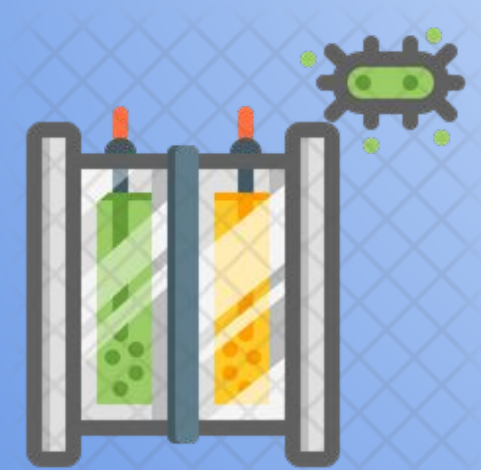
MICROBIAL fuel cells!

Harvesting* clean *energy from the ground?



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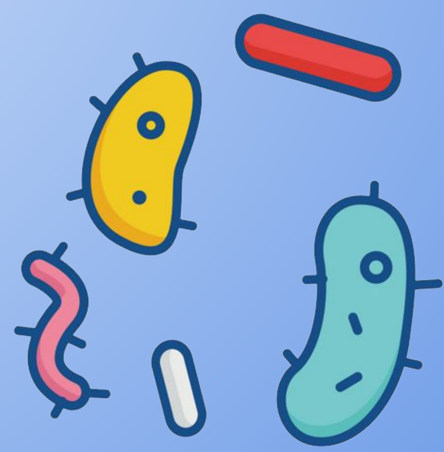


Main Question?

Can microbial fuel cells produce renewable electricity from mud/soil samples?

Sub questions:

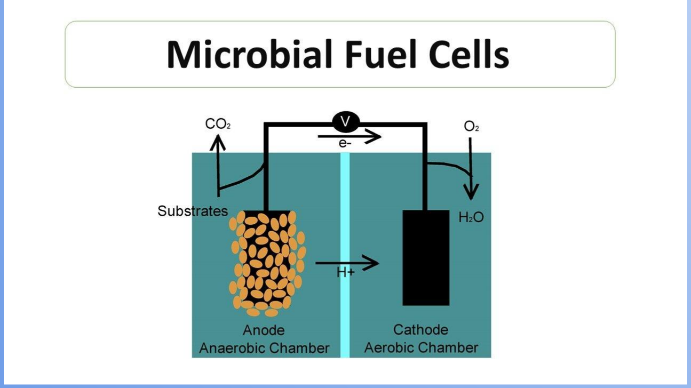
How much electricity can be generated from a microbial fuel cell?

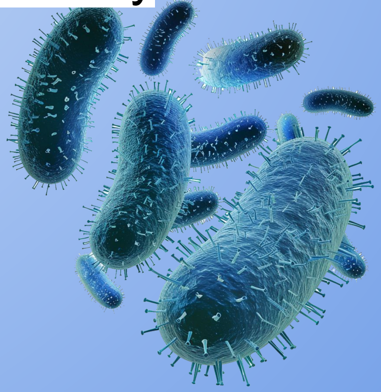
Which substrates help with producing the most electricity?

Can aeration to a cathode chamber help with electricity production in an microbial fuel cell

Intro/Topic/Relevance to Humanity:

My topic is on Microbial Fuel Cells (MFCs). MFCs are bio-electrochemical cells that use bacteria/electrogens to break organic matter into hydrogen ions$^+$, CO_2, and electrons. This is one of the best environmentally friendly ways to make electricity from biomass. Traditional bioenergy is produced by burning biomass (combustion) and creates heat, then it is put in a generator to make electricity. This traditional approach creates creates lots of **greenhouse gases** and contributes to **global climate change**. It is also inefficient, as it requires a lot of machinery and electrical infrastructure. Whereas a microbial fuel cell does not require a lot of infrastructure and the related energy to make electricity. Instead biomass is converted (using bacteria) into electricity. This **could** save greenhouse gas emissions, and could be a "newer" way to create renewable electricity.





Vocabulary

1. **Catalyst:**

A catalyst is a substance that speeds up a chemical reaction, or lowers the temperature or pressure needed to start one, without itself being consumed or changed during the reaction[3].

2. **'Bio'catalyst:**

A substance, such as an enzyme or hormone, that initiates or increases the rate of a chemical reaction.

3. **Salt bridge: (PEM)-[Proton exchange membrane]**

It is a tube filled with an electrolyte/conductive solution. The purpose of the salt bridge is to keep the chambers of an MFC electrically neutral and allow the free flow of ions to exchange with 2 or (More) cells. If there is no salt bridge, positive and negative charges will build up around the electrodes causing the reaction to stop.

4. **Electrodes:**

   An electrode is an electrical conductor used to make contact with a nonmetallic part of a circuit (Sometimes power source).

Vocabulary

5. **Oxidation:** A chemical reaction that takes place when a substance comes into contact with oxygen or another oxidizing substance. (Ex. Rust)[7]
6. **Electrochemical cell:** An electrochemical cell is a device that either generates electricity from chemical reactions or uses electricity to cause chemical reactions.[9]
7. **Bacteria:** Single celled microorganisms that are found almost everywhere on earth; like the soil, water, and even the human body.
8. **Conductivity:** The measure of the ease at which an electric charge or heat can pass through a material.
9. **Biofilm:** A community of living microorganisms embedded in a slimy or protective substance that provides protection against external aggressors or predators, like antibiotics, or disinfectants, as well as a host's immune system
10. **Electrogen:** Special family of bacteria that decompose organic matter in anaerobic conditions and can break down the matter into electrons and protons (etc.)

Questions*

-Can MFCs make renewable energy?
-Can MFCs create enough electricity for homes + remote areas?
-How much electricity can a MFC make?
-How much money does a MFC cost?
-Are MFCs bad for the environment?
-How is Agar a membrane (PEM)?
-How are electrons forced to move from Substrate → Circuit?
- How much O2 is required to disrupt the anaerobic part of the MFC
-What is an anode & cathode
-where does bacteria come from for microbial fuel cells + (what type?)
-How does the presence of oxygen or other gases affect the bacterial activity in MFCs?
-What is the potential for using MFCs as a sustainable power source in developing countries or disaster-stricken areas?
-How can microbial fuel cells contribute to reducing carbon footprints or decreasing emissions for climate change?

Background Research

What is a Microbial Fuel cell?

A microbial fuel cell (MFC) is a bio-electrochemical system (or a fuel cell) that converts biochemical energy to electrical energy through reactions catalyzed by microorganisms under anaerobic conditions.[1]

What are the main components of soil?

Soil is a material made of five ingredients. These are minerals, soil organic matter, living organisms, gas, and water.[4]

Who invented microbial fuel cells?

The idea of using microbes to produce electricity was created in the early 20th century. Michael Cressé Potter investigated the subject in 1911. But his findings received very little attention.

Background Research

What is a Double Chamber MFC?

A double-chamber MFC consists of an anode and cathode compartment separated by a proton exchange membrane (PEM) to avoid electron movement between the compartments.

What is a Single Chamber MFC?

In single compartment microbial fuel cells (SCMFC), there is only one anode chamber in which wastewater to be treated is placed along with the microbial catalysts*.

* A process of utilizing microbes for CO2 transformation to organic molecules along with electrons that are obtained from cathode.

What is an anode and a cathode?

A cathode and an anode are the two electrodes found in a battery or an electrochemical cell, which help the flow of electric charge. A cathode is the positive electrode, where reduction (gain of electrons) occurs. An anode is the negative electrode, where oxidation (loss of electrons) takes place.[6]

Background Research

What things can power a microbial fuel cell?

- **Organic substrates**: Wastewater, food scraps, agricultural waste, and complex and simple organic sugars (e.g. cellulose/glucose).
- **Sunlight**: In photosynthetic MFCs, where algae or cyanobacteria* generate organic matter through photosynthesis.
- **Urine**: Organic compounds in human or animal urine.
- **Sediment**: Natural organic matter in marine, river, or lake sediments.
- **Wastewater**: Organic pollutants in wastewater from households, industries, or agriculture.

The above are only a few examples.

*Cyanobacteria are a type of bacteria that can perform photosynthesis, just like plants.

Background Research

What is ion exchange?

The exchange of ions of the same charge between an insoluble solid and a solution in contact with it.[12]

What is a polysaccharide?

A polysaccharide is a long chain of molecules (usually carbohydrates) that are followed by the smaller molecules that are called monosaccharides. Polysaccharides are usually insoluble in water and will make colloidal suspensions.[14]

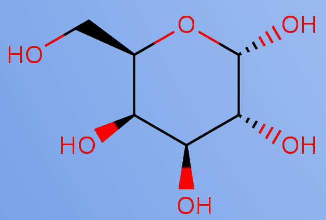
What are monomers?

Monomers are atoms or small molecules that bond together to form more complex structures such as polymers.

Background Research

What is the chemical compound for agar?

Agar is a mixture of polysaccharides, typically extracted from the cell walls of red algae. They are composed of agarose and agaropectin. Agarose is made up of d-galactose and 3,6 anhydro-l-galactose units. **These are 2 types of sugar molecules (monomers) that form agarose. D-galactose is a simple sugar form, while Anhydro-L-Galactose is a certain form of galactose. The 3-6 means the 3rd and 6th carbon atoms in the galactose molecules.** [16, 15]



D-Galactos
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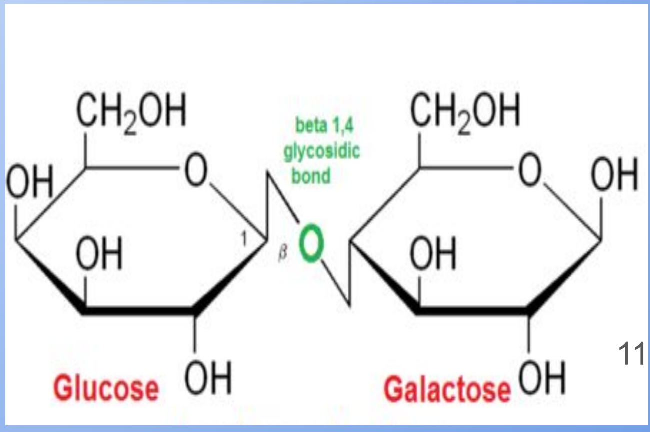


Background Research

***ester, any of a class of organic compounds that react with water to produce alcohols and organic or inorganic acids.**

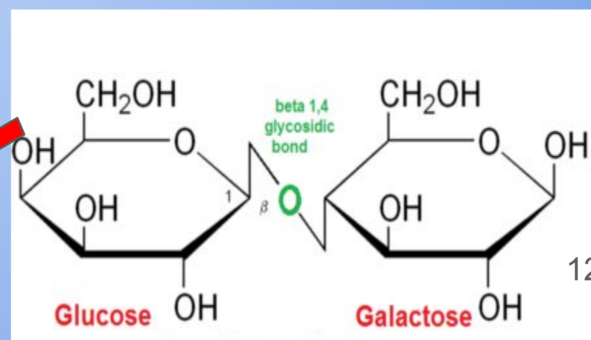
<u>What is the chemical compound for agar? (P.T 2)</u>

G-Galactose and 3,6 anhydro-l-galactose are connected by alternate α-(1,3) and β-(1,4) glycosidic bonds. **(This describes the type and pattern of chemical bonds connecting sugar molecules together. A glycosidic bond is a type of bond that links a sugar molecules to other molecules)** Agarose is the gelling part of agars chemical composition and makes up 85% of agar. While agrospectin provides viscous properties. Agrospectin is made of D-Galactose and L-galactose (Basic sugar molecules that make the majority of Agaropectin), Sulfate groups (they contain sulfate esters* that give some gelling capabilities), and D-gluconic acid.

The molecular formula for agar is $C_{14}H_{24}O_9$.[15, 16 ,17]

C1 - (1st sugar) » (1,3 Glycosidic Bond) » C3 - (2nd sugar)

C1 - (1st sugar) » (1,4 Glycosidic Bond) » C4 - (2nd sugar)



Background Research

What allows Agar to be a proton exchange membrane?
Many reasons allow agar to be a proton exchange membrane, including:

Proton conductivity: Agarose, the main component of agar has hydroxyl groups (-OH) that help with the flow of protons/H^+

Chemical stability: Agar is chemically stable and can handle acidic and basic conditions found in MFCs. Also it's tough structure protects OH groups from splitting apart.[22]

Biocompatibility: Agar is normally extracted from red algae, making it suitable for biological systems like MFCs [20]

Cons* Agar is a gel at room temperature, remaining firm at temperature as high as 65°C. Agar melts at approximately 85°C, a different temperature from that at which it solidifies, 32-40°C. Agar thickens harder the cold it gets.[21]

Background Research

Where do bacteria come from in an MFC?

Many types of bacteria are found in benthic areas. When these bacteria eat, their by products can be Carbon, Hydrogen$^+$, and electrons. When a soil sample is put into an anode chamber/or a anaerobic environment, this allows the bacteria to form a bigger colony. This increases the production for the Carbon, Hydrogen$^+$, and electrons.

What are some species of electrogens?

Some species are:

- Escherichia coli
- Shewanella
- Enterococcus faecalis
- Rhodoferax ferrireducens
- Saccharomyces cerevisiae

Are Electrons present in compost?

Compost create a rich habitat for electrogenic bacteria because they provide the bacteria with plentiful amounts of organic matter for the bacteria to consume. Many studies have shown that compost substrate will increase the by products of electrogens.

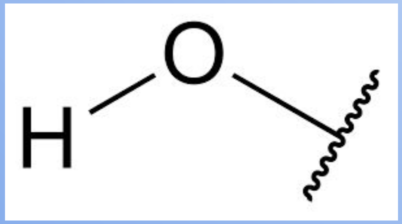
Background Research

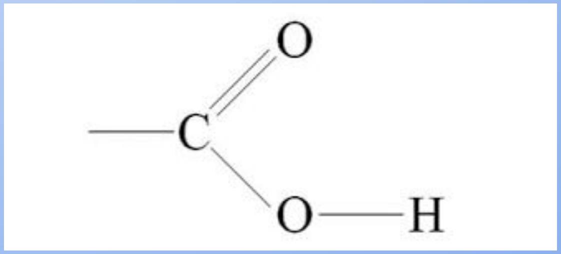
How can activated charcoal collect electrons?

Activated charcoal/activated carbon can attract/collect electrons for 2 reasons:

1. **Graphite microcrystals:** Within Activated charcoal, there are regions of graphitic microcrystals. These crystals have a structure similar to graphite, where carbon atoms are arranged in in hexagonal layers. In these hexagonal layers, some electrons are delocalized (Allow free flowing electrons)
2. When **Activated charcoal** is “activated” there are many pours on the carbon structure. This is the biggest reason why they attract electrons.
3. **Chemical structure:** When Activated Charcoal is “activated” (activation is when the carbon structure is put through a chemical process) the activation bonds hydroxyl, carboxyl, and other oxygen groups to the carbon. These groups can interact with electrons, enhancing the carbon's ability to hold electrons [24,25]

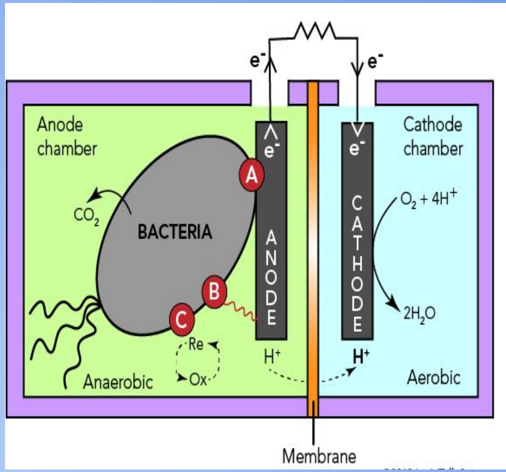
-OH





-COOH

Background research



What are the components of a microbial fuel cell?

1. **Anode compartment:** The compartment where organic substrates are introduced, and the bacteria act as the biocatalysts.
2. **Cathode compartment:** The compartment where the positively charged hydrogen ions and protons attach themselves with oxygen to create water.
3. **Salt bridge (Proton exchange membrane):** A semipermeable membrane that permits a certain amount of protons, from the anode to the cathode compartment.
4. **Electrodes:** anode and cathode, which help with the transfer of electrons (Creating electricity)
5. **External circuit:** This includes wires connecting to both electrodes and a battery (Electrical storage) or a digital multimeter (Measure voltage and current)

Background research

How does a double chamber microbial fuel cell work?

First, organic substrates are introduced into the anaerobic anode compartment, where bacteria colonize the anode and substrate. This forms a biofilm and acts as a **biocatalyst.** Then the bacteria consume and metabolize the organic substrates by anaerobic respiration and decomposition. The bacteria decomposes complex organic molecules (EX. sugars) into simpler compounds (products), mainly carbon, electrons and hydrogen ions$^+$. The electrons present in the chamber are attracted to the anode because of pores and a conductive material. The electrons then go through the external circuit (wires). Meanwhile on the other side, the hydrogen ions$^+$ (or protons) are forced in the opposite direction (because they are the opposite force) through the PEM. The PEM is made of a neutral and conductive substance so the hydrogen ions$^+$ flow through the PEM and go to the cathode compartment. In this compartment the hydrogen ions$^+$ bond with oxygen to create water. This then completes the reaction. The flow of electrons through the external circuit influences the current which can be used to calculate electricity.

How to calculate power?

To calculate the power of a microbial fuel cell, It is needed for 2 things:

The formula for power is, Power = Current (I) x Voltage (V)

Current is Joules per second or Amps. This means the flow of electricity.

Voltage is the measure of difference in electric potential energy, between 2 points of a circuit.[26]

Variables:

Manipulated: Different types of soil/mud, and building the microbial fuel cell.
Responding: Amount of electricity produced.
Controlled: The control in this experiment was topsoil (referred to as MFC.3 throughout the experiment).

Benthic mud, and compost are rich in aquatic and decomposed nutrients. This is because benthic mud contains rich sediment carried from the river bed, and is eroded into fine minerals because the water hits the benthic mud (thus eroding it). Compost is made of decomposed organic matter which is high in nutrients.

Topsoil on the other hand, has a less nutrient high composition and provides moderate minerals and organic matter (etc.) so it serves as a baseline. Also topsoil is a generic, and most basic soil that is found everywhere.

Constants: same benthic mud, same benthic mud source same anode and cathode material (activated carbon), Same Digital multimeter, Same environment of experiment, type of microorganism/bacteria, distance between electrodes, same PEM membrane.

<u>Variables:</u>

Why have a control?

Control variables are needed to ensure the reliability and what stays the same in an experiment.

- Controlled variables are important because you can compare them to other trials, when a control variable is implemented then it becomes easier to compare other trials to the control group. Then I can see the (mathematical) difference between different trials, which in short can help draw conclusions.

My predictions:

If three different substrates are placed in a MFC and are given a chance to produce electricity, then I think all of the substrates will only produce less than 1.5W because, the bacteria will have only grown a small colony and bacteria take a long time to break down substrate.

The compost will generate 0.7-1.4W because it has the most bacteria of all the substrates and the most hostile living conditions for the bacteria. Then the benthic mud samples will generate 0.3-0.5W because the decomposed organic matter has settled in the benthic zone providing more nutrients to the bacteria than the topsoil. The topsoil will generate 0.09-0.2 W because calgary's topsoil is very dry; and this is not a very suitable condition for bacterial growth.

Hypothesis 1.0

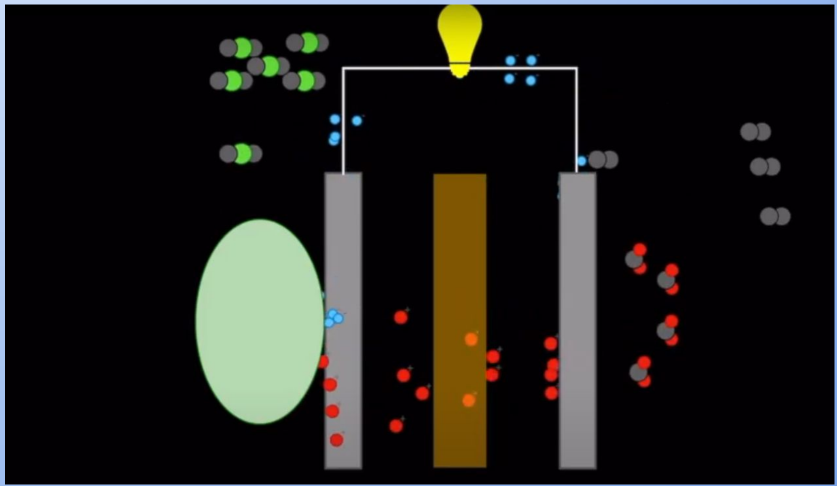
If three substrates are put in a MFC to produce electricity; and bacteria are given a chance to break down the substrate, then the Compost soil will produce the most electricity from the MFC because, the compost soil will attract more bacteria for a number of reasons.

- First compost provides a great abundance of organic matter and nutrients for the bacteria to feast on.
- Second as compost biodegrades, it generates heat. This temperature increase will be beneficial for bacteria to live in.
- Last, compost is usually created from organic manner. The majority of the moisture from all the organic matter improves living conditions for the bacteria.

Also the topsoil and benthic mud samples may not have as much of organic matter as the soil because soil has other components in it such as minerals. Compost on the other hand consists of 70% and more organic matter. While it is uncertain with the 2 soils.[23]

Hypothesis 2.0

If a microbial fuel cell is built and is aerated for 7 days, and not aerated for another 7 days, then the time period where the microbial fuel cell is aerated will produce more electricity than the non aerated time period because, when the cathode chamber is aerated, the oxygen availability increases. This will then enhance the amounts reactions at the cathode. In MFCs, electrons flow from the anode to the cathode, oxygen acts as the final electron acceptor. Higher oxygen levels at the cathode chamber lead to a more efficient reduction of oxygen to water, thus producing more electricity.



Materials:

Chambers

- Compression fitting
- Sandpaper, medium-grit
- Permanent marker
- Ruler
- Lab notebook
- Containers (Acrylic or plastic)(3.2L)(6)
- Safety goggles
- Drill or drill press with 3/4-in. spade drill bit, 2-millimeter (mm) drill bit
- Adhesive (like acrylic cement or DevCon Plastic Welder)
- Paper towel
- Popsicle sticks, or any unwanted skinny stick.

Making the Electrodes

- Activated charcoal
- Copper mesh
- Wood
- Monkey wrench
- Wire strippers
- Nickel epoxy or other conductive epoxy
- Copper wire, 12-gauge (12 pieces, 18 in. each)
- Digital multimeter.
- Electrical tape

Materials:

PEM

- Baking tray
- Plastic wrap
- Aluminum foil
- Measuring cup
- Tap water
- Pot
- Glass rod
- Spoon
- Digital kitchen scale
- Agar, 30 g
- Table salt, 6 g

Materials:

Getting the benthic mud samples

- Buckets (3)
- Plastic wrap
- Shovel
- Hoe
- Pitch/Fork

Assembling the Fuel Cell

- Measuring cup
- Large bowl
- 72 tbsp of salt
- Spoon
- Aquarium air pump/aerator with tubing
- Safety goggles
- Mud sample

Testing the MFC

- Alligator clip cables 6

Procedure: Section #1

Electrodes

1. With scissors, cut the copper mesh into 6 rectangles with the dimensions of 6 cm x 18cm. Fold these into 6cm x 6cm squares into 3rds.
2. Cut 6 strips of wire with lengths of around 1 ft ½ and strip 6in of insulator on one side, and 1-2 cm on the other.
3. Layer Activated charcoal, Nickel epoxy, and copper mesh into this specific pattern: Copper mesh, epoxy, and then charcoal (E.t.c). Do this quickly and push down onto the electrode.
4. Before pushing on the electrodes, put a wire in one of the folds with the 6in side, layer with as much epoxy as needed.
5. After completing steps 1 and 2, put the electrode on top of a wooden piece (Chunk of a 2x4 or scrap wood).
6. Next, add another nearly identical piece of wood and place it on top of the electrode. Place a monkey wrench onto the 2 wooden pieces and tighten as much as possible.
7. Leave this for 6-12 hrs
8. After 6-12 min, take the monkey wrench off. (Note* if the electrode layers are not stuck together, try the process again, only adding a little more glue)
9. When the electrode is in one assembly, take each of the four pieces of copper wire and with the wire strippers, strip off 6 inches of the insulator on one end of each piece.
10. Repeat steps above as much as possible until there are 6 electrodes.

Procedure: Section #2

Making the Salt Bridges

1. Place and stand up vertically all 3 compression fittings on a baking sheet, put aluminum foil around one side of the compression fitting tightly so no liquid can escape the tube. Repeat this to all compression fittings.
2. Measure 300 milliliters (mL) of water and pour it into the pot.
3. Using the scale, measure out 30 g of agar. Set the measured agar aside. Now measure out 6 g of salt.
4. Place the pot of water on the stove and bring it to a boil. When the water is boiling, add the agar and stir it with the glass rod until it is dissolved.
5. Once the agar is dissolved, take the pot off of the heat and add 6 g of salt. Stir with a spoon until the salt is dissolved.
6. While the solution is still hot, carefully pour the solution into the tubes/compression fitting. If the tubes leak, or tighten, remove the foil and refill them.
7. Once the tubes are filled and stable (i.e. haven't fallen over, leaked liquid, etc.) for 10 minutes, carefully move the backing sheet to the refrigerator. Let the tubes sit in the refrigerator overnight. These tubes are the salt bridges.
8. The next day, come back and place the salt bridges into a plastic baggie and seal it. This prevents the salt bridges from drying out. They should be a firm, jelly-like substance but not completely solid.
9. Take the bridges out when is is ready to be used.

Section #3

Procedure:

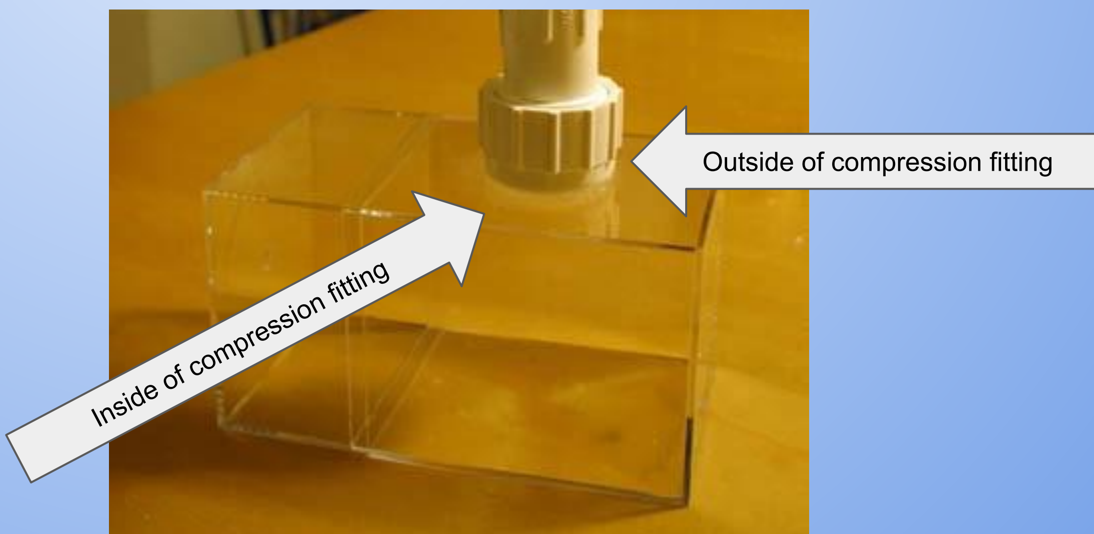
Building the anode & cathode chambers:

1. Unscrew the two ends of the compression fitting and throw out the rubber fitting and discard end caps. Using sandpaper, roughen the endcaps of the compression fitting.
2. Take the sandpaper and roughen two opposite sides of two of the plastic containers. (Roughen two patches the circumference of the compression fitting, across from each other.)
3. Using the permanent marker, make a mark in the center of the roughened side of one of the plastic containers. Also create 2 lines crossing through exactly half of the container (vertically, and horizontally)
4. With a sharpie, place the center compression fitting on the center of the mark, and trace a circle around the compression fitting.
5. Measure the location of where the circles are on the container (EX. the circle is 6 cm above the bottom of container, and 4 cm left of the center line)
6. Apply all markings to all containers.
7. Put on the safety goggles. Drill a hole 8-2 millimeters in diameter on top of two of the plastic container lids.
8. Using the drill, drill a hole on the permanent marker marks on the sides on all
9. containers. (Note: Drill slowly or the acrylic might crack. Brush off any plastic debris. There should now have two plastic containers that each have a hole in one side.)

Procedure:

Section #3

1. Screw in compression fitting into 2 containers so that there is a tiny bit of room to squeeze adhesive on both sides of the container. Squeeze epoxy around out/inner edges of the container that are around compression fitting, apply with a stick (popsicle stick) around the part of the compression fitting that is out/in of the container.
2. After 2 hours repeat step one, only with acrylic cement. Apply the acrylic cement with fingers to close any gaps more precisely. Repeat this process until all microbial fuel cells are made. Leave for another 2 hours.
3. After the time has passed, check to see if the two joints are watertight. Fill the containers with water past the holes/joints. Wait for 5 minutes. If there is no water leaking out, then proceed to the next section.
4. If there is excess water coming out of a joint, empty the containers and dry them off completely with paper towels. Carefully squeeze acrylic cement around the endcap joint that leaked. Squeeze out enough cement that a seal is make. Wait for 10 hours and retest the watertightness. Try again if this doesn't work. (If it still doesn't work, remake the assembly with fresh parts.)



Procedure:

Obtaining the Benthic Mud Samples/Substrate

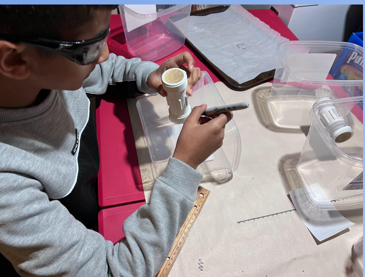
1. Go to the location of your stream where there is a rich patch of mud.
2. Fill buckets (with shovel hoe, and pitch fork), and make sure to get enough of the benthic sample to fill the anode chamber. *NOTE: if there are lots of rocks or grass use the pitch fork to separate them.
3. Collect some of the stream water and put it into the bucket (Only if mud/soil is dry)
4. (repeat steps 1 -3 to only collect topsoil)
5. Collect some compost soil near available sources
6. After all samples are collected and put into buckets, then put plastic wrap onto them (so they don't dry out.)

Procedure:

Assembling the Microbial Fuel Cells

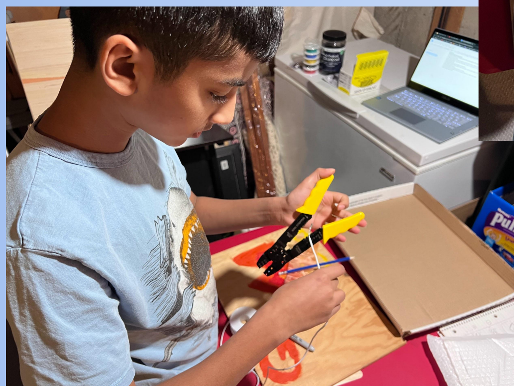
1. Make a conductive salt solution using the water samples. Measure out 12 cups of tap water into the large bowl. Add 6 Tbsp. of salt to the bowl and stir with a spoon until the salt has been dissolved. Fill the cathode chambers of the three microbial fuel cells with the salt solution. (Add more solution according to the size of containers.
2. Take an electrode (this will be a cathode) and thread it through the smaller hole of one of the lids with two
3. holes. Place the lid with the holes and the connected cathode back onto the cathode chamber. Make sure the electrode is submerged. Repeat this step with another electrode and the other lids with the holes. Seal each cathode chamber with a lid.
4. Connect the tubing to the aquarium pump. Push the tubing into the cathode chambers under the lid. Be sure to submerge the end of the tubing under water. (NOTE* only do this step after 7 days of observations)
5. Now, wearing gloves and safety goggles, fill half of the anode chamber of a microbial fuel cell with the benthic mud sample. Make sure that there are no bubbles in the mud. Push the mud sample down or gently tap to remove any bubbles. Take one of the electrodes (this will be an anode) and bury it in the mud. Then place more of the mud into the anode chamber, covering the anode. Push the free end of the electrode copper wire into the 2-mm holes in the container lids. Replace the lid onto the container to make sure that the electrode is hanging freely without hitting any of the walls or the bottom.
6. Repeat filling the anode chamber with the benthic mud sample and inserting the anode with the other two microbial fuel cells by repeating step 5 for the two microbial fuel cells.
7. The microbial fuel cells are now complete and you should have three MFCs in total.

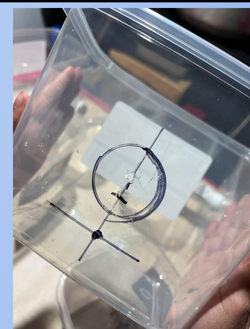
Observations: Making the MFC



Electrodes: while making the electrodes, the charcoal was very fine. This lead to me applying the epoxy in a zigzag pattern around the entire area of the electrode.

PEM: The PEM went according to the procedure, and stirring after around 40 seconds, the agar mixture started to get a thick consistency and became hard to stir. When the agar was heated, it made a very foul smell similar to stail or gray water. After I poured the agar mixtures into to the compression fittings, I noticed that is was a light yellow in colouration and it was the most opaque and I couldn't see through it at all.





Observations: Day 1

MFC.1: This microbial fuel cell generated instant electricity. It created 97 mV at first, and started to climb higher to 101.2 volts and was slowly generating a higher current. It went to 102mV for a couple seconds and then dropped down to 101.2 for the majority of the testing period.

MFC.2: This microbial fuel cell generated instant electricity. It created 104.5 instantly and stayed at a constant current.

MFC.3: This microbial fuel cell did not make instant electricity, and I had to wait 3 minutes before it gave the readings of 45.3mV it slowly climbed to 49mV in the span of about 5 min. It then started to drop to 45mV, 4 min after.

Observations: Day 2

MFC.1: This MFC lost a lot of its current/electricity (34mV) and kept on fluctuating between 67.8 and 68mV after 5 min the digital multimeter read 68mV.

MFC.2: This MFCs anode chamber looked dry, and there was no water above the compost substrate (like day 1.) The MFC read 67.9mV without fluctuating between different readings.

MFC.3: This MFC looked the same as day 1 and read 57.4mV, and increased electricity production. This MFC did not fluctuate.

*NOTE: all of the cathode chambers looked less aerated than Day 1

Observations: Day 3

MFC.1: This MFC had water that settled on top of the benthic mud. It had a blue colouration. There were also some worms, and snails exploring the settled water on the top. This microbial fuel cell started at 75mV and climbed to 89.2mV in 2min. The cathode chamber looked the same as day 2.

MFC.2: This MFC had a leak in the anode chamber and was cleaned up today with epoxy and acrylic. The microbial fuel cell fluctuated at 80 mV for a minute, and after the minute it started climbing to 111.5mV. The compost soil in the anode chamber looked a little dry compared to day 1 because of the leak.

MFC.3: This MFC had no significant differences compared to the previous days. It started at 45 mV for a couple of seconds until it started climbing to 102.4mV

Observations: Day 4

MFC.1: This MFC did not fluctuate, there were no significant visible changes.

MFC.2: This MFC did not fluctuate, there were no significant visible changes. This MFC decreased its mV reading alot.

MFC.3: This MFC did not fluctuate, there were no significant visible changes.

Observations: Day 5

MFC.1: This MFC, fluctuated very little compared to previous days and went from 83.6 mV-95 mV in under 30s. The water looked a little bit cloudy (anode chamber) and more snails and worms were visible in the settled water above the soil. The soil colour looked a little bit more gray than the black colouration it had on day 1.

MFC.2 This MFC did not fluctuate and gave a strait reading of 110 mV. The anode chamber had no water on the top of the soil because of a leak. Their was also another leek in the cathode chamber and the water level was a little higher than the PVC compression fitting. (I am planning on changing the water and fixing the leek today)

MFC.3 This MFC fluctuated for about 3 min and started with a reading of 90 mV and went all the way up to 105.3mV. There was no significant differences to the anode and cathode chambers.

Observations: Day 6

MFC.1: This MFC had big, thick greenish bubbles on top of the settled water on the anode chamber. The water that settled on the top was translucent, and there were lots of algae growth. The algae had a brown colouration and grew in little patches. This MFC started its reading at about 61 mV and went up to 73.4 in about 2 mins.

MFC.2: This MFC was not leaking and the leek was now fixed. The cathode had some charcoal patches settling on the bottom. This MFC did not fluctuate and gave a reading in about 5 secs.

MFC.3: This MFC fluctuated a lot, it went from 70 mV and settled on 98.6 mV in 5min. Their were no noticeable changes to the MFC itself.

Observations: Day 7

MFC.1: This MFC did not fluctuated at all, and gave a strait reading of 93.9 mV. The anode chamber had pockets of compressed air in them. When I touched the anode chamber (Pushed my finger into it) the air shot up from under the mud. This caused a snail to burst out of the water, banging against the lid.

MFC.2: There was again another leek. This leek was caused by the glue not curing. The leek was in the same spot. (It was on the backside of the compression fitting on the cathode chamber.) This MFC did fluctuate. It went from 96.3 mV to 155.4 in the span of about 2min.

MFC.3: This MFC did not have any significant visible differences compared to previous days. It fluctuated, it went from 82.4 mV and went up to 103.8 in the span of 4min.

Observations: Day 8

MFC.1: This MFC had a thick dark green film on top of the anode chamber. There was also a lot of worm waste near the top and bottom of the settled water. This MFC was very surprising, and did not fluctuate. This MFC gave a reading of 152.1 mV before the oxidation. After oxidation it gave a reading of 155.1 mV.

MFC.2: This MFC also did not fluctuate. It gave a reading of 123.6 mV before aeration, and a reading of 118.3 after aeration. I do not think aeration decreased the mV production because the microbial activity is very erratic and can change in a short period of time. There were no big visual differences in the fuel cell.

MFC.3: This MFC fluctuated over the span of about 3 mins for both before and after readings of aeration. It gain 1 mV between readings (before and after)

Observations: Day 8(A)

NOTE* these calculations are not accurate and are a close estimate of what I think the Dissolved oxygen content would be:

<u>Dissolved oxygen calculations:</u>

Method: I decided to calculate the the total dissolved oxygen content from day 7, and add the full amount of dissolved oxygen content on day 8. Then every day I will replenish the lost oxygen to the cathode chambers. From the research I have done, MFC need oxygen in the cathode chamber to complete the chemical reaction to produce electricity.

Dissolved oxygen, Day 7:

- On day 1, the average dissolved oxygen content would be about 9.45mg/L at 18° (temperature of the experiment) with calgary's tap water.[27]
- Since I added 6 tbsp of salt, the ratio between salt and water would be 30 parts per thousand (ppt). Due to the salt content in water, dissolved oxygen content would now be 18% less that 9.45mg/L. This is because the dissolved salt disrupts the balance (equilibrium), and makes it harder for the oxygen molecules to dissolve in water as the salt displaces the places where oxygen should dissolve. Thus making the dissolved oxygen content lower.
- Now the mg/L ratio is 7.749mg/L. The formula is: 9.45mg/L x (1-0.18) =7.749mg.

Observations: Day 8(A)

<u>Dissolved oxygen calculations:</u>

- There is 3L of salt water in one cathode chamber (3L x 7.749)= 23.247mg
- Dissolved oxygen in Calgary decreases about 20% a day.[27]
- This means by day 7 there is no dissolved oxygen left in the water.

<u>Calculating the amount of oxygen to pump into the chamber.</u>

The the aerator has a flow rate of 24 gallons per hour. Converting that to liters is 90.84L/hour. To calculate how much air it pumps per minute (90.84 ÷ 60) = 1.514L per min.

Next, I need to find how much oxygen is in the air. Oxygen make up around 21% of air. (0.21 x 1.514 = 0.317) 0.317 liters of oxygen per min.

To convert 0.317 to mg of oxygen is 453.69mg/min. Not all of the the oxygen will be converted into dissolved oxygen. [27] I have assumed at least 20% will be dissolved. This will take about 2 min. I added 3 min more just for a safety factor just incase some oxygen does not get dissolved. All of the extra oxygen will escape out of the water until it reaches an equilibrium. Each day it will lose 20% of the dissolved oxygen content. All days after day 8 will be aerated 2 min before measurements.

Observations: Day 9

MFC.1: This MFC looked the same as day 8, only a little bit greener. This MFC fluctuated for about 1 min and gave a reading of 195.2 mV. The mA table for MFC.1 looked if they had an erratic pattern before aeration, but after aeration the numbers are climbing higher.

MFC.2: This MFC seems to be climbing in mV significantly higher than previous days. This MFC did not fluctuate and looks the same as day 8.

MFC.3: This MFC did not fluctuate and gave a strait reading of 124.3 mV. This MFCs mA table looks erratic. There were no noticeable visible changes to this MFC.

Observations: Day 10

MFC.1: This MFC did not fluctuate and increased its mV reading so much I had to turn the dial on the multimeter to ‘mV without decimal places’. The anode chambers mud is now very gray and fine.

MFC.2: This MFC had a huge increase in it mV reading. It did not fluctuate when it gave the reading of 164.3 mV. The mA reading was very surprising as it gave a reading of only 0.04 mA.

MFC.3: This MFC did not fluctuate and gave expected readings. There were no noticeable changes.

Observations: Day 11

MFC.1: This MFC had some sort of orange algae plant growing around the anode chamber. The bubbles forming on the settled water in the anode chamber were so thick they were holding some algae onto it. This MFC did not fluctuate and gave a strait reading. I noticed in my data spreadsheet that all the mV reading seemed to increase a little more each day. This MFC also gave a mA reading of 1.1, which was very surprising.

MFC.2: This MFC also did not fluctuate. The data table showed the same pattern as MFC.1, as MFC.2 was increasing its mV reading a lot.

MFC.3: This MFC did not have any significant visible changes, and did not fluctuate either.1

Observations: Day 12

MFC.1: This MFC did not fluctuate again, and increased about 120.5 mV! There was a significant amount of orange algae growth on the water (Anode chamber). It looked disgusting similar to vomit. There was also some sort fungal growth on the lid, it looked like very veiny frost formation. I could identify 5 different organisms thriving in the MFC. These creatures were worms, snails, algae, some really tiny isopods, and fungi. This MFC started to bubble a lot faster than previous days, I think this was because the oxygen was saturated more.

MFC.2: This MFC started to bubble a lot faster than previous days, I think this was because the oxygen was saturated more. No other visible changes.

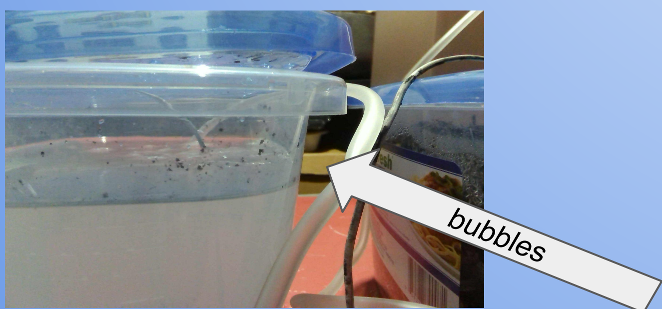
MFC.3: This MFC started to bubble a lot faster than previous days, I think this was because the oxygen was saturated more. No other visible changes.

Observations: Day 13

MFC.1: This MFC did not fluctuate and gave a strait reading of 508.9 mV and 1.78 mA. The water on the anode chamber looked like a dark dirty yellow instead of a cloudy yellow. The overall state/condition of the MFC looked very similar to day 12.

MFC.2: This MFC bubbled so fast during aeration. While aeration the air seemed to carry water along with it while rising up in the air. This caused water droplets to fly upwards on the lid. There were also lots of bubbles in the cathode chamber (as well as the rest of MFCs)

MFC.3: This MFC did not fluctuate and gave expected readings. There were no noticeable changes.

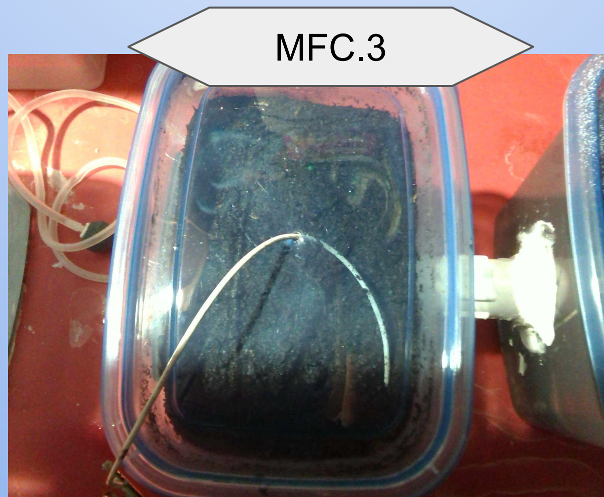


Observations: Day 14

MFC.1: This MFC had super cloudy, dark orange water settled on top of the anode chamber. It created a whopping 1442.8 mW! This MFC was very similar to day 13, only it did made all the main changes listed in day 13, only doing them a lot more. There was also significant fungal growth on the lid. This made it impossible to see through the top of the lid.

MFC.2: This MFC did not fluctuate (as well as the rest of the MFCs). This MFC also bubbled the same a day 13.

MFC.3. This MFC bubbled the fastest out of all the MFCs. This MFC did not fluctuate and gave expected readings. There were no noticeable changes.



Data Table Voltage (mV)

Date: (Dec-Jan)	**27th**	**28th**	**29th**	**30th**	**31th**	**1st**	**2nd**	**3rd**	**3rd**	**4th**	**5th**	**6th**	**7th**	**8th**	**9th**
Day number:	**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**	**Day 8**	**Day 8A**	**Day 9**	**Day 10**	**Day 11**	**Day 12**	**Day 13**	**Day 14**
MFC.1	102.0	68.0	89.2	83.4	95.0	73.4	93.9	152.1	155.1	195.2	220.0	311.6	432.1	508.9	721.4
MFC.2	104.5	67.9	111.5	69.7	110.6	113.7	115.4	123.6	118.3	136.7	164.3	231.4	250.5	291.5	331.2
MFC.3	49.1	57.4	102.4	80.7	105.3	98.6	103.8	110.5	111.0	124.3	137.3	154.8	165.4	182.3	193.1

Data Table Current (mA)

Date: (Dec-Jan)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 8A	Day 9	Day 10	Day 11	Day 12	Day 13	Day 14
Day number:	27th	28th	29th	30th	31th	1st	2nd	3rd	3rd	4th	5th	6th	7th	8th	9th
MFC.1			0.09	0.12	0.03	0.12	0.30	0.50	0.60	0.71	0.77	1.10	1.11	1.78	2.00
MFC.2			0.10	0.10	0.20	0.24	0.37	0.21	0.20	0.19	0.04	0.39	0.49	0.52	0.98
MFC.3			0.24	0.13	0.11	0.90	0.21	0.19	0.29	0.19	0.16	0.30	0.31	0.30	0.35

Data Tables Power (mW)

Date: (Dec-Jan)	27th	28th	29th	30th	31th	1st	2nd	3rd	3rd	4th	5th	6th	7th	8th	9th
Day number:	**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**	**Day 8**	**Day 8A**	**Day 9**	**Day 10**	**Day 11**	**Day 12**	**Day 13**	**Day 14**
MFC.1			8.03	10.01	2.85	8.81	28.17	76.05	93.06	138.59	169.40	342.76	480.50	905.84	1442.8
MFC.2			11.15	6.97	22.12	27.29	42.70	25.96	23.66	25.97	6.57	90.25	122.75	151.58	324.58
MFC.3			24.58	10.49	11.58	88.74	21.80	21.00	32.19	23.62	21.97	46.44	51.27	54.69	67.59

Analysis

- First it was needed to enter 2 different readings of data, voltage and current into the spreadsheet.

Voltage:

- Created a table with daily voltage readings (mV) for each MFC for days 1-14.
- Then calculated the average voltage for each set of data for an MFC over 14 days.
- Determined the maximum and minimum readings for each MFC for days 1 to 14.
- Created a graph with the data collected above (Voltage vs Time)
- Plotted the most accurate trendline (I experimented with all the different types, and settled on exponential*)

Analysis

Current:

- Created a table with daily current readings (mA) for each MFC for days 1-14.
- Then calculated the average current for each set of data for an MFC over 14 days.
- Determined the maximum and minimum readings for each MFC for days 1 to 14.
- Created a graph with the data collected above (Current vs Time)
- Plotted the most accurate trendline (I experimented with all the different types, and settled on exponential* for MFC.1 and 2, linear for MFC.3)

Analysis

Power:

- First it was needed to calculate the power production for the MFCs (Power=V×I, or Power = Voltage × Current)
- Then it was needed create a spreadsheet for the power generated (mW) from the MFCs for 14 day
- Then calculated the average power for each set of data for an MFC over 14 days.
- Determined the maximum and minimum readings for each MFC for days 1 to 14.
- Created 3 graphs: No aeration (Day 1-7 Vs Time), Aeration (Day 8-14 Vs Time), and Wattage over 14 days (Power Vs Time)

Change:

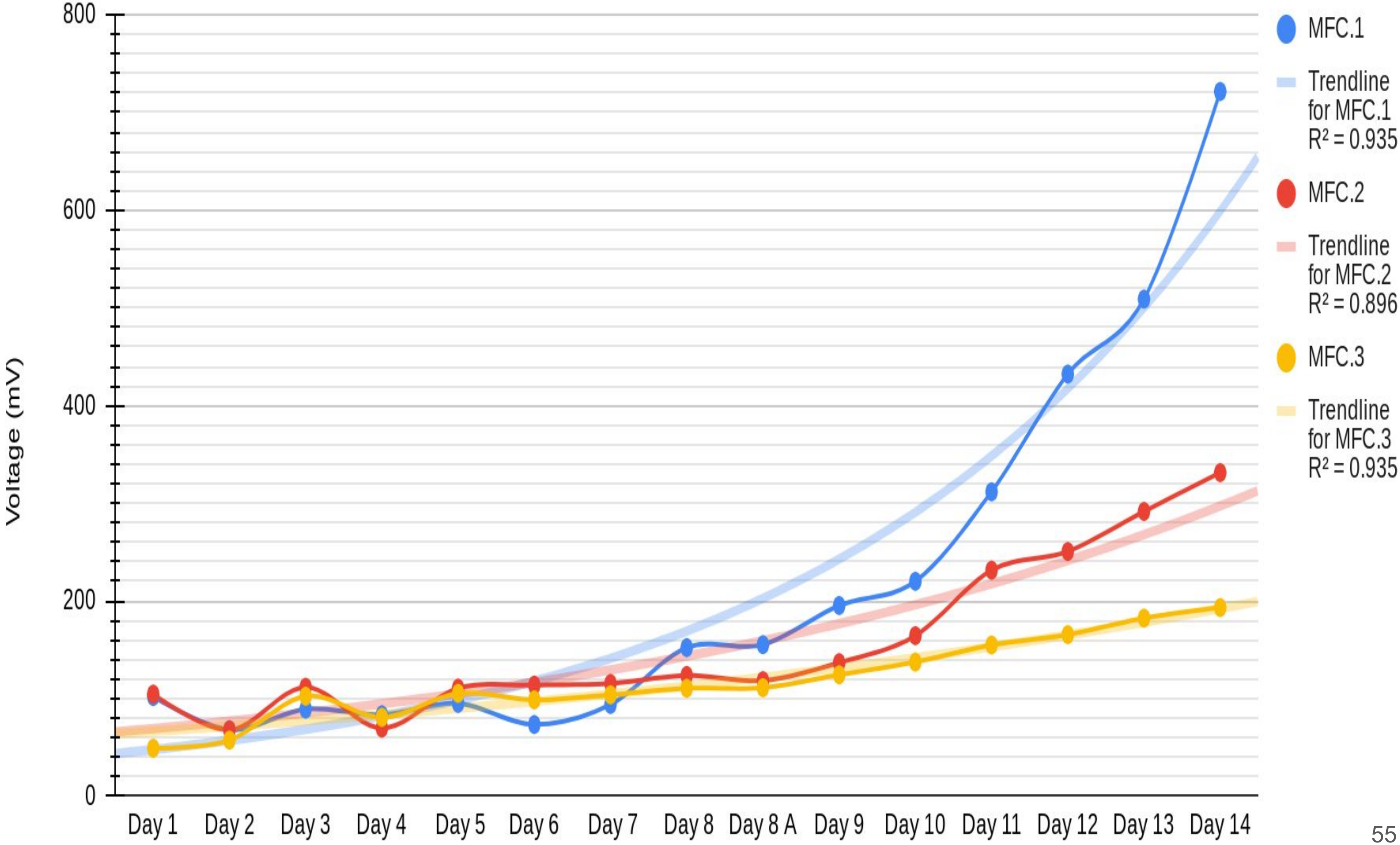
- First it was need to calculate the change and percent change between day 7 and day 14 (No aeration, and aeration)
- (This is calculated by Day 14 - Day 7) ⟵ Change
- (Change ÷ Day 7 = Percent change)
- Then It was needed to put it into a table and then one chart/graph

Percent Change (Compared to control)

- First it was needed to calculate the percent change from each MFC compared to the control.
- This is calculated by ↙
- (MFC_ - MFC.3) ÷ MFC.3 = Percent change.
- Then it was needed to put the data into a table and put it into one graph.

Voltage (mV) over 14 days:

***Day 8 and 8A is the before and after measurements of aeration**



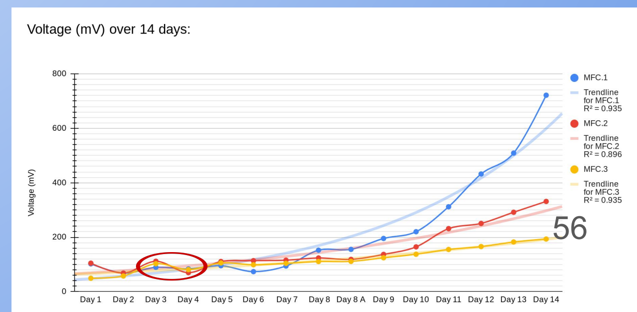
Analysis and results:

Trend lines:

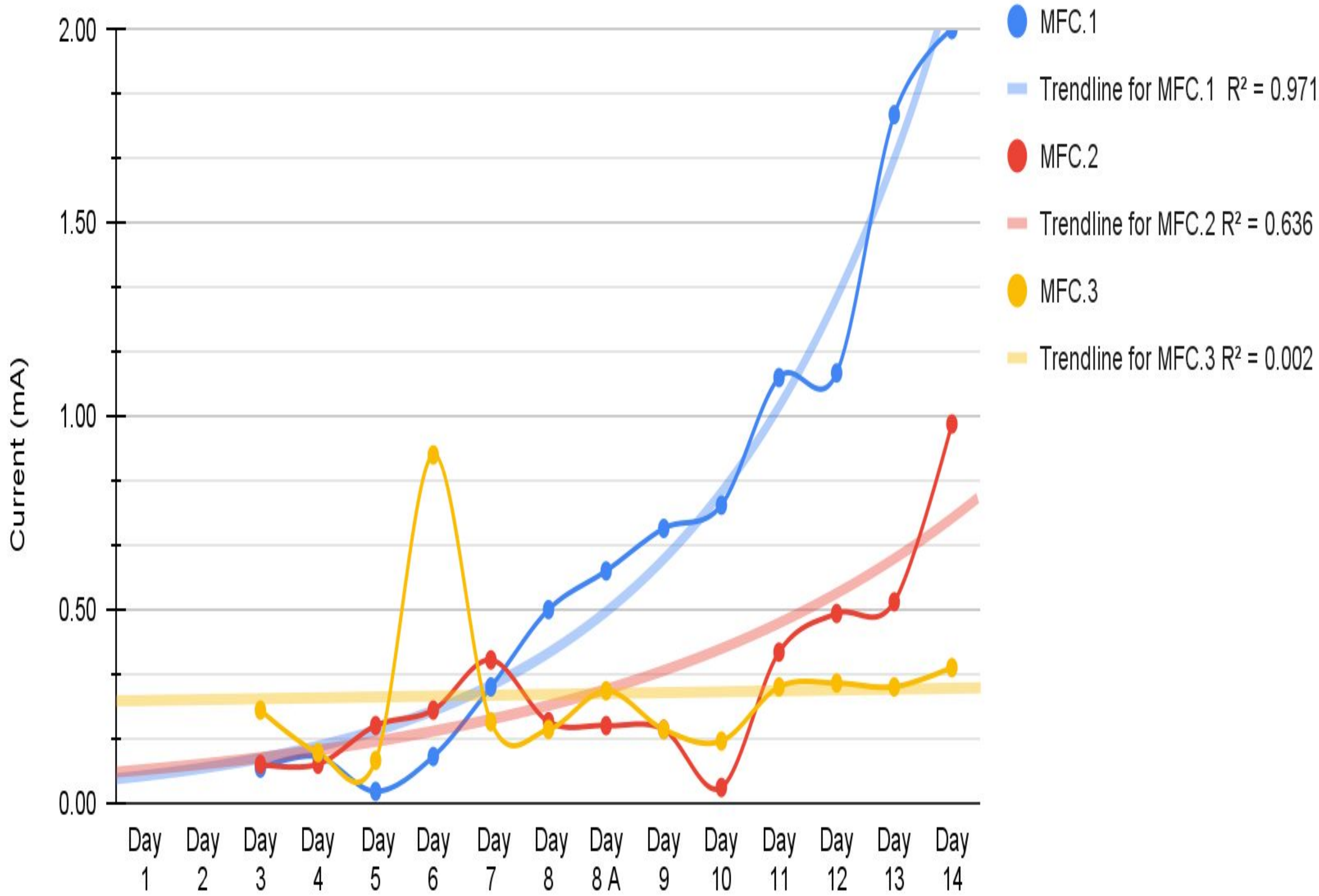
1. MFC.1 Exponential
2. MFC.2 Exponential
3. MFC.3 Exponential

1. This Graph shows the amount of mV produced by each MFC over 14 days.
2. For the first 7 days, each of the MFCs incline/increase in mV was very similar to each other.
3. MFC.2 had the most significant increase/incline, then MFC.3, and MFC.1.
4. Throughout days 1-7, the incline was very erratic and all the MFCs kept of spiking up and down in the amount of mV they were producing. This was mainly because of the microbial activity happening inside the MFC was inconsistent (living organisms are not perfect like machinery and are not going to produce reliable electricity), or slight measurement error on days 3 and 4.
5. When aeration was introduced to the MFCs, the voltage production started to skyrocket (after day 8) from 10-40 mV per day, to 50-120 mV per day.
6. MFC.1 had the most increase per day, 80-120 mV per day, second MFC.2 with around 70-90 mV per day, and lastly MFC.3 with around 50-60 mV per day.
7. The exponential trendline that I chose worked the best with finding the pattern and incline for the graph because bacteria have an exponential growth rate [28], meaning that they will continue to grow and decompose the substrate in the MFCs until there is no organic matter left. This means if their is a decrease in organic matter content in the MFC, the voltage will drop down. If the organic matter in an MFC is replaced, the MFC will continue to increase the voltage production exponentially.
8. The R^2 value (regression coefficient) is very high (over 80%). This means the formula for the exponential trend is accurate, and there is a recognisable pattern for incline on the graph. This is good because the MFCs are not make random amounts of “electricity” and it is possible to predict how many mV the MFCs will produce over time.

Voltage table:	MFC.1	MFC.2	MFC.3
Average:	220.09	156.05	118.40
Max:	721.40	331.20	193.10
Min:	68.00	67.90	49.10



Current (mA) over 14 days:

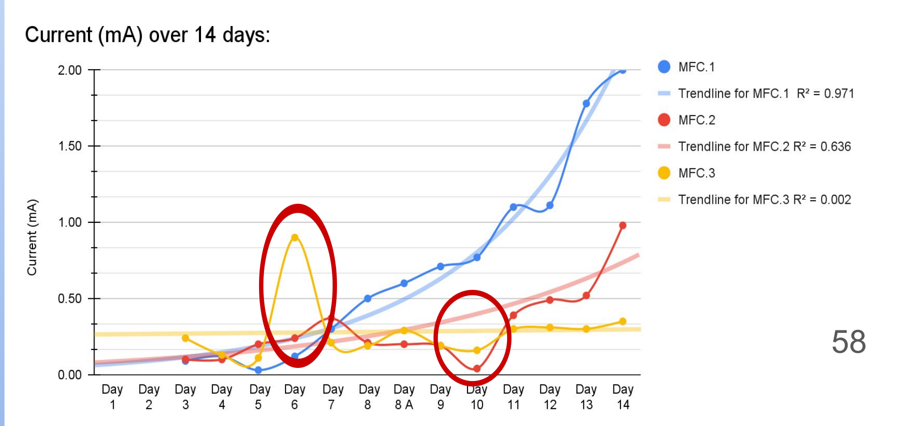


Analysis and results:

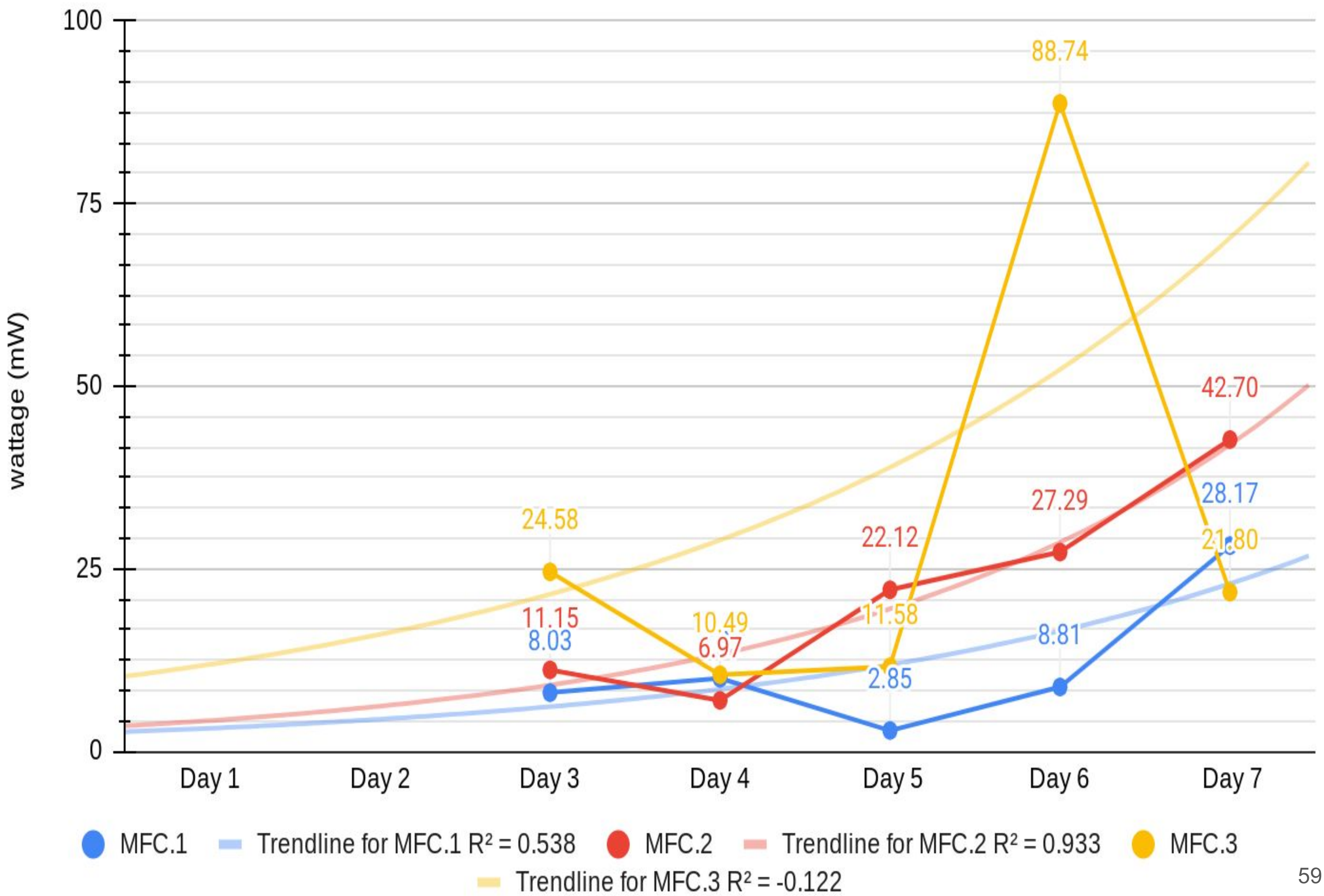
Trend lines:
1. MFC.1 Exponential
2. MFC.2 Exponential
3. MFC.3 Linear

1. This graph shows the mA produced by each MFC over 14 days.
2. For the first 7 days (No aeration) the incline was very erratic. This was mainly because of the microbial activity happening inside the MFC was inconsistent (living organisms are not perfect like machinery and are not going to produce reliable electricity), or slight measurement error. MFC.3 was the most erratic, spiking up from a range of 0.001-0.3 and and spiking up to 0.9 mA on day 6. This was most likely caused by a fault in the digital multimeters accuracy in reading the current.
3. After aeration, MFC.1 started to sky rocket once again, giving a a top read of 2 mA on day 14. Second MFC.2 with a top and final reading of 0.98 mA. Finally MFC.3 with a top reading of 0.9 mA, and a final reading of 0.35 mA.
4. The R^2 value (regression coefficient) is very high over 80% for MFC.1. MFC.2 had the second highest R^2 value of 0.63 or 63%. Finally MFC.3 had a linear trendline because it fit the best. MFC.3 had the lowest R^2 Value of 0.002. MFC.3 had a low R^2 Value mainly because of the the huge spike in the graph, on day 7 had no quaralation with the rest of the pattern and incline on the graph.
5. MFC.1 had the highest Average, Max, and Min. Then MFC.2 and finally MFC.3 with the lowest Average, Max, and Min.
6. There is no measurement on the first 2 days because I didn't know I needed current readings to calculate power.

	MFC.1	MFC.2	MFC.3
Average:	**0.71**	**0.31**	**0.28**
Max:	**2.00**	**0.98**	**0.90**
Min:	**0.03**	**0.04**	**0.11**



No Aeration: (mW)



Analysis and results:

Trend lines:

1. MFC.1 Exponential
2. MFC.2 Exponential
3. MFC.3 Exponential

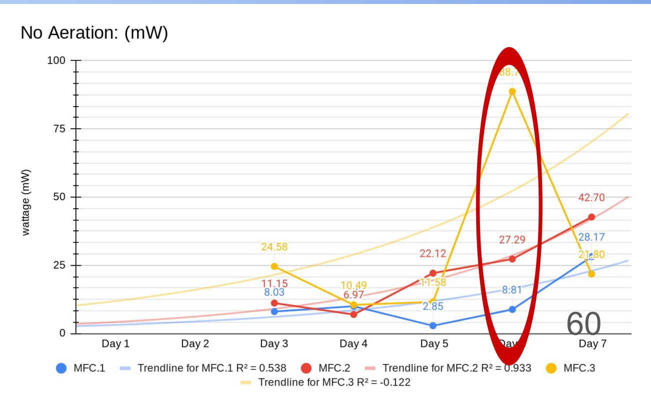
1. This graph shows the amount of electric power produced from Days 1-7 (No aeration).
2. Days 3-4 there was a decrease in the power produced, as the incline sloped down. MFC.1, and MFC.2 had a very similar pattern as they decreased power on the 4th day, but eventually climbed to the 20-40 mW range by gaining a consistent amount of mW per day.
3. MFC.3 had the most erratic incline of all the MFCs and had no visible pattern. The huge spike on day 6 was most likely an outlier, and there is no obvious answer to why there was a big spike. (Outlier when measuring the current on day 6).
4. MFC.2 had the highest R^2 Value of 0.93 or 93%, then MFC.1 with a R^2 Value of 53%, and lastly MFC.3 having a R^2 Value of -0.122. MFC.3 had a very erratic incline with no pattern whatsoever. This was most likely caused from huge measurement error and microbial activity being erratic (different than consistent activity).
5. Because of the big spike in the data on day 6, this caused MFC.3 to have the highest Average and Max. MFC.3 also managed to get the highest Min, then MFC.2, and lastly MFC.1 with the lowest Average, Min, and Max.
6. Since the big outlier affected MFC.3's first table/data set, I created another table to show more accurate readings in the tables. Now MFC.2 has the higher Average, Max, and Min. Then MFC.1, and lastly MFC.3 with significantly different readings than the first table.

Non aeration:	MFC.1	MFC.2	MFC.3
Average:	11.57	22.05	31.44
Max:	28.17	42.70	88.74
Min:	2.85	6.97	10.49

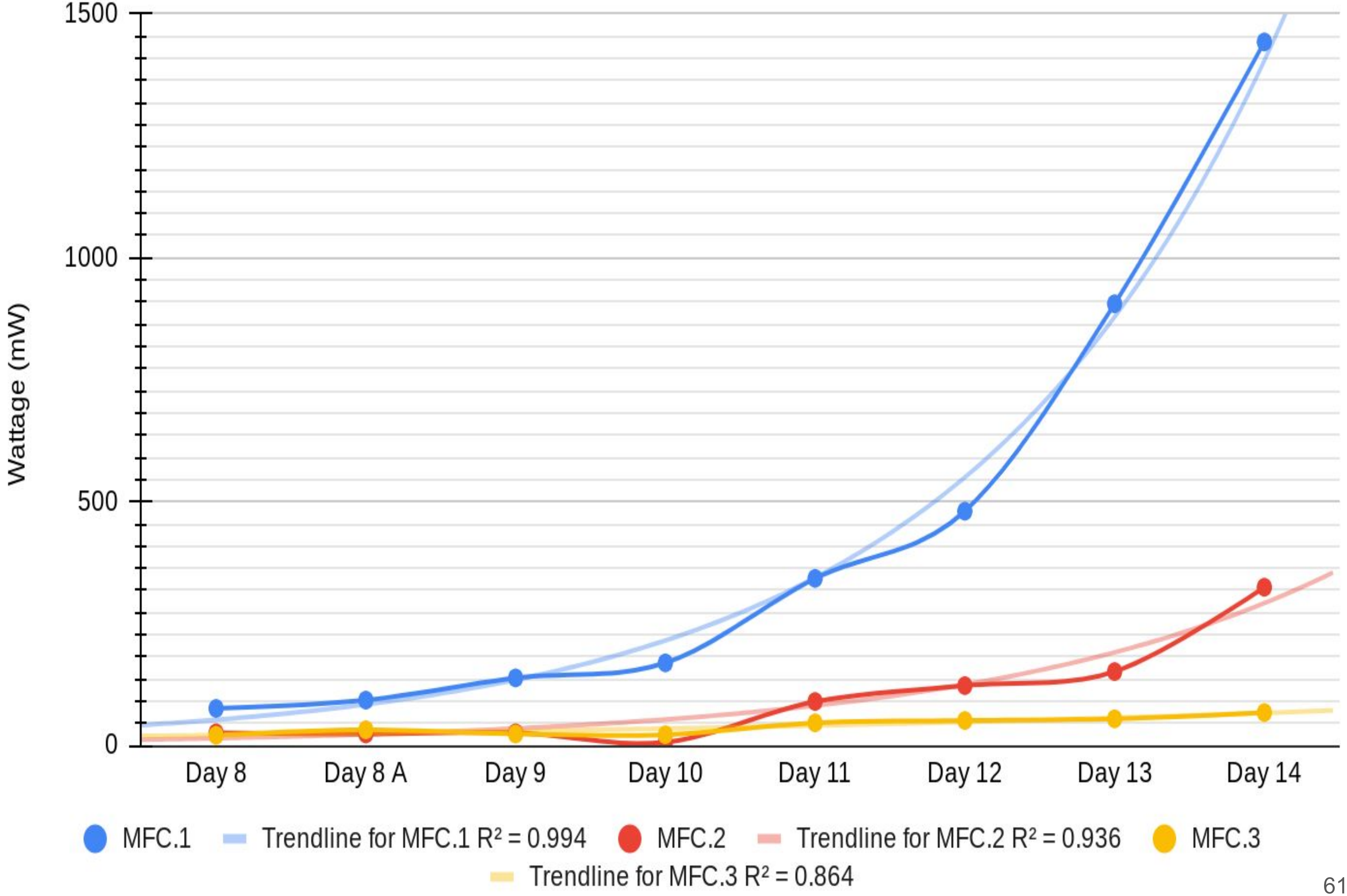
includes all data

Non aeration:	MFC.1	MFC.2	MFC.3
Average:	11.57	22.05	13.69
Max:	28.17	42.70	24.58
Min:	2.85	6.97	0.00

Excludes MFC.3 Day 6



Aeration: (mW)



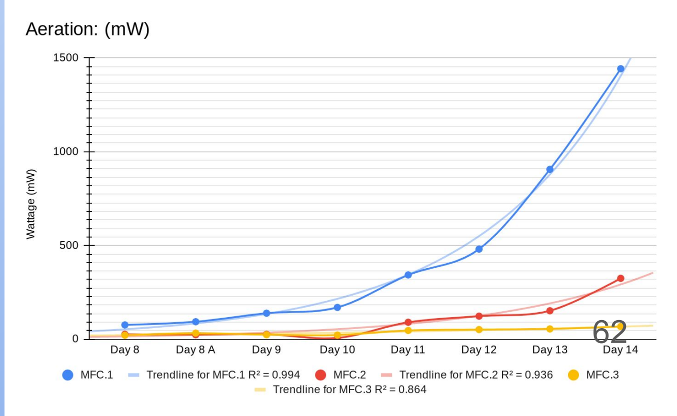
1500
1000
500
0
Wattage (mW)
Day 8
Day 8 A
Day 9
Day 10
Day 11
Day 12
Day 13
Day 14
MFC.1
Trendline for MFC.1 R² = 0.994
MFC.2
Trendline for MFC.2 R² = 0.936
MFC.3
Trendline for MFC.3 R² = 0.864

Trend lines:

1. MFC.1 Exponential
2. MFC.2 Exponential
3. MFC.3 Exponential

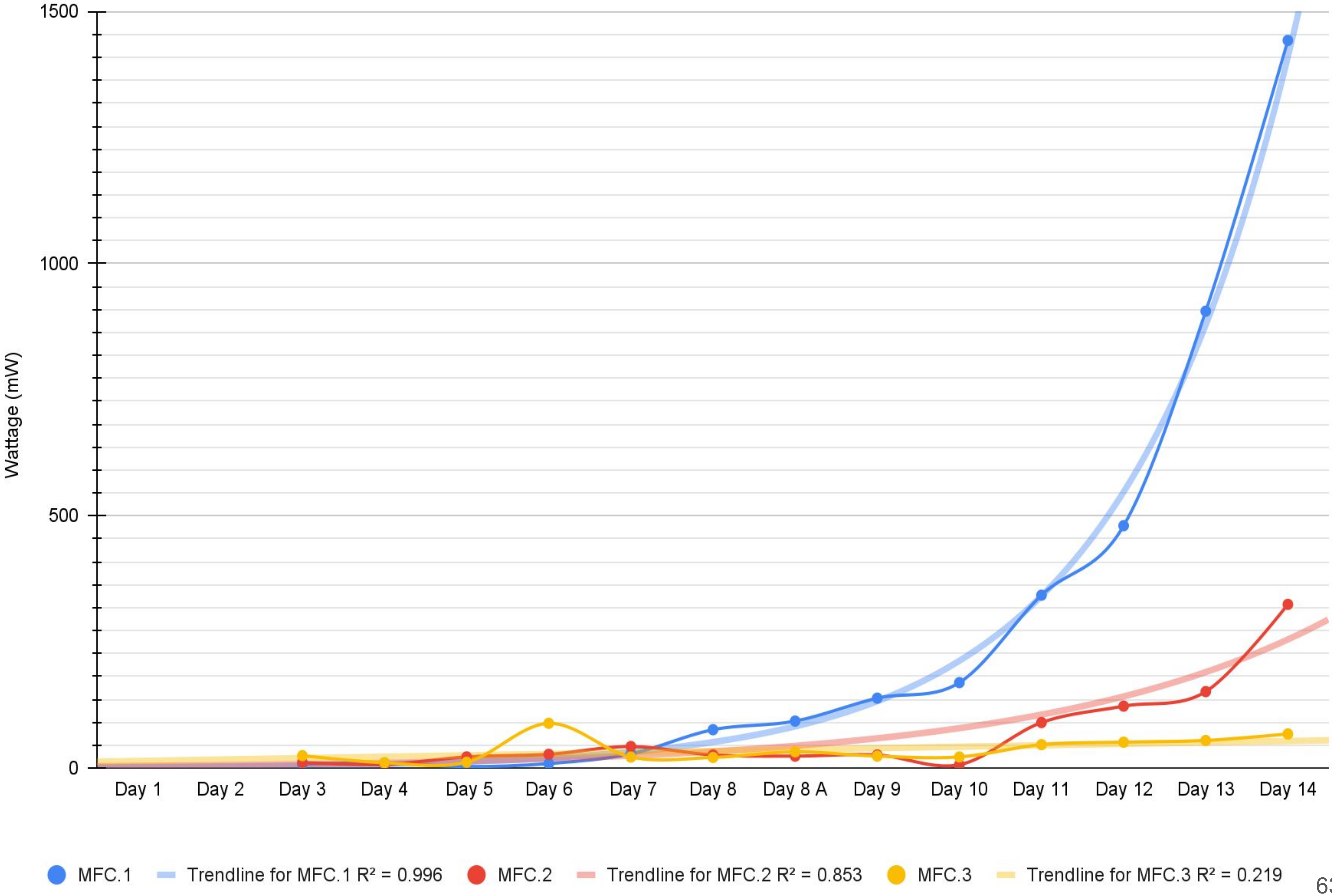
Analysis and results:

1. This graph shows the amount of electric power produced from Days 8-14 (No aeration).
2. All the MFCs had a significantly higher and more consistent slope compared to the “No Aeration” graph, and every day there was an increase in power production
3. On day (8-8A) there was no significant increase in the mW reading, although it did increase a little bit (2-5 mW). This was not significant enough to decide whether aeration affected power production.
4. All of the MFCs inclines, on days 8-14 did not give erratic readings compared to the “No Aeration” Graph. This is because I believe there was no outliers and reliable readings taken for this graph.
5. From days 8-10, the all of the MFCs increased there mW production by about 20-40 mW per day. After day 10, MFC.1 skyrocketed in its mW production. It started to produce 200-536.96 mW per day. MFC.2 increased its mW by 50-65 mW, and lastly MFC.3 with the lowest increase in its mW production (20-25 mW).
6. The R^2 value (regression coefficient) is very high (over 80%) for all the MFCs. MFC.1 had a R^2 Value of 0.99 or 99%. This is good because the formula applied to the trend line is almost 100% correct, meaning the MFC will continue to create more electricity over time. MFC.2 had the second highest R^2 value of 0.93 or 93%. Lastly MFC.3 with an R^2 Value of 0.86 or 86%.
7. MFC.1 produced the highest Average, Max, and Min because of the high mW readings it produced. Then MFC.2, and lastly MFC.3



Aeration:	MFC.1	MFC.2	MFC.3
Average:	456.12	96.41	39.84
Max:	1442.80	324.58	67.59
Min:	76.05	6.57	21.00

Power (mW) over 14 days:



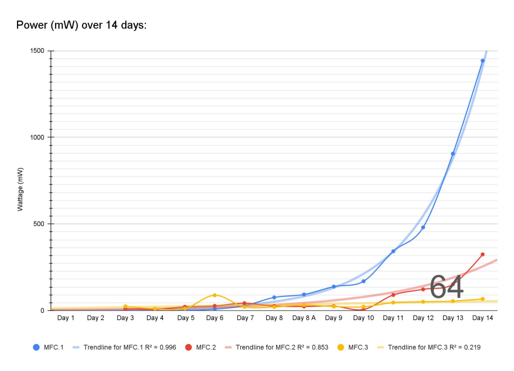
Trend lines:

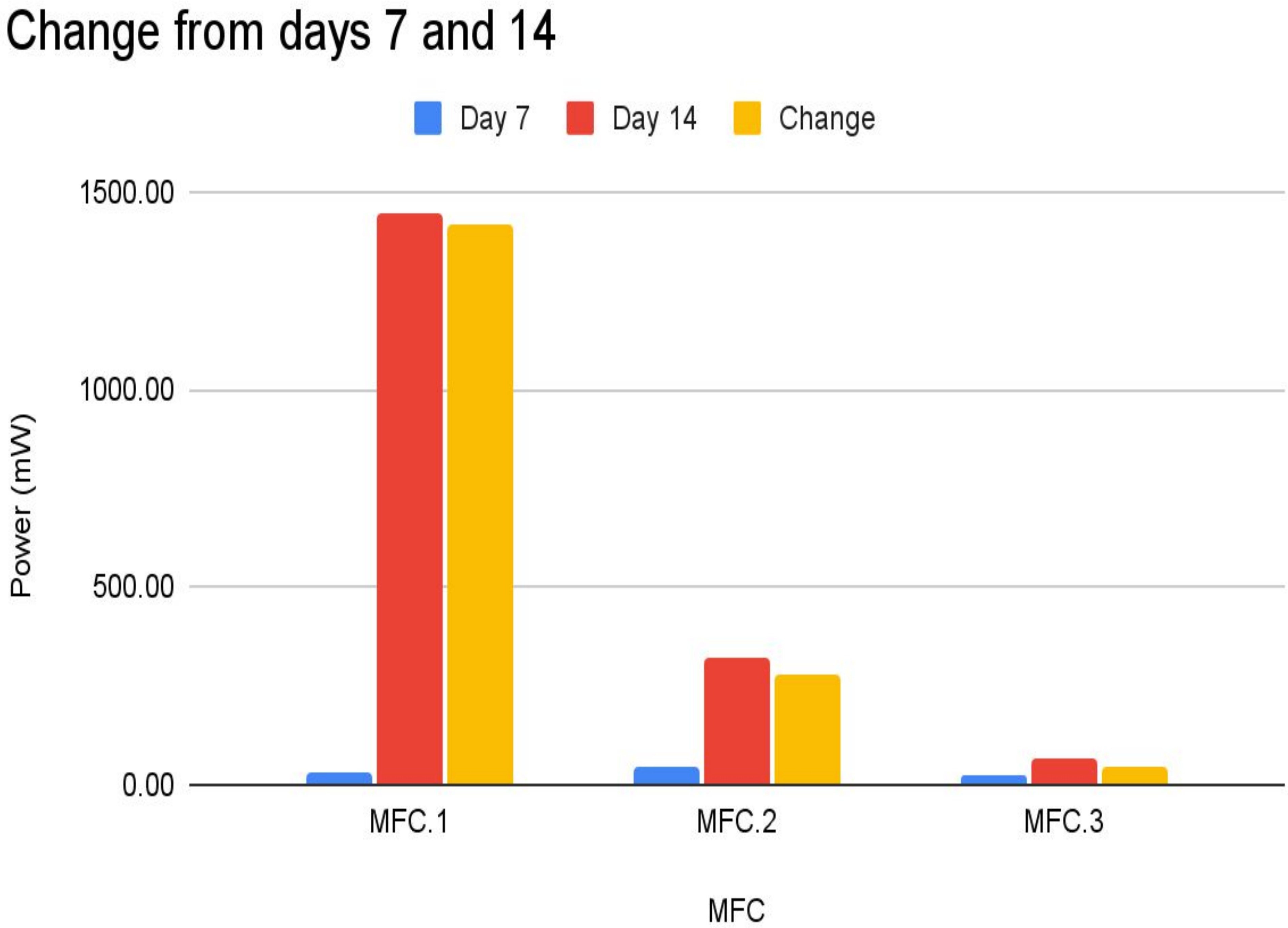
1. MFC.1 Exponential
2. MFC.2 Exponential
3. MFC.3 Linear

Analysis and results:

1. This graph shows the amount of electric power (mW) produced from all days of the experiment (days 1-14).
2. This graph is a combination of the 2 graphs, “No aeration” and “Aeration” graphs composed into one graph.
3. For the first part of this experiment (No aeration) the mW reading were very low, and below 90 mW for all of the MFCs. This could be because the bacteria only established a small colony, only decomposing small amounts of the substrates. On day 6, MFC.3 had an outlier and this resulted in the graph spiking up suddenly above the majority of the readings (MFC.3 only).
4. When aeration was introduced to the MFCs, the mW production started to skyrocket in MFC.1, all the way to 1442.8 mW on day 14.
5. This graph provides a more accurate and easier way to see the R^2 Value because it uses all of the data recorded in the experiment. MFC.1 had the highest R^2 Value of 99.6%, then MFC.2 have the second highest R^2 Value of 85%, and lastly MFC.3 using a linear trendline and giving an R^2 Value of 21.9%. MFC.3 gave really erratic results throughout the course of 14 days so it did not give the best R^2 Value. MFC.3’s R^2 is very low, meaning that it is hard get a precise answer to how much it will increase over time.

All 14 Days:	MFC.1	MFC.2	MFC.3
Average:	285.14	67.81	36.61
Max:	1442.80	324.58	88.74
Min:	2.85	6.57	10.49



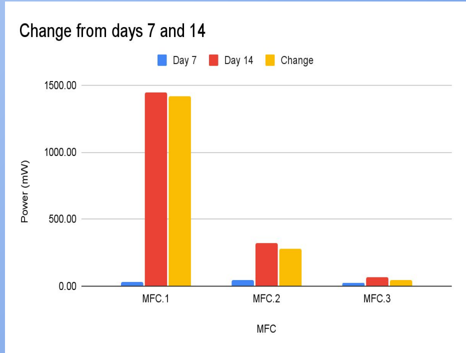


Change from days 7 and 14
Day 7
Day 14
Change
1500.00
1000.00
500.00
0.00
Power (mW)
MFC.1
MFC.2
MFC.3
MFC

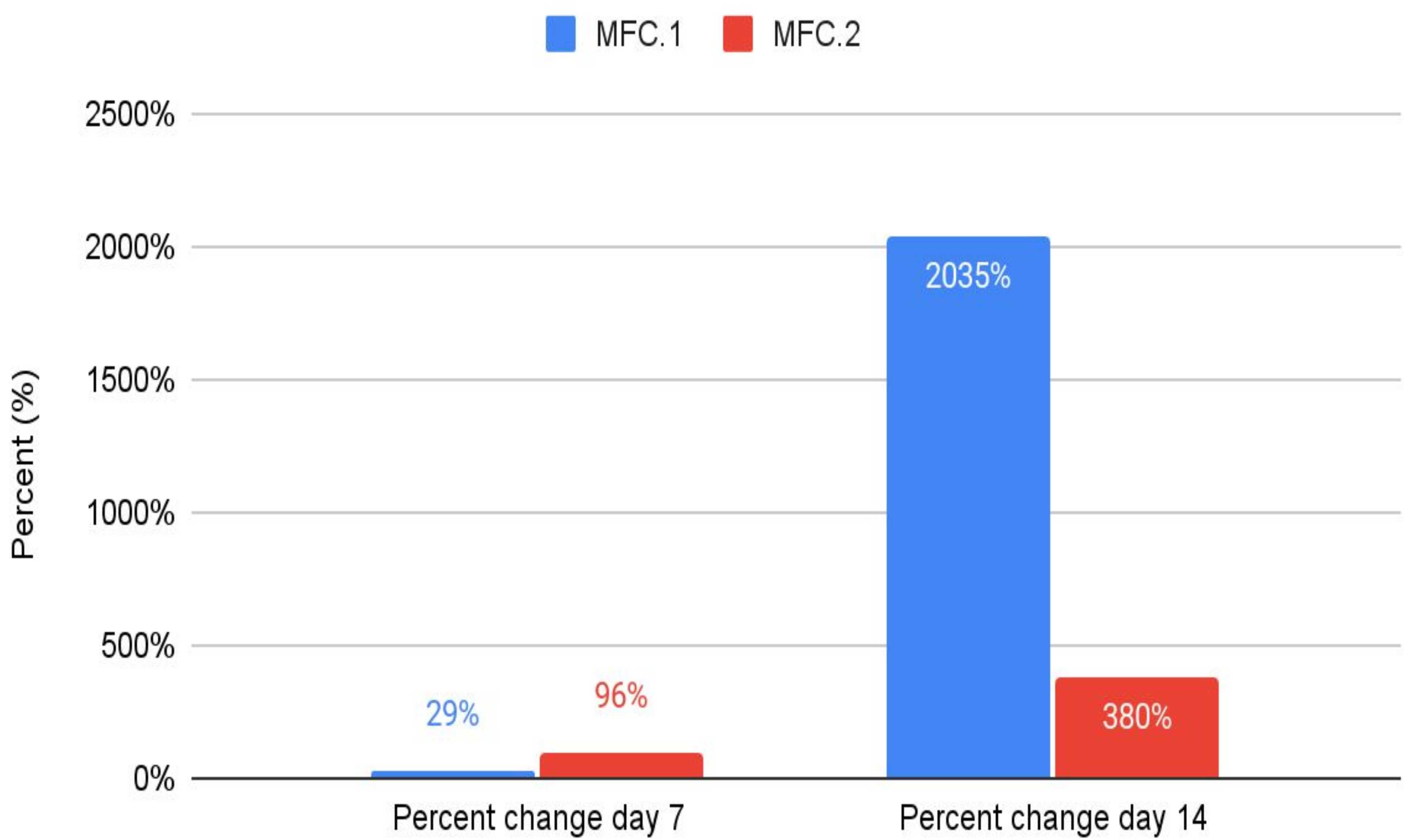
Analysis and results:

1. This graph shows the change in power (mW) from day 7, to 14 for each MFC
2. MFC.1 had the greatest increase in power production from day 7 to day 14, (1414.63 mW.) MFC.1's change in mW production was 5× more than MFC.2 and about 30× more than MFC.3 . MFC.1 also had the highest percent change reading 5021.8%, or MFC.1 produced 50× more power on day 14 than day 7.
3. MFC.2 had the second highest increase in power production from day 7 to day 14 (281.88mW.) MFC.2 had the 2nd highest percent change (620.2%) which is 3× higher than MFC.3
4. MFC.3 had the lowest change in power production (45.79 mW.) MFC.3 also had the lowest percent change (210.1%) only doubling the amount of electricity produced from day 7 to day 14.

MFC	Day 7	Day 14	Change	% change
MFC.1	28.17	1442.80	1414.63	5021.8%
MFC.2	42.70	324.58	281.88	660.2%
MFC.3	21.80	67.59	45.79	210.1%

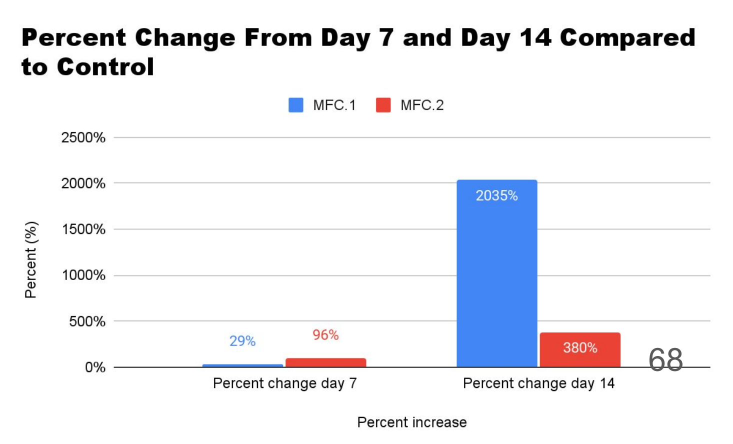


Percent Change From Day 7 and Day 14 Compared to Control



Analysis and results:

1. This graph is a combination of MFC.1 and 2’s **‘percent increase’** compared to MFC.3 during the no aeration and aeration time periods of my experiment.
2. During no aeration, both MFC.1 and 2 had a percent increase lower than 100%. MFC.2 had a higher percent increase than MFC.1 reading 56% while MFC.1 was only 29% higher than MFC.3 **.**
3. During aeration, both MFC.1 and 2 had a percent increase way higher than 100%. MFC.1 had the highest percent increase reading 2035% or 20× more mW production than MFC.3.
4. MFC.2 had a lower percent increase than MFC.1 only having a percent increase of 380% or about 4× more power production than MFC.3



Conclusions

The following are conclusions based off of my analysis, results, and observations:

- In conclusion, all 3 MFCs produced electricity. This means they were built precise enough to sustain all the necessary reactions required for electricity production. (MFC.1-3)
- In conclusion my hypothesis 1.0 was wrong and MFC.1 (benthic mud) produced the most electricity. It produced 1442.8 mW on the last day of experimentation (day 14). MFC.1 produced about 4x more power than MFC.2 and 21x more power than MFC.3. This is because benthic mud has the most rich soil, meaning that it will have better nutrients and more abundance of organic matter for the bacteria/microbes to populate and reproduce. Benthic mud has a higher abundance of easily accessible nutrients because, the water/river where the benthic mud is collected from hits the mud constantly, eroding the nutrients and and making it finer for bacteria to decompose the mud. *Also the bacteria found in benthic zone are ideally suited for decomposing tough organic matter found in the benthic zone, thus making it more efficient and faster for decomposing substrates.* MFC.1 also had other decomposers in the substrate such as worms, algae, fungus, snails, (E.T.C) The nutrients was broken down into smaller components, making it easier for MFC.1s bacteria to decompose its substrate.

Conclusions

- MFC.1 and 2 had a consistent bacterial growth pattern compared to MFC.3. This is because there is more nutrients in benthic mud and compost soil than topsoil. When bacteria are exposed to lots of accessible nutrients, bacteria can reproduce more to decompose a substrate. MFC.3 did not have lots of accessible nutrients for the bacteria to colonize, thus leading to erratic and slow bacterial growth.

- MFC.2 and 3 did not produce as much power as MFC.1. This is because these MFCs did not have other organisms to help break down organic matter. MFC.2 and 3s bacteria had to decompose large organic mass, this was a big task for the bacteria and therefore it took longer for the bacteria to grow and reproduce. This is reflected in the power graphs that shows a lower incline compared to MFC.1.

Conclusions

In conclusion, my hypothesis 2.0 was correct, the MFCs power production spiked up immediately after aeration was introduced. Aeration had little to no effect on the voltage readings because the potential energy only comes from the anode chamber which is controlled by the bacterial growth.

Aeration <u>**is**</u> designed to affect current because when the cathodes are exposed to lots of oxygen, this allows reactions (Positive charges bonding with oxygen) to happen faster. When the reactions happen faster, this allows the electrons to move faster, thus increasing the current flow.

Sources of Error

1. **Measurement error**: In taking the reading of voltage and current, the digital multimeter may have read the readings incorrectly because the alligator clips where loosely connected to the copper wire. Instead of applying an insulator, (like electrical tape) to the alligator clips, the current could have varied the current or voltage readings, depending of the position the two metal sides (Alligator clips, and copper wire). Thus this could affect the way the digital multimeter read the readings.
2. **Temperature:** In this experiment, the temperature was not regulated at one specific temperature through the 14 days of testing. This could have impacted the results because the bacteria may have catalysed the reactions faster according to the temperature they like best. The majority of bacteria have a specific temperature they like to thrive, and reproduce in. Because it is not certain which type bacteria where in my experiment, when the temperature went up/down, the bacteria might have had a surge of activity.
3. **Leakage:** MFC.2 and 3 had 1-2 leaks, this let numerous amounts of salt to drain out of the cathode chamber, this may of lowered the voltage/current reading because there was a low amount of salt to regulate positive/negative charges in the MFCs, thus slowing the reactions down.
4. **Acidity:** The PH levels could have varied in the MFCs, this affected the results because, bacteria can grow better in less/more acidic environments, as other microorganisms, and byproducts in the anode chamber (produced by bacteria) could have changed the acidity around all of the MFCs

Applications

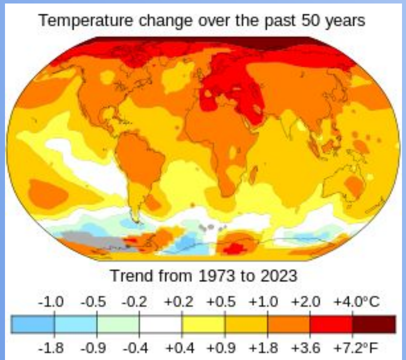
Why should we use MFCs? (there are hundreds of applications for MFCs, I will only highlight the biggest ones)

1. MFCs can save **greenhouse gas emissions** from unclean energy production. This is because compared to electricity production from fossil fuels. Burning fossil fuels releases nitrogen oxides into the atmosphere, and can contribute to smog and acid rain. This can also harm water quality, biodiversity and habitats. MFCs take a cleaner approach, they can create electricity directly from a substrate or a waste product and directly converts it into electricity via bacteria. MFCs still can create greenhouse gas emissions, but not nearly as much as conventional methods (like fossil fuels, combustion, e.tc)
2. MFCs can generate electricity by breaking down organic matter, this can create and **renewable and sustainable energy source.** This can produce electricity to power houses/appliances, making our way of life easier. It can also provide an easy access to electricity, as we live around a huge abundance of soil.
3. Many countries and areas around the world don't have access to electricity. MFCs could fix that problem by creating electricity directly from the soil/waste. Remote areas would not have to pay lots of money for transporting electricity and building the equipment necessary to do so. Instead MFCs could give direct access to electricity.
4. MFCs can be set up to create electricity from ***local waste sources***, such as compost plant, and a wastewater treatment plant. With a constant supply of waste, MFCs can can run continuously turning waste into electricity. This can also reduce some pollution.

Applications

Why should we save greenhouse gas emissions in Canada? We should save greenhouse gas emissions because:

1. **Climate change:** Greenhouse gas emissions are the biggest reason to climate change and global warming. This can cause severe weather events such as heatwaves, droughts, and floods to happen more frequently.
2. **Ecosystems:** Rising temperatures and changes in weather patterns can endanger ecosystems and organisms even more. This is because it causes habitat loss. Erratic weather patterns
3. **Health risks/Pollution:** Climate change can worsen health issues by polluting our environment. This can create better living environments for bacteria and other viruses increasing the risk of respiratory diseases, heart diseases, (etc.)
4. **Food and water security:** Extreme weather events caused by global warming can disrupt agricultural production. This can lead to food shortages and droughts. This can have a big effect, especially in developing countries.



Science note*

After the experiment was finished, I tested the MFCs for 10 more days out of curiosity. This experiment has 24 days of data:

Application-Homes

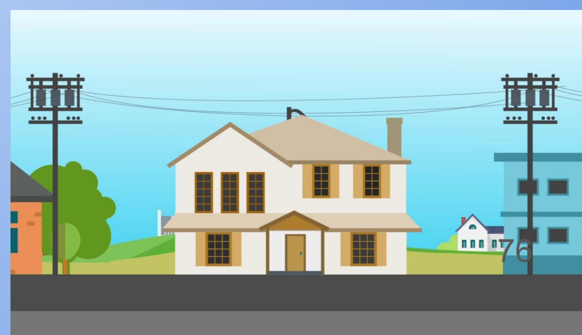
Calculations on google sheets:

<u>MFCs can power houses using benthic mud:</u>

- MFCs can produce 2.45 kWh in 24 days (from benthic mud). After that, the power started decrease. If more organic matter is added to the soil, without removing the bacteria, it will produce 6.854 kWh a month*.

(This is calculated by applying the formula (1.88e^0.473x) to all of the unknown days. X represents the unknown days, and is multiplied by 0.473. e means exponent. Another way to write this formula is 1.88 × (0.473x). After the formula is applied to the unknown days, all the days (days 1-30) are multiplied by 24 (hrs) to get Miliwatt hours. The conversion to get kilowatt hours is **(**mWh ÷ 1000**)** ÷ 1000 = kWh)

- The average house in canada consumes 600 kWh per month [30]. If 1 MFC can produce 6.85 kWh, then 88 MFCs can power a house per month. (600 kWh ÷ 6.85 = 87.59 < 88)
- These MFC's need to be fueled by 264 kg of soil (88 mfc's × 3kg of soil = 264 kg of soil. This can easily fit in a small backyard.



*Close estimate:

Application

MFCs can save greenhouse gas emissions from unclean electricity production in Alberta, for homes:

- On average, Alberta produces 0.4 tonnes of CO2 equivalents for each MWh of electricity produced. This is 470 grams of Co2 equivalents per kWh.[31]
- If an average house consumes 600 kWh in 1 month, it will produce 0.282 metric tonnes. (600 kWh x 470g = 282,000g →0.282t)
- According to research, MFCs can save greenhouse gas emissions up to 80%. MFCs can save 0.2256t of Co2e per house, in 1 month (0.282t x 0.8 = 0.0564t)
- If all houses used MFCs to power their houses, they could save around 368,454.432t of $Co2^e$ for alberta (1,633,220 $^{(homes)}$ x 600 kWh x 470g x 0.2 = 368,454,432,000g → 368,454.432t of CO_2e)

*The research above is from **Statistics Canada:** and the data is only from 2021

Application

*the number of metric tons of CO2 emissions with the same global warming potential as one metric ton of another greenhouse gas

MFCs can save money from carbon tax on greenhouse gas emissions from unclean electricity production for homes:

- Alberta produces 0.4 tonnes of Co2 equivalents per MWh. This is 470 grams of Co2 equivalents* per kWh.[31]
- Carbon tax for Albertans is $80 per tonne, a an average household consumes around 600 kWh.
- If an MFC powers a house, it can save $2.256 per month (0.00047t x 600 kWh x 80$ = $2.256 per month) and $27.072 per year. ($2.256 x 12 = $27.072)
- If all houses in Alberta used MFCs to power there houses, they could save $44,214,531.84 a year (1,633,220 (Homes) x $27.072)

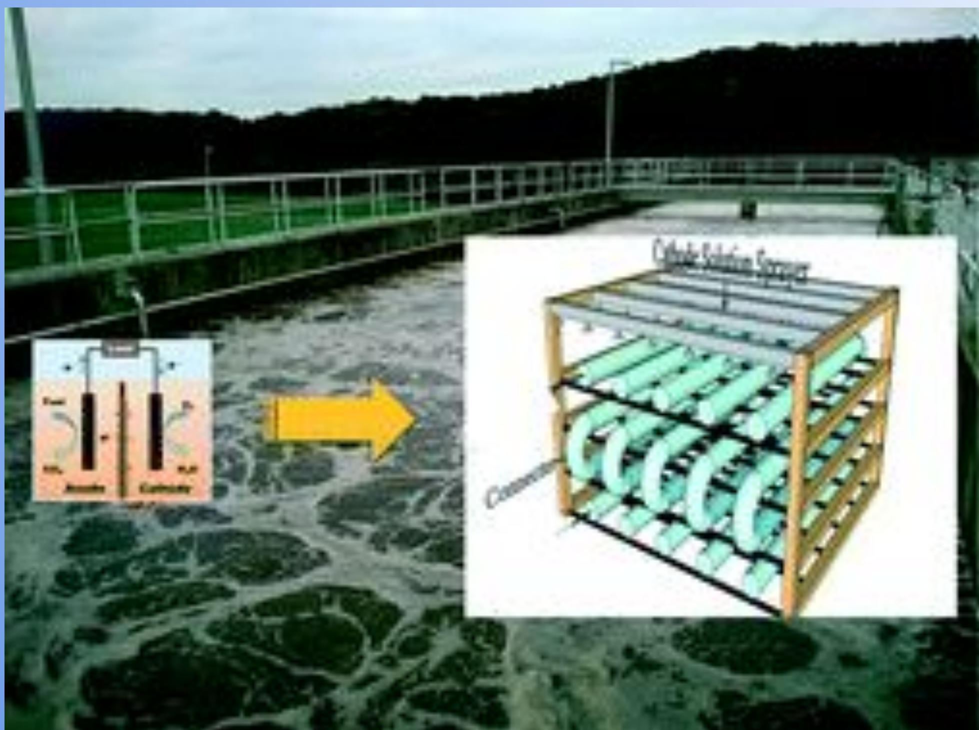
The money saved could be put toward:
Healthcare - hire around 130 new family doctors ($340,000 per doctor)
Education - could built around 2 new schools ($24 million per school)

<u>Other examples are:</u>
Fixing more roads.
Funding Microbial fuel cell research.
Build more protective area's for wildlife parks.
Improving the condition in first nation reserves/Off grid communities.

Application

MFC’s can create powers from landfills and wastewater treatment plants.

- MFCs have the potential to save countless amounts of Co2 equivalents from Waste water treatment plants and landfills. In the future, we might have the technology to built a big MFC’s around Wastewater treatment plants
- This could save lots of greenhouse gas emissions because the microbes and bacteria can break down the waste found in wastewater treatment plants.
- The microbes could break the waste and greenhouse gasses into simpler components instead of just releasing the gasses into our atmosphere.
- This could be implemented in the future, and expanded with further research.



MFC’s creating electricity on a wastewater treatment plant.

Application

<u>MFCs can power Off-grid communities and areas:</u>

- Many places in the world do not have accessible electricity sources.
- Around 20-30 countries have less that 50% of their populations having access to electricity.
- 8.4-19.5% of South Sudan, Chad, Papua New Guinea, and Niger's populations have access to electricity.[32]
- This means 91.6-80.5% of their populations do not have electricity. One way to fix this disaster is to install microbial fuels cells: Microbial fuel cells could be built in these areas to ensure more people have electricity.
- These countries have very little power consumption per capita, and MFC can be used to power small appliances, like stoves to meet essential needs
- According to World Health organization ***<u>Website:</u>*** Around 1.9 million people die every year because of household energy issues. If MFCs are installed in these poor areas of the world, this could lead to people dying less each year .

Application

<u>MFC’s can power small house appliances:</u>

- Electric stoves in alberta use about 550 kWh/year [35]or 45.833kWh/month. One MFC (Benthic mud) can produce 6.854 kWh/month. Seven Benthic mud MFC’s can power an electric stove per month. (45.833 ÷ 6.854 = 6.687kWh<7kWh)
- Alberta produces 0.4 tonnes of Co2 equivalents per MWh. This is 470 grams of Co2 equivalents per kWh.[31] If MFC’s power a stove, they can save 21541.51g of CO2 equivalents per month or (21.54151kg of CO2) → (45.833kWh × 470g = 21541.51g of CO2^{e}.
- Electric ovens use about 72 kWh per month (If you used your oven for about an hour a day)[34] then 11 benthic mud MFC’s can power an electric oven. (72 kWh ÷ 6.854 = 10.5<11)
- If MFC’s power an electric oven they can save 33840g of CO2^{e} (72kWh × 470g = 33840g or 33.84kg of CO2^{e}.

Application

<u>MFC's can power remote Indigenous reserves:</u>

- Many First nation reserves across canada are living in poor conditions that are both extremely unhealthy and unsafe. It is very challenging to find a specific reserve that lacks electricity. Most reserves range from 200-12,000 people with the largest reserve in Canada having 12,757 people. For the calculations I will be doing the city Iqaluit (which is located in nunavut) because it is very similar to a first nations reserve in that it is a remote city (not on the grid) and there is little data on energy and electricity on Indigenous reserves.
- Homes in Iqaluit use ~1000 kWh per month [36]. Benthic mud MFC's can make 6.854 kWh per month. 146 MFC's can power a house ($1000 \div 6.854 = 145.9 < 146$)
- MFC's can power a 1000 houses. 146000 can power a 1000 houses ($146 \times 1000 = 146000$)

Application

MFC's can power remote Indigenous reserves: (pt.2)

- How are MFC's in implemented in Iqaluit? There are many rivers in Iqaluit that can have lots of benthic mud. This mud can go toward fueling the MFC's to power the homes.
- Why is implement MFC's in Iqaluit good? First iqaluit makes there electricity from diesel and petroleum generators which produce lots of greenhouse gas emissions. Iqaluit produces 780 grams of CO2e per kWh. This can lead to houses using 780 kg of greenhouse gas emissions. If a MFC powers a house in Iqaluit it can save the ~780 kg of greenhouse gas emissions in the air*.

*Not all of the 780 kg will be removed
(very close estimate)

Application

MFC’s can be used as a backup power system for emergencies:

- Many countries around the world can be disaster stricken, meaning countries they have been hit by a natural disaster (in most cases) and people who have experienced significant damage or suffering because of this.
- How will MFC’s be implemented: MFC’s will have to be implemented before disasters so they can store enough energy to be used in these circumstances. MFC’s can be implemented underground, in landfills, and along coastlines to ensure their is rich soil to fuel the MFC’s.
- Countries can benefit from this because:

1. **Emergency Response:** MFC’ can providing lighting in emergency shelters and disaster zones for safety and night time operations. MFC’s could als help provide electricity to operating essential medical devices like ventilators and defibrillators in hospitals and clinics.
2. **Reconstruction and Recovery:** Power tools and machinery for rebuilding infrastructure can help recovery of disasters. The electricity enables the operation of temporary housing facilities with basic amenities.

Application

<u>**MFC’s can be used as a backup power system:**</u>

- For the calculations, I will be using the Philippines as an example.
- The Philippines experiences a variety of disasters, including eruptions, earthquakes, and typhoons. This country is considered one of the most at-risk in the world for natural disasters.
- **MFC’s have the potential to power machinery to help rebuilt disasters that might happen in the philippines**. It is very hard to find data on how much electricity is needed for the machinery, (estimate 1000kwh) MFC’s can have the potential to create enough electrical power to power the machinery.
- When natural disasters hit the philippines, this can affect its power grid because when a disaster happens, earthquakes and debris can effect transmission lines and the grid. MFC’s installed can help that problem by producing electricity from the ground instead of the grid (providing more accessible access to electricity) . MFC’s can power houses in the philippines. 29 MFC’s can power filipino homes (200kwh [per house] [37] ÷ 6.854kwh = 29.18 > 29)

MFC’s can be implemented in communities, and under the ground. MFC’s need to be installed before the disaster, so when a disaster hits, the MFC’s can produce accessible electricity right from where you are, and there are no need for power lines.

Sources and Cites

1. https://www.sciencedirect.com/topics/biochemistry-genetics-and-molecular-biologhttps://www.sciencedirect.com/topics/biochemistry-geneticsobial-fuel-cel
2. https://www.youtube.com/watch?v=bEClaInLmRw&t=15s
3. https://www.britannica.com/science/catalyst
4. https://climate-woodlands.extension.org/basic-soil-components/
5. https://chem.libretexts.org/Bookshelves/Analytical_Chemistry/Supplemental_Modules_(Analytical_Chemistry)/Electrochemistry/Voltaic_Cells#:~:text=The%20purpose%20of%20the%20salt,causing%20the%20reaction%20to%20stop.
6. https://www.merriam-webster.com/dictionary/electrode
7. https://www.gov/publications/dictionaries/cancer-terms/def/oxidation
8. https://www.youtube.com/watch?v=a2v7ph3kLXo
9. https://byjus.com/chemistry/electrochemical-cell/#:~:text=An%20electrochemical%20cell%20is%20a,energy%20to%20cause%20chemical%20reactions
10. https://pubchem.ncbi.nlm.nih.gov/compound/Agar
11. Agar - an overview | ScienceDirect Topics
12. https://www.britannica.com/science/ion-exchange-reaction
13. https://link.springer.com/article/10.1007/s11581-016-1876-x

Sources and Cites

14. https://study.com/academy/lesson/polysaccharide-definition-examples-quiz.html#
15.https://www.sciencedirect.com/topics/chemistry/agar#:~:text=and%20Gelidium
16.https://www.degruyter.com/document/doi/10.1515/psr-2017-0018/html?lang=en
17.https://ginobiotech.com/agar-composition-overview/
18. https://link.springer.com/article/10.1007/s13205-021-02802-y#Bib1
19. https://pubs.acs.org/doi/10.1021/es0491026
20. https://www.sciencedirect.com/science/article/abs/pii/S0378775319307438
21. https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/agar
22. https://chem.libretexts.org/Bookshelves/Organic_Chemistry/Organic_Chemistry_(Morsch_et_al.)/17%3A
23.https://www.google.com/search?q=what+%25+of+organic+matter+is+in+compost&sca_esv=a07c2ae409b09fe4&rlz=1CAHBFI_enCA1103CA110
24. https://pmc.ncbi.nlm.nih.gov/articles/PMC6620762/#:~:text=Activated%20charcoal%20adsorbs%20many%20noxious,8%2C%2015%2C%2016).

Sources and Cites

25. https://www.news-medical.net/health/What-is-Activated-Charcoal.aspx#:~:text=Activated%20charcoal%20is%20a%20special,and%20coconut%20shells%2C%20among%20others.
26. https://www.wikihow.com/Calculate-Power-Output#:~:text=To%20calculate%20electrical%20power%2C%20use,is%20passing%20through%20the%20circuit.
27. https://ccme.ca/en/res/dissolved-oxygen-freshwater-en-canadian-water-quality-guidelines-for-the-protection-of-aquatic-life.pdf
28. https://bio.libretexts.org/Courses/North_Carolina_State_University/MB352_General_Microbiology_Laboratory_2021_(Lee)/06%3A_Microbial_Physiology/6.03%3A_Bacterial_Growth_Dynamics
29. https://www.youtube.com/watch?v=3SdEo2Se-Ac

↑ Google sheets features I used:

30. https://www.okotoks.ca/sites/default/files/2020-12/Managing_Electricity_at_Home_2015_web_final.pdf
31. https://www.alberta.ca/albertas-greenhouse-gas-emissions-reduction-performance#:~:text=The%20emissions%20intensity%20of%20Alberta's,per%20kilowatt%20hour%20in%202022.
32. https://pubs.rsc.org/en/content/articlelanding/2018/ew/c7ew00293
33. https://www.statista.com/statistics/264631/number-of-people-without-access-to-electricity-by-region/#:~:text=South%20Sudan%20ranked%20as%20the,population%20having%20access%20to%20electricity.
34. https://oee.nrcan.gc.ca/publications/statistics/aham/2019/ranges.cfm
35. https://www.ae.ca/articles/siksika-nation-develops-strategic-approach-to-improve-condition-of-housing-supply/
36. https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/provincial-territorial-energy-profiles/provincial-territorial-energy-profiles-nunavut.html
37. https://solarnrg.ph/blog/appliances-use-most-electricity-philippines/#:~:text=Below%2C%20you'll%20find%20a,use%20certain%20devices%20at%20home.