables	V	V	V	V	V	V	V	V	V	V
Voltages (V)	0.167	0.199	0.209	0.217	0.220	0.228	0.232	0.274	0.311	0.292
	mA	mA	mA	mA	mA	mA	mA	mA	mA	mA
Milliamps (mA)	0.22	0.28	0.29	0.30	0.33	0.35	0.33	0.40	0.42	0.45



Create a Single-chamber MFC Sample – Type 1B (Metal Electrodes).

- Step1: Build the electrodes.
- Step 2: Collect soil samples & attach the electrodes.
- Step 3: Measure the Voltage and record the data (1B).

Result:
The MFC using metal (Cu + Zn) electrodes produces larger and stabler electricity in short period.

Result 1B (Electrodes: Cu + An)

Fixed Variable MFC Same Location, Temperature Multimeter, Alligator Clips, Soil (**Garden soil**)	Independent Variables (Time Elapsed: Hourly) 2021.05.01									
	9am	10am	11am	12 noon	1pm	1pm	1pm	4pm	5pm	6pm
Dependent Variables	V	V	V	V	V	V	V	V	V	V
Voltages (V)	1.468	1.454	1.445	1.432	1.431	1.451	1.409	1.411	1.443	1.439
	mA	mA	mA	mA	mA	mA	mA	mA	mA	mA
Milliamps (mA)	0.89	0.87	0.84	0.85	0.85	0.81	0.83	0.81	0.82	0.82

Fixed Variable Location, Temperature, Multimeter, Alligator Clips, Soil (**Backyard Garden**)	Independent Variables (Time Elapsed - Daily)									
	Day 1 (01/05)	Day 2 (02/05)	Day 3 (03/05)	Day 4 (04/05)	Day 5 (05/05)	Day 6 (06/05)	Day 7 (07/05)	Day 8 (08/05)	Day 9 (09/05)	Day 10 (10/05)
Dependent Variables	V	V	V	V	V	V	V	V	V	V
1A - Voltages (V) Carbon Felt	0.167	0.291	0.358	0.351	0.367	0.362	0.348	0.351	0.352	0.364
	V	V	V	V	V	V	V	V	V	V
1B - Voltages (V) Metal (Cu + Zn)	1.368	1.355	1.371	1.351	1.339	1.336	1.343	1.349	1.341	1.336

Experiment 1A. Graphite Fiber Electrodes.

Experiment 1A.

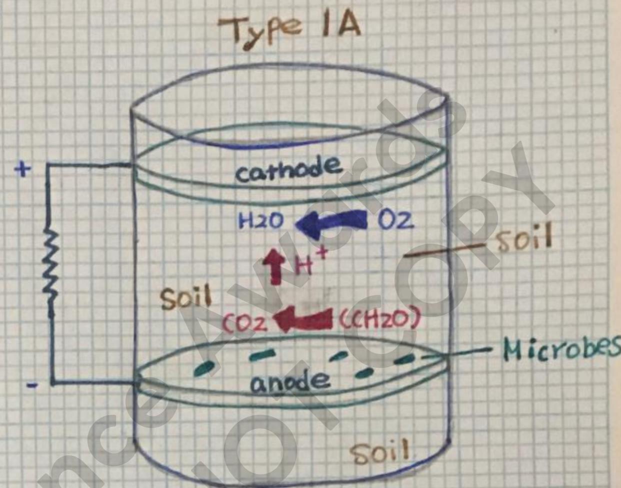
Date: 2021. 05. 01

Independent Variables: Time elapsed (hourly)

Soil Type: Garden Soil

Results

Time	Voltages (V)	Milliamps (MA)
9am	0.167	0.22
10am	0.199	0.28
11am	0.209	0.29
12noon	0.217	0.30
1pm	0.220	0.33
2pm	0.228	0.35
3pm	0.232	0.33
4pm	0.274	0.40
5pm	0.311	0.42
6pm	0.292	0.46



Experiment 1B.

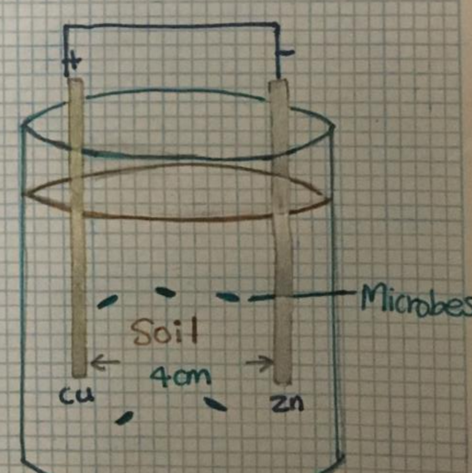
Date: 2021. 05. 01

Independent Variables: Time elapsed (hourly)

Soil Type: Garden Soil

Results

Time	Voltages (V)	Milliamps (MA)
9 am	1.468	0.89
10am	1.454	0.87
11 am	1.445	0.84
12 noon	1.432	0.85
1 pm	1.431	0.85
2pm	1.451	0.81
3pm	1.409	0.83
4pm	1.411	0.81
5pm	1.443	0.82
6pm	1.439	0.82



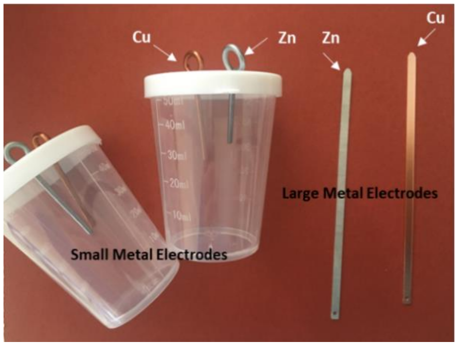
Experiment 1B. Metal Electrodes

2021.05.14	Experimental Record
 	• Soil Sampling for next experiments: - Benthic Mud. - Forest Topsoil. - Backyard Garden Soil.  

2021.05.15	Experimental Record
	• **<u>Experiment 2A</u>** – Distances between electrodes. (Garden Soil) - 1cm - 3cm - 5cm - 7cm **Result:** Electrode distance has no obvious correlation with the generated voltages.

Result of 2A – Distance between Electrodes

Fixed Factors MFC Same Location, Temperature Multimeter, Alligator Clips, Electrodes Materials.	Independent Variable – Distance between Electrodes			
	1 cm	3 cm	5 cm	7 cm
Dependent Variables	V	V	V	V
Voltages (V)	1.592	1.592	1.593	1.602
	mA	mA	mA	mA
Milliamps (mA)	1.61	1.59	1.75	1.52



- **Experiment 2B** – Sizes of the electrodes. (Garden Soil)
  - 10cm (Larger electrodes)
  - 3cm (Smaller electrodes)

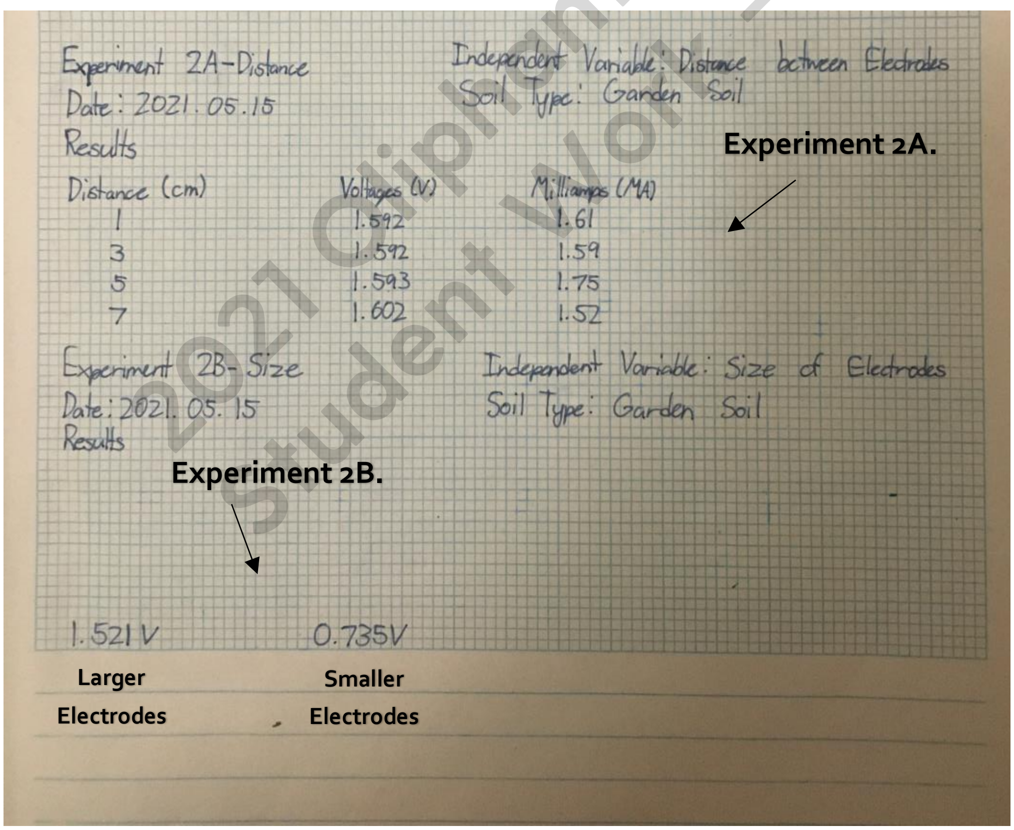
Result:

The size of the electrodes affects the power generation, the larger electrodes generate larger electricity.

Result of 2B – Size of Electrodes

Fixed Factors MFC (15/05)	Independent Variable – Size of Electrodes	
	Large Metal Electrodes **(10cm long)**	Small Metal Electrodes **(3cm long)**
Dependent Variables	V	V
Voltages (V)	1.521	0.735

Experiment 2A & 2B: Distance between Electrodes & Size of Electrodes.


Experiment 2A-Distance
Date: 2021.05.15
Results
Independent Variable: Distance between Electrodes
Soil Type: Garden Soil

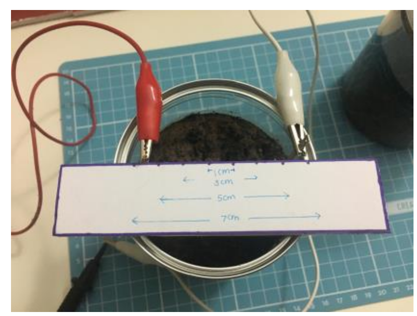
Experiment 2A.

Distance (cm)	Voltages (V)	Milliamps (MA)
1	1.592	1.61
3	1.592	1.59
5	1.593	1.75
7	1.602	1.52

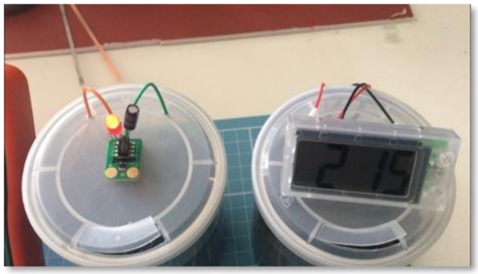
Experiment 2B- Size
Date: 2021. 05. 15
Results
Independent Variable: Size of Electrodes
Soil Type: Garden Soil

Experiment 2B.

1.521 V — Larger Electrodes
0.735V — Smaller Electrodes



2021.05.16 ~ 2021.05.25	Experimental Record



- **Experiment 3A** – will the LED blink?
- **Results:** Successful – all MFCs can drive the LED to blink.
- Recorded the data for 10 days.
- The MFC sample using mud has the shortest interval between two blinks, followed by forest soil sample and finally the backyard garden soil.
- The chart in ***Appendix 3.*** helps the problem shooting, to achieve the goal of the experiment.

Result of 3A: The Time Duration between Two Blinks.

Fixed Variable MFC Same Location, Temperature Multimeter, Alligator Clips.	Independent Variables (Time between Two Blinks)									
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10
	16/05	17/05	18/05	19/05	20/05	21/05	22/05	23/05	24/05	25/05
Dependent Variables (Seconds)	Sec	Sec	Sec	Sec	Sec	Sec	Sec	Sec	Sec	Sec
Sample 1 Soil 1 – Benthic Mud	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Failed Experiment Suspended. (Check the connection and Recreated)		
Sample 2 Soil 2 – Forest Topsoil	Nil	Nil	Nil	14.26	6.37	2.30	1.73	1.82	1.91	1.81
Sample 3 Soil 3 – Backyard Garden	Nil	Nil	Nil	Nil	10.68	3.68	2.73	2.12	2.08	1.94
Sample 1 recreation.	Nil	15.20	5.56	5.10	2.97	1.83	1.43	1.38	1.32	1.16

2021.05.16 ~ 2021.06.04	Experimental Record

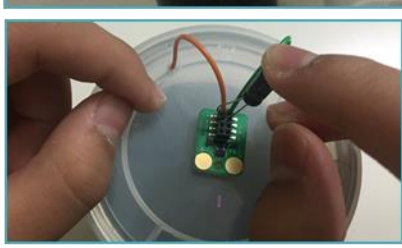
- **Experiment 3B** - Electricity generation in Different Types of Soil.
- **Independent Variable:** Soil Types.
- Recorded the data for at least 20 days.
- **Results:**
  All three MFCs generate different levels of electricity, meaning that the bacteria in the soil can convert chemical energy into electrical energy. Their trends are similar, they are low at the beginning of creation, then gradually increase with time and reach a stable status after a few days. The power of MFC1 (0.476V after 6 weeks) & MFC2 (0.431V after 6 weeks) is still rising steadily, but the MFC3 has begun to decline from the third week (nutrients are needed after Day 25 to keep 0.35V to light the LED in MFC3).

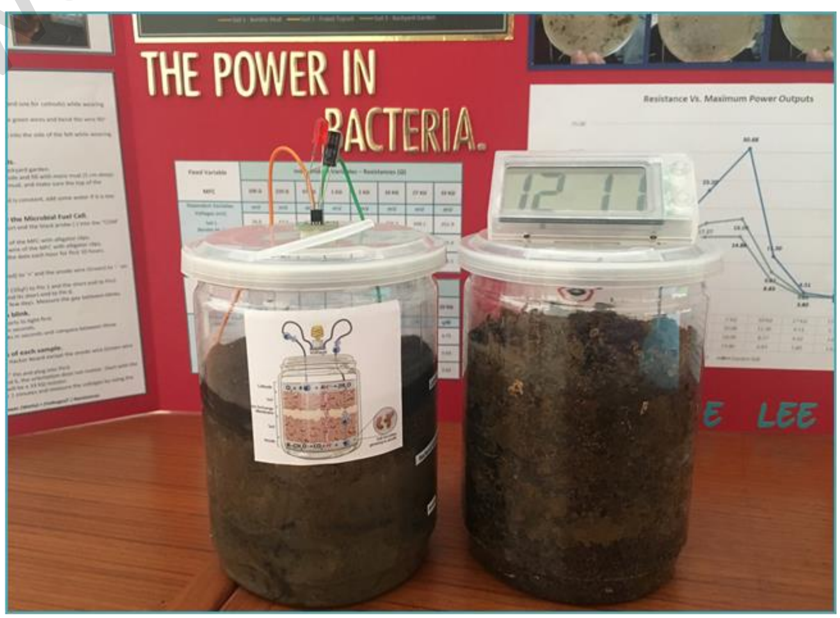
Result of 3B: Electricity Generation (Voltages) in Different Types of Sediments.

Fixed Variable: Same Location, Temperature Multimeter, Alligator Clips, electrodes materials.	Independent Variables – Different Types of Soils									
	Day 1 (16/05)	Day 2 (17/05)	Day 3 (18/05)	Day 4 (19/05)	Day 5 (20/06)	Day 6 (21/05)	Day 7 (22/05)	Day 8 (23/05)	Day 9 (24/05)	Day 10 (25/05)
Dependent Variables Voltages (V)	V	V	V	V	V	V	V	V	V	V
Soil 1 (Benthic Mud)	0.083	0.189	0.255	0.351	0.389	0.396	0.399	0.406	0.417	0.426
Soil 2 (Forest Topsoil)	0.056	0.173	0.228	0.266	0.343	0.368	0.370	0.381	0.379	0.381
Soil 3 (Backyard Garden)	0.067	0.159	0.221	0.312	0.345	0.357	0.353	0.368	0.358	0.357

	Day 11 (26/05)	Day 12 (27/05)	Day 13 (28/05)	Day 14 (29/05)	Day 15 (30/05)	Day 16 (31/05)	Day 17 (01/06)	Day 18 (02/06)	Day 19 (03/06)	Day 20 (04/06)
	V	V	V	V	V	V	V	V	V	V
Soil 1 (Benthic Mud)	0.431	0.433	0.428	0.431	0.427	0.441	0.439	0.443	0.437	0.442
Soil 2 (Forest Topsoil)	0.369	0.375	0.380	0.388	0.391	0.381	0.395	0.403	0.403	0.411
Soil 3 (Backyard Garden)	0.326	0.324	0.313	0.317	0.324	0.319	0.303	0.308	0.298	0.301

For more experimental data of Experiment 3B, please refer to the handwritten logbook on the next page.





Experiment 3B

Independent Variable: Time elapsed (daily)

Date: 2021.05.16 – 2021.06.23

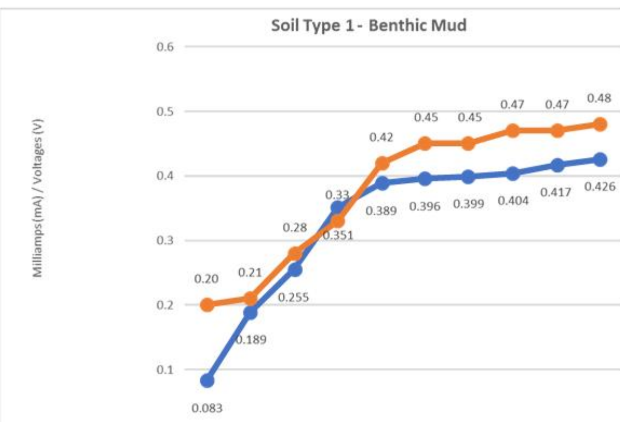
Results

Experiment 3B.

Time (Day)	Voltages (V) 1 (Mud)	2 (forest)	3 (Garden)	
1	0.083	0.056	0.067	
2	0.189	0.173	0.159	
3	0.255	0.228	0.221	
4	0.357	0.266	0.312	
5	0.389	0.344	0.345	
6	0.396	0.368	0.357	
7	0.399	0.370	0.353	
8	0.406	0.381	0.368	
9	0.417	0.379	0.358	
10	0.426	0.381	0.357	
11	0.431	0.369	0.326	
12	0.433	0.325	0.324	
13	0.428	0.380	0.313	
14	0.431	0.388	0.317	
15	0.427	0.391	0.324	
16	0.441	0.381	0.319	
17	0.439	0.395	0.303	
18	0.443	0.403	0.308	
19	0.437	0.403	0.298	
20	0.442	0.411	0.301	
21	0.446	0.425	0.291	
22	0.439	0.428	0.296	
23	0.448	0.431	0.203	
24	0.449	0.434	0.188	
25	0.455	0.435	0.316	← Adding nutrient (5g sugar, 95ml water)
26	0.453	0.454	0.352	
27	0.464	0.441	0.345	
28	0.467	0.441	0.357	
29	0.471	0.462	0.336	
30	0.469	0.447	0.314	
31	0.466	0.448	0.311	
32	0.461	0.436	0.316	
33	0.463	0.433	0.318	
34	0.465	0.438	0.322	
35	0.466	0.435	0.326	
36	0.469	0.439	0.321	
37	0.473	0.441	0.319	
38	0.468	0.443	0.322	
39	0.474	0.439	0.321	
40	0.476	0.431	0.326	

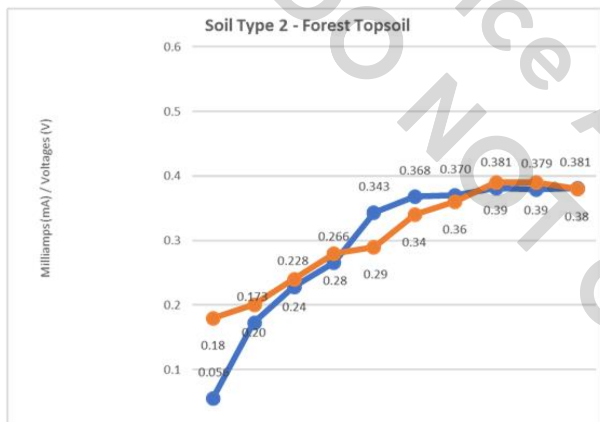
Comparison of Electricity Generation in Different Soils.

1. Soil Type 1 – Benthic Mud.



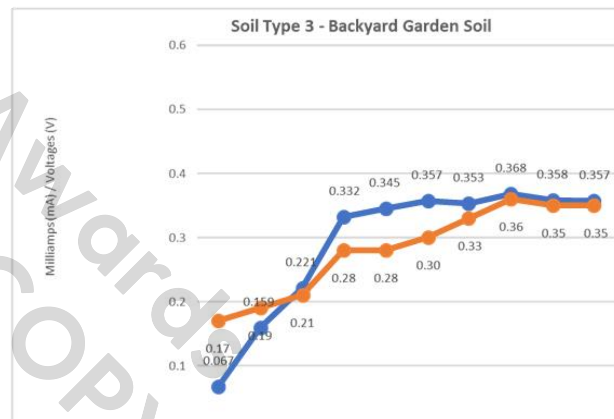
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10
Voltages (V)	0.083	0.189	0.255	0.351	0.389	0.396	0.399	0.404	0.417	0.426
Milliamps (mA)	0.20	0.21	0.28	0.33	0.42	0.45	0.45	0.47	0.47	0.48

2. Soil Type 2 – Forest Topsoil.

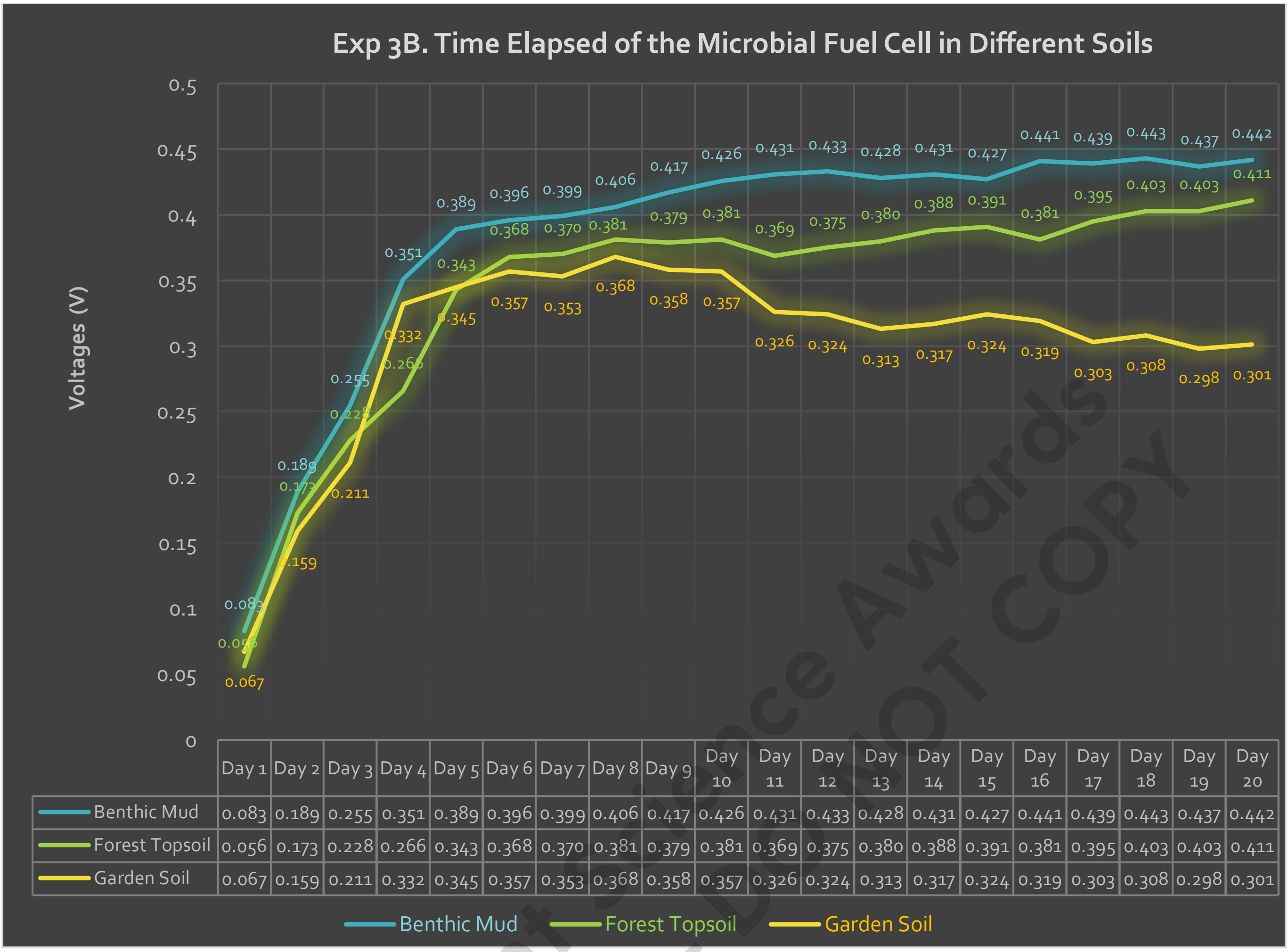


	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10
Voltages (V)	0.056	0.173	0.228	0.266	0.343	0.368	0.370	0.381	0.379	0.381
Milliamps (mA)	0.18	0.20	0.24	0.28	0.29	0.34	0.36	0.39	0.39	0.38

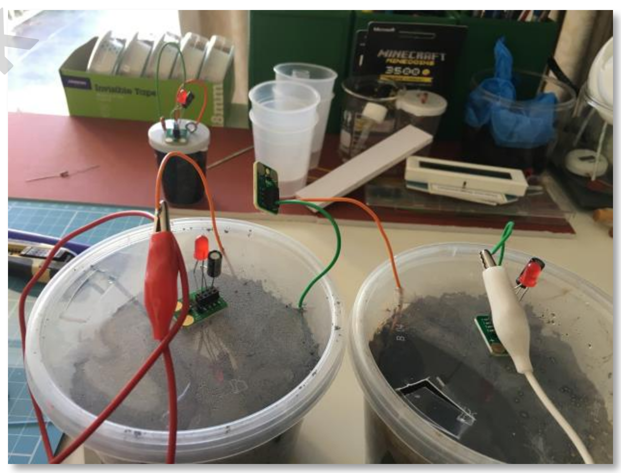
3. Soil Type 3 – Backyard Garden Soil.



	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10
Voltages (V)	0.067	0.159	0.221	0.332	0.345	0.357	0.353	0.368	0.358	0.357
Milliamps (mA)	0.17	0.19	0.21	0.28	0.28	0.30	0.33	0.36	0.35	0.35



	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12	Day 13	Day 14	Day 15	Day 16	Day 17	Day 18	Day 19	Day 20
Benthic Mud	0.083	0.189	0.255	0.351	0.389	0.396	0.399	0.406	0.417	0.426	0.431	0.433	0.428	0.431	0.427	0.441	0.439	0.443	0.437	0.442
Forest Topsoil	0.056	0.173	0.228	0.266	0.343	0.368	0.370	0.381	0.379	0.381	0.369	0.375	0.380	0.388	0.391	0.381	0.395	0.403	0.403	0.411
Garden Soil	0.067	0.159	0.211	0.332	0.345	0.357	0.353	0.368	0.358	0.357	0.326	0.324	0.313	0.317	0.324	0.319	0.303	0.308	0.298	0.301



June

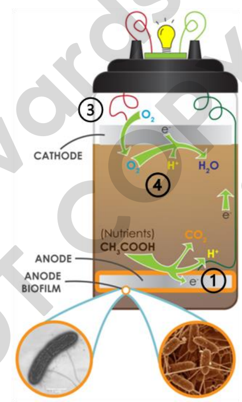
2021

Scientific Inquiry – The Power of Bacteria – The Microbial Fuel Cells (MFCs)

The MFCs Logbook

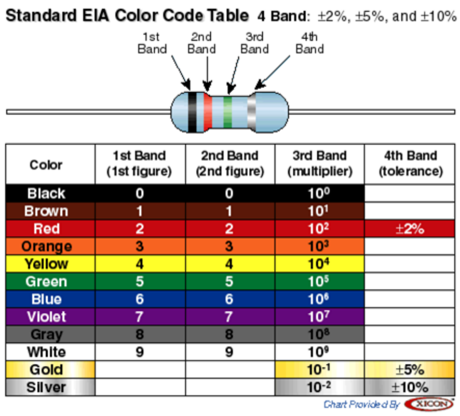
"What can affect the Microbial Fuel Cells? What is best environment for bacteria in the Microbial Fuel Cells?"

During May and June, several experiments had been created to investigate how bacteria generate electricity and the impacts of various materials and factors on the power generation by Microbial Fuel Cells (MFCs).



Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
		1 →	2 →	3 →	4 →	5 Experiment 4. Resistors & Power Output.
6 →	7 →	8 →	9 →	10 →	11 Experiment 5. Connection in Series.	12 →
13 →	14 →	15 →	16 →	17 →	18 Experiment 6. Types of Nutrients	19 →
20 Organized all records and data.	21 Organized all records and data.	22 →	23 →	24 Experiment 3A (Day 40)	25 Organized pictures for report/logbook.	26 Organized pictures for report/logbook.
27 Organized pictures for report/logbook.	28	29	30			

2021.06.05	Experimental Record



Color	1st Band (1st figure)	2nd Band (2nd figure)	3rd Band (multiplier)	4th Band (tolerance)
Black	0	0	10^0	
Brown	1	1	10^1	
Red	2	2	10^2	±2%
Orange	3	3	10^3	
Yellow	4	4	10^4	
Green	5	5	10^5	
Blue	6	6	10^6	
Violet	7	7	10^7	
Gray	8	8	10^8	
White	9	9	10^9	
Gold			10^{-1}	±5%
Silver			10^{-2}	±10%

Experiment 4. Resistors and the Maximum Power.

- **Independent Variable: Voltages with Different Resistors.**

Power (Watt) = (Voltages)^2/ Resistances (ohms)

Results:

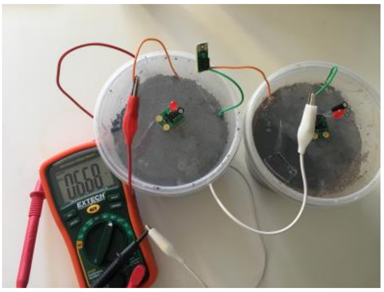
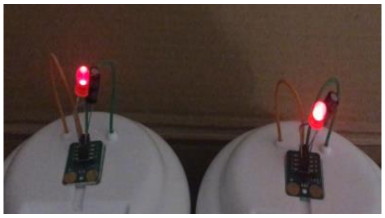
The voltages are higher if using larger resistors. From the equation above, the maximum power output can be calculated.

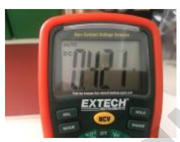
The peak powers of the MFCs were all found using a 2kΩ resistor and the peak powers are 30.68 ųW (Mud), 18.09 ųW (Forest) and 14.86 ųW (Garden) respectively. The sample with mud has the highest maximum power output and the garden soil has the lowest power output, meaning the benthic mud can generate more power than garden soil.

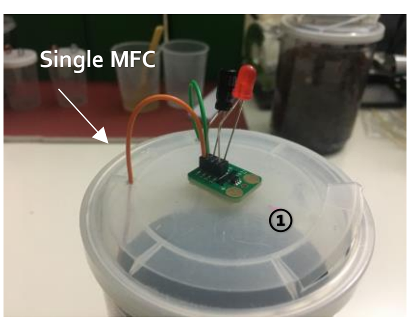
Result 4: Resistors & the Maximum Power Output.

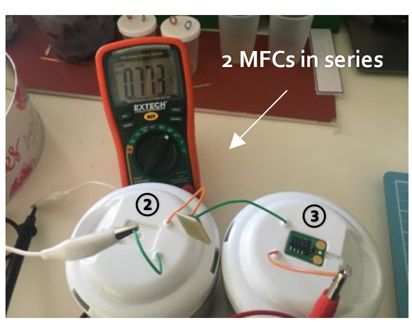
Fixed Variable Same Location, Temperature Multimeter, Alligator Clips, electrodes materials.	Independent Variables – Resistances (Ω)							
	100 Ω	220 Ω	470 Ω	1 KΩ	2 KΩ	10 KΩ	27 KΩ	33 KΩ
Dependent Variables Voltages (mV)	mV	mV	mV	mV	mV	mV	mV	mV
Soil 1 (Benthic Mud)	26.8	47.9	85.5	152.3	247.7	336.2	349.1	351.9
Soil 2 (Forest Soil)	26.0	46.4	80.8	131.4	190.2	289.3	329.6	345.9
Soil 3 (Backyard Garden Soil)	27.6	48.3	78.8	121.3	172.4	261.3	320.3	345.5

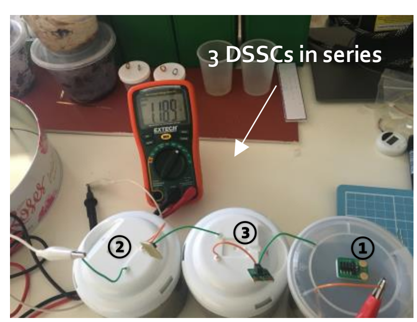
Fixed Variable MFC	Independent Variables – Power Output (ųW) & Voltages (mV)															
	100 Ω		220 Ω		470 Ω		1 KΩ		2 KΩ		10 KΩ		27 KΩ		33 KΩ	
Dependent Variables Voltages (mV) & Power (ųW)	mV	ųW	mV	ųW	mV	ųW	mV	ųW	mV	ųW	mV	ųW	mV	ųW	mV	ųW
Soil 1 (Backyard Garden)	27.6	7.62	48.3	10.60	78.8	13.21	121.3	14.71	172.4	14.86	261.3	6.83	320.3	3.80	345.5	3.62
Soil 2 (Forest Topsoil)	26.0	6.76	46.4	9.79	80.8	13.89	131.4	17.27	190.2	18.09	289.3	8.37	329.6	4.02	345.9	3.63
Soil 3 (Benthic Mud)	26.8	7.18	47.9	10.43	85.5	13.55	152.3	23.20	247.7	30.68	336.2	11.30	349.1	4.51	351.9	3.75

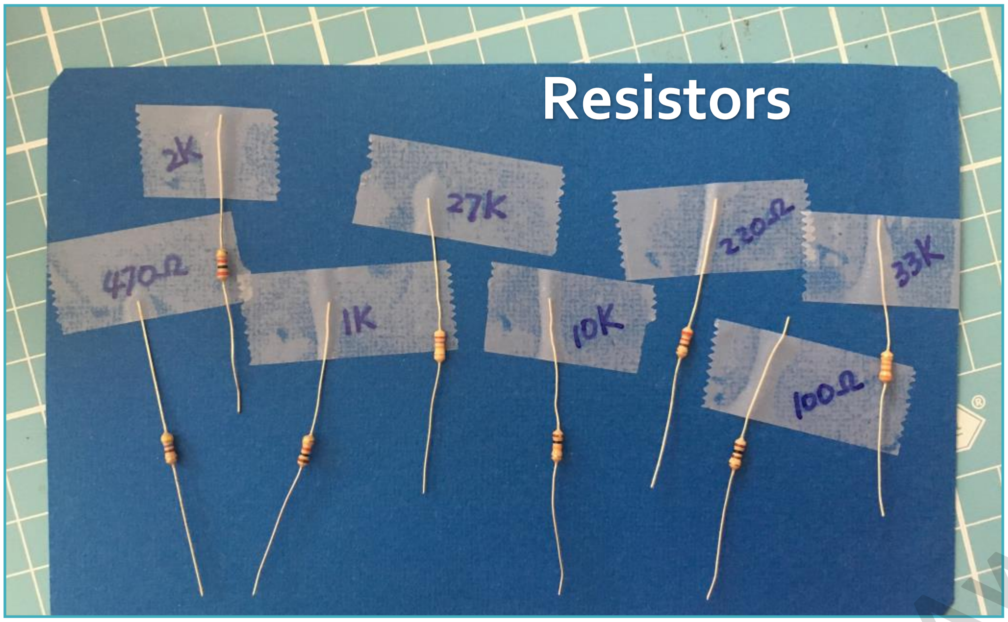
2021.06.11	Experimental Record
 	• Started **Experiment 5.** • **Independent Variable: Numbers of the MFCs.** • Connecting 2 or 3 MFCs in series and comparing the voltages with a single MFC. **Results:** When the cells are connected in series, the voltage and current are unstable due to the internal resistance, so the generated voltage will be reduced. • **Voltage of ②③ in series < Voltage of (②+③)** • **Voltage of ①②③ in series < Voltage of (①+②+③)**

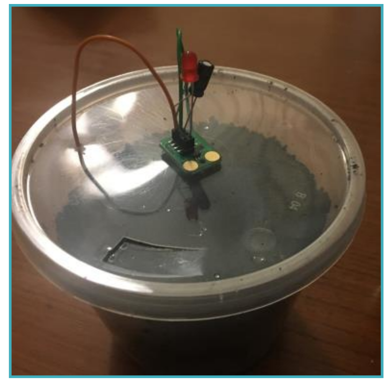
Fixed Factors MFC	**Independent Variable – Connections of the MFCs.**				
	MFC ①	MFC ②	MFC ③	② &③ connected in series.	①, ② &③ connected in series.
Same Location, Temperature Multimeter, Alligator Clips, Electrodes Materials.					
Dependent Variables	**V**	**V**	**V**	**V**	**V**
Voltages (V)	**0.421**	**0.403**	**0.396**	**0.773 < 0.799**	**1.189 < 1.220**
		②+③ = **0.799**			
	①+②+③ = **1.220**				

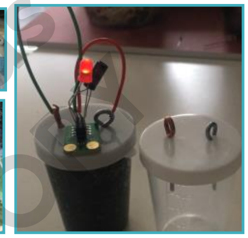






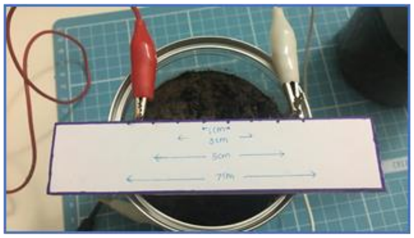


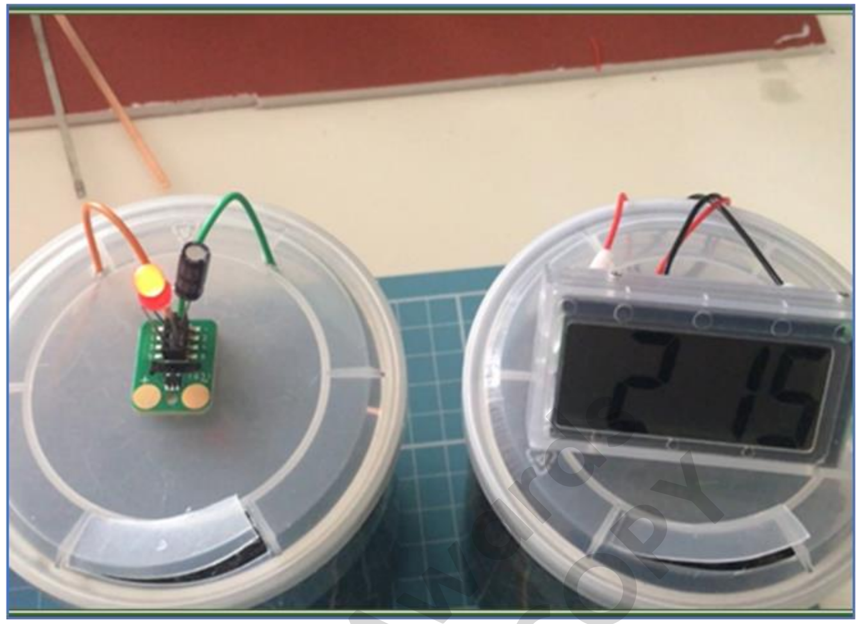




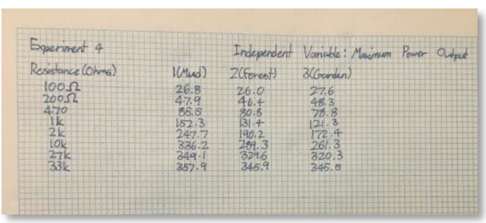
2021.06.18	Experimental Record
Nutrients: **(1) 5g Sugar + 95ml Water** **(2) 5g Glucose + 95ml Water** **(3) 5g Fructose + 95ml Water** Add 5ml of different kinds of nutrients, and measure the voltages at the beginning, 1, 3 and 5 hours after adding the sugar water.	• Started **Experiment 6.** • **Independent Variable: Types of Nutrients.** **Results:** From the data above, the power generations have been improved after adding nutrients. Compared with the control group without adding any nutrients, the MFC with glucose has the best power increase effect, followed by sugar and the MFC with fructose is the worst. The longer the standing time, the higher the power generated (within 5 hours). Sugar, glucose and fructose can be used as the nutrients for bacteria to generate electricity.

Fixed Factors MFC Same Location, Temperature Multimeter, Alligator Clips, Soil, Electrodes Materials.	Independent Variable – Nutrients Added on the Soil.			
	No nutrient Added	5ml (1) Sugar Water	5ml (2) Glucose Water	5ml (3) Fructose Water
Dependent Variables Voltages (V)	V	V	V	V
15 mins	0.087	0.125	0.146	0.119
1 hour	0.102	0.138	0.166	0.123
3 hours	0.114	0.167	0.189	0.137
5 hours	0.136	0.187	0.247	0.166





2021.06.20 ~ 2021.06.21	**Experimental Record**



Experiment 4 Independent Variable: Maximum Power Output

Resistance (Ohms)	1(Mud)	2(Forest)	3(Garden)
100Ω	26.8	26.0	27.6
200Ω	47.9	46.4	48.3
470	86.6	80.8	78.8
1k	152.3	131.4	121.3
2k	247.7	190.2	172.4
10k	336.2	289.3	261.3
27k	349.1	329.6	320.3
33k	357.9	345.9	346.0

Organized all records and data.

2021.06.25 ~ 2021.06.27	**Experimental Record**

Organized pictures for report & logbook.

July

2021

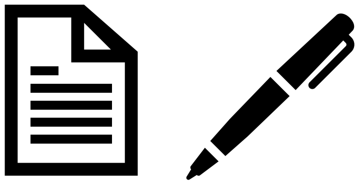
Scientific Inquiry – The Best Colour of Rainbow Dye-Sensitized Solar Cells (DSSCs).

The Power in Bacteria: The MFCs.

Started writing the report, logbook, and OSA Risk Assessment Form for my project during July 2021 and will upload the report and all documents required on July 20th before the due date.

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
				1 Report Writing	2 Report Writing	3 Report Writing
4 Report Writing	5 Report Writing	6 Report Writing	7 Report Writing	8 Report Writing	9 Report Writing	10 Report Writing
11 Report Writing	12 Report Writing	13 Report Writing	14 Report Writing	15 **OSA Risk Assessment Form**	16	17
18	19	20 **Upload Report**	21 **Due Date**	22	23	24
25	26	27	29	29	30	31

2020.07.01 ~ 2020.07.14	Experimental Record



- Started writing report.
- A three-week school holiday is a good chance to concentrate on writing experimental reports.
- Because of COVID-19, it is not possible to arrange family travel, so it is very suitable to write report at home.

2020.07.15	Experimental Record

OSA RISK ASSESSMENT FORM

for all entries in (✓) ☐ Models & Inventions and ☐ Scientific Inquiry

This must be included with your report, log book or entry. One form per entry.

NAME: ______________________ ID: ________

SCHOOL: ______________________

Activity: Give a brief outline of what you are planning to do.

Are there possible risks? Consider the following:

- Chemical risks: Are you using chemicals? If so, check with your teacher that any chemicals to be used are on the approved list for schools. Check the safety requirements for their use, such as eye protection and eyewash facilities, availability of running water, use of gloves, a well-ventilated area or fume cupboard.
- Thermal risks: Are you heating things? Could you be burnt?
- Biological risks: Are you working with micro-organisms such as mould and bacteria?
- Sharps risks: Are you cutting things, and is there a risk of injury from sharp objects?
- Electrical risks: Are you using mains (240 volt) electricity? How will you make sure that this is safe? Could you use a battery instead?
- Radiation risks: Does your entry use potentially harmful radiation such as UV or lasers?
- Other hazards.

Also, if you are using other people as subjects in an investigation you must get them to sign a note consenting to be part of your experiment.

Risks	How I will control/manage the risk

(Attach another sheet if needed.)

Risk Assessment indicates that this activity can be safely carried out

RISK ASSESSMENT COMPLETED BY (student name(s)): ______________________

SIGNATURE(S): ______________________

☐ By ticking this box, I/we state that my/our project adheres to the listed criteria for this Category.

TEACHER'S NAME: ______________________

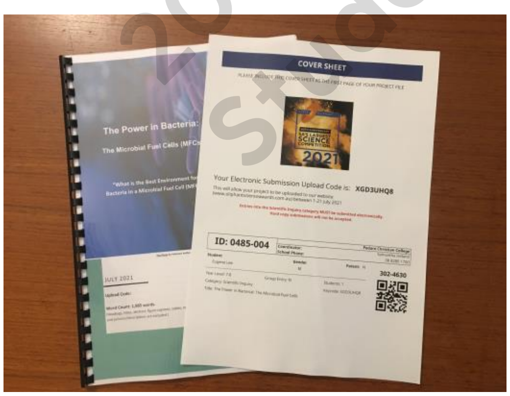
SIGNATURE: ____________ DATE: ____________

- Started writing OSA Risk Assessment Form.
- Brief abstract about the purpose of this project.
- This project belongs to low risk, it is not difficult to learn the basic knowledge and the manufacturing process is simple and safe, which is suitable for students to study and do experiments.

Risks:

1. **Biological Risks:** Enclosed footwear and gloves must be worn while sampling soil. Wash skin area that comes in contact immediately and after experiments. Remove gloves after handling bio-hazardous material to prevent cross contamination.
2. **Electrical Risks:** Do not put the electrodes near power plugs. Do not disperse the fibers in the air to prevent electrical shortages. Connect the electrodes and components correctly.

2020.07.20 ~ 2020.07.21	Experimental Record



- Back to school.
- **Uploaded the project:**
  1. Front cover page
  2. Main report
  3. Logbook
  4. OSA Risk Assessment Form
- Finished the task of Oliphant Science Award Scientific Inquiry 2021.