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Utilizing Microbial Fuel Cells For Simultaneous Treatment Of Solid Waste Water And Energy Generation

[1]Adeniyi O. A., [2]Bakri A.J., [3]Samuel O. Fadipe, [4]Shakirat B. A., [2]Adebayo O.C. & Oyetunde R.A.
[1]Department of Civil Engineering, Yaba College of Technology, Yaba, Lagos, Nigeria.
[2]Department of Mechanical Engineering, Yaba College of Technology, Yaba, Lagos, Nigeria.
[3]Department of Civil Engineering, Morgan State University, Maryland, USA.
[4]Department of Geophysics, Federal University of Technology Minna, Niger State

ABSTRACT

The proposed biocatalyst utilized in the microbial fuel cell (MFC) experiment demonstrated exo-electrogenic activity, with species such as Mycobacterium and Shewanella (Pseudomonas) sourced from sewer wastewater. Chemical parameters from the initial experimental trial did not comply with Environmental Protection Agency (EPA) limits. The total suspended solids (TSS) in the second MFC trial were the only parameter to meet the EPA threshold of 50 ppm, with influent and effluent concentrations of 96 ppm and 23.1 ppm, respectively. Consequently, supplementary treatment methods are required to achieve EPA discharge standards. The second trial indicated that the MFC setup effectively reduced metal concentrations, including Cr, Mn, Pb, and Zn, to levels that satisfy EPA surface water effluent discharge criteria.

Keywords: microbial fuel cell, anode chamber, cathode chamber, wastewater, energy generation.

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1. INTRODUCTION

Microbial fuel cells (MFCs) are emerging as a transformative technology in the realm of wastewater treatment, not only for their ability to purify water but also for their unique capability to harness energy from the treatment process itself (Logan et al., 2006). This dual benefit represents a significant shift from traditional treatment methods, which are typically energy-intensive and contribute to the overall carbon footprint of water management systems (Rabaey & Verstraete, 2005). MFC technology exploits the natural process of cellular respiration, wherein microorganisms metabolize organic matter present in wastewater (Du et al., 2007). This metabolic process, fundamental to microbial life, involves the conversion of nutrients into adenosine triphosphate (ATP), the molecular unit of currency for energy within biological cells (Berg et al., 2002). The energy generated sustains microbial life and supports various cellular functions. The exothermic redox reactions that occur during cellular respiration were first linked to the potential for electricity generation by M.C. Potter, a botanical professor at the University of Durham in the early 20th century (Potter, 1911). Potter's pioneering work laid the foundation for utilizing microbes as biocatalysts in electricity production.

In 1911, he conceptualized the idea of generating electricity using Saccharomyces cerevisiae, a type of yeast, in the biochemical reactions. Building on Potter's vision, modern MFCs have been engineered to optimize the direct conversion of chemical energy to electrical energy through the metabolic activities of electrogenic microbes (Franks & Nevin, 2010). These microbes, often referred to as electricigens, are capable of transferring electrons to an electrode during their respiratory processes (Lovley, 2006). The electrode, in turn, acts as an electron acceptor, completing the circuit and allowing for the flow of electricity. The anodic chamber of an MFC is where the wastewater is introduced, containing the organic pollutants that serve as fuel for the microbes (He et al., 2005). As these microorganisms consume the organic matter, they release electrons and protons. The electrons are transferred to the anode and flow through an external circuit to the cathode, generating an electric current. Meanwhile, the protons migrate through a proton exchange membrane to the cathodic chamber, where they combine with oxygen and the electrons from the circuit to form water, thereby completing the redox reaction (Liu et al., 2004).

Recent advancements in MFC technology have focused on enhancing the efficiency of electron transfer, scaling up the system for practical applications, and exploring the use of diverse microbial consortia for the degradation of various pollutants (Cheng et al., 2009). Researchers are also investigating the integration of MFCs with other renewable energy sources and the potential for nutrient recovery from wastewater, aiming to create a more sustainable and circular approach to wastewater management (Aelterman et al., 2006). The promise of MFCs lies not only in their environmental benefits but also in their potential to provide a source of renewable energy in off-grid and resource-limited settings (Pant et al., 2010). As the technology matures, MFCs may become a cornerstone of eco-friendly wastewater treatment facilities, contributing to energy self-sufficiency and the reduction of greenhouse gas emissions associated with conventional water treatment processes (Harnisch & Schröder, 2010).

2. MATERIALS

2.1 Anode and Cathode Housing Chambers

For both the anode and cathode chambers, a plastic paint container with a volume of 4L each was used.

Fig. 1: Four liter (1 gallon) plastic bucket

2.2 Anode & Cathode electrode material

Stainless steel mesh was used in place of titanium and graphite brush.

Fig. 2: Stainless steel mesh

2.3 Salt Bridge

The most used material is Nafion 117 because of its high proton conductivity. The main disadvantage is its high price. Therefore, we used a cotton rope (1m long) bought from curtains shop and twisted several times as the permeable membrane (final length of 25cm) in constructing the salt bridge.

Fig. 3: Concentrated salt solution with twisted cotton rope.

2.4 Copper Wires

Copper wire was used as the material for connecting the external circuit between the cathode and anode electrode. It serves as an extension to draw electron charge from the anode and cathode material in contact with the substrate.

2.5 Extra Material

Other materials used for the construction of the MFC include: scissors, PVC elbow bend, valve sealant, short hand saw for cutting the PVC pipe, and efficient glue sealant (such as 4mins gum), stainless steel mesh, water pump for supplying oxygen and an analogue Multi meter for data acquisition.

Fig. 4: PVC pipe, elbow joint, air valve, tap head and excess stainless steel wire mesh

Fig. 5: Multi-meter & soldering iron & other materials.

2.6 Substrate

The exo-electrogenic bacterial in the substrate needed for the experiment can be sourced from a number of places. According to Du et al (2007), they are found in soil, marine sediment, solid waste water, fresh water sediment and activated sludge. The source of microorganisms was strictly from solid waste water obtained from the man hole maintenances chamber at the Department of Polymer and Textile building in Yaba College of Technology Lagos, Nigeria on co-ordinate (5º51'58.55"N, 3º2'17.95"E). A 1.5liter container was used to collect the waste water in order to have an approximate measurement of the quantity of substrate obtained before taking it to the lab to perform the experiment.

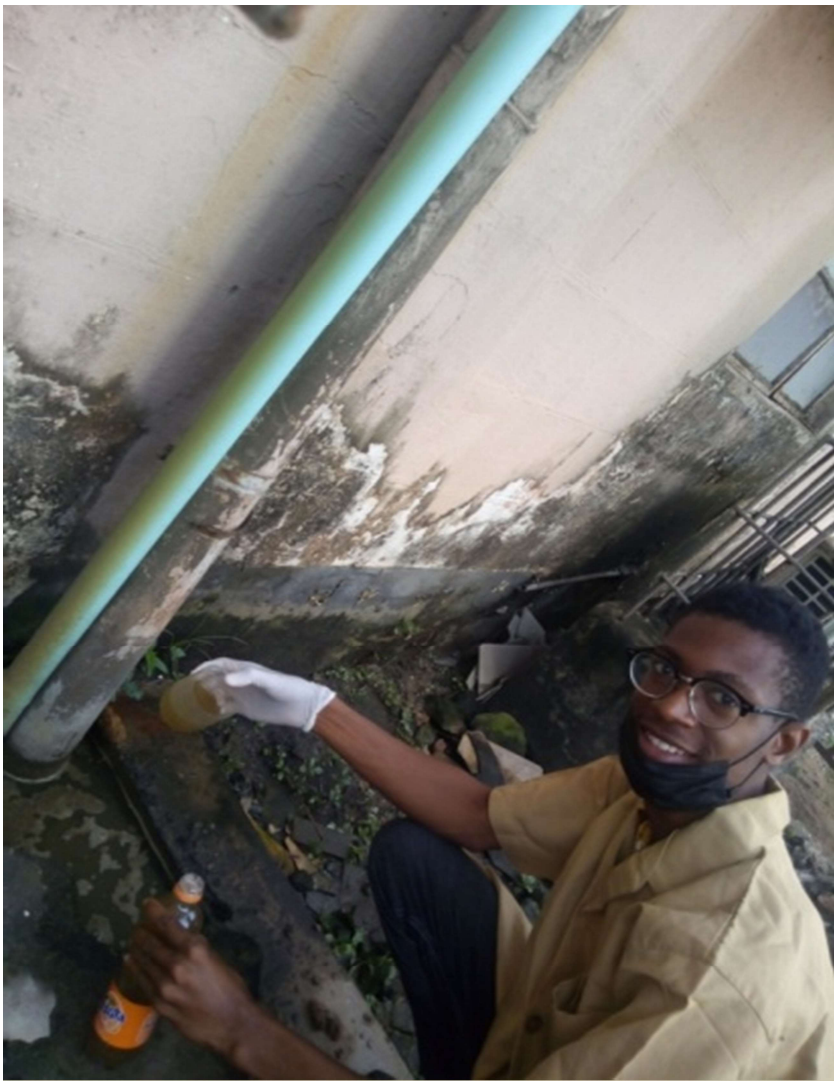

Fig. 6: Solid waste water obtained from Textile building in Yaba College of Technology.

3. METHODOLOGY PROCESS

3.1 MFC Setup Construction.

The construction of the double-chamber microbial fuel cells (MFCs) involved the following steps:

- **Step 1**: Preparation of a salt bridge began with soaking twisted cotton cloth in a highly concentrated NaCl solution for several hours. This cloth was then fitted into a PVC pipe with a one-inch diameter and a length of 20 cm.
- **Step 2:** Two holes were created in each plastic container using a hot soldering iron to insert the ends of the salt bridge. Any leaks were sealed with sealing glue.
- **Step 3:** Additional holes were made at the top of the cathode container: one for the conducting wire and another for the aquarium air pump pipe. A hole was also created on the side for the effluent discharge tap. In the anode chamber, holes were indented at the top and bottom for the substrate inlet valve and the sludge outlet valve, respectively.
- **Step 4:** Stainless steel mesh electrodes were constructed by folding the mesh several times to achieve a surface area of 600 cm^2 (60*10).
- **Step 5:** Copper wires were connected to both electrodes using sealing glue to ensure a secure attachment.
- **Step 6**: Electrodes were placed in their respective compartments, ensuring that the anode chamber remained airtight, and the cathode chamber was left aerated. A digital multimeter was then connected to the wires extending from the cathode and anode electrodes.
- **Step 7:** Sludge was introduced into the anode chamber through the inlet valve, covering the salt bridge and submerging the electrodes to ensure anaerobic conditions were maintained.

Fig. 7: Complete assembly of continuous flow MFC setup.

Fig. 8: Influent substrate withdrawn from Department of Polymer and Textile building in Yaba College of Technology for first trail.

Fig. 9: Effluent discharge withdrawn from the MFC cathode chamber after first trail.

Fig. 10: Influent substrate withdrawn from Department of Polymer and Textile building in Yaba College of Technology for second trail.

Fig. 11: Effluent discharge withdrawn from the MFC cathode chamber after second trail.

4. EXPERIMENTAL TEST RESULT

Table 4.1: FIRST EXPERIMENTAL TRIAL TEST RESULTS IN CONTRAST WITH EPA LIMITS.

PARAMETERS	INFLUENT	EFFLUENT	EPA LIMITS
Appearance	Not Clear	Not Clear	Clear
Odour	Objectionable	Objectionable	Odourless
Sediments	Heavy	Heavy	Nill
pH [no Unit]	7.55	8.16	6 – 9
Temperature (°C)	27.1	27.2	40.0
Electrical Conductivity (μScm^{-1})	13,290.0	2,710.0	2,000
Total Suspended Solids (ppm)	106.0	52.0	50.0
Total Dissolved Solids (ppm)	12,100.0	2,015.0	2,000
Total Solids (ppm)	12,206.0	2,067.0	2,000
Turbidity	112.0	67.0	5.0
Dissolved Oxygen, DO (ppm)	7.973	7.230	6.0
BOD_5^{20} (ppm)	152.7	117.8	50
COD (ppm)	198.31	128.96	80
	MICROBIOLOGY		
Organisms (cfu/ml)	EFFLUENT	INFLUENT	EPA LIMITS
Salmonela	2.3×10^2	2.1×10^2	1.0×10^{-1}
E.Coli	1.4×10^1	1.1×10^{-1}	1.0×10^{-1}
Shewanella Oneidensis	1.6×10^1	1.2×10^1	1.0×10^{-1}
Streptococcus Aureus	2.1×10^2	1.3×10^2	1.0×10^{-1}
Pseudomonas spp.	1.5×10^2	1.2×10^2	1.0×10^{-1}

Table 4.2: SECOND EXPERIMENTAL TRIAL RESULTS IN CONTRAST WITH EPA LIMITS.

PARAMETERS	INFLUENT	EFFLUENT	EPA LIMITS
Appearance	Not Clear	Not Clear	Clear
Odour	Objectionable	Objectionable	Odourless
Colour	Blackish	Brownish	Nil
Sediments	Heavy	Light	Nil
pH [no Unit]	6.48	7.41	6 – 9
Temperature (°C)	29.1	29.1	40.0
Electrical Conductivity (μScm^{-1})	3,070.0	44,200	2,000
Total Suspended Solids (ppm)	96.3	23.1	50.0
Total Dissolved Solids (ppm)	29,460.0	2,320.0	2,000
Total Solids (ppm)	29,556.3	2,343.1	2,000
Turbidity	116.0	87.0	5.0
Dissolved Oxygen, DO (ppm)	9.392	7.635	6.0
BOD_5^{20} (ppm)	154.06	143.24	50
COD (ppm)	200.07	186.03	80
Sulphate, SO_4^{2-} (ppm)	319.0	138.2	200

MICROBIOLOGY			
PARAMETERS	INFLUENT	EFFLUENT	EPA LIMITS
Organisms (cfu/ml)	INFLUENT	EFFLUENT	EPA LIMIT
BurkholderiaCepacia	2.1 X 10^3	1.6 X 10^2	1.0 X 10^1
Mycobacterium	ND	ND	
Total Heterotrophic Bacteria	1.4 X 10^1	1.0 X 10^1	1.0 X 10^1
Total Heterotrophic Fungi / yeast	1.9 X 10^1	1.1 X 10^1	1.0 X 10^1
Salmonela	2.4 X 10^2	1.9 X 10^2	1.0 X 10^1
E. Coli	1.3 X 10^1	1.0 X 10^1	1.0 X 10^1
Shewanella Oneidensis	1.5 X 10^1	1.1 X 10^1	1.0 X 10^1
Streptococcus Aureus	2.2 X 10^2	1.2 X 10^2	1.0 X 10^1
Pseudomonas spp.	1.7 X 10^2	1.1 X 10^2	1.0 X 10^1
METALS			
Cr (ppm)	0.011	0.005	0.5
Mn (ppm)	0.003	Nil	1.0
Pb (ppm)	0.015	Nil	0.05
Zn (ppm)	0.077	0.076	1.0
Sulphate, SO42- (ppm)	319.0	138.2	200

4.1 Analysis of results.

4.1.1 Physical parameters.

The analysis of physical parameters, including temperature, color, odor, electrical conductivity, and turbidity, was conducted on the influent and effluent from both the initial and subsequent MFC experiments. These parameters did not comply with the EPA surface water discharge limits, indicating the necessity for additional treatment methods to meet these standards. The incorporation of bio-sand filters is a potential solution, as suggested by Mensah, I. T. and Udofia, E. A. (2018), who observed significant improvements in pH and color, with a notable clarification of turbidity in the effluent after treatment with a bio-sand filter (BSF) system. Their research supports the use of BSF to enhance the physical and microbial quality of sewage effluent at the household and institutional levels before environmental discharge, especially in locations lacking centralized sewage treatment facilities. Despite this, the reduction in turbidity achieved by the MFC setup, from 112 to 67 ppm, should not be disregarded as it represents a noteworthy step towards achieving water quality standards.

4.1.2 Chemical parameters.

The chemical parameter includes pH, total suspended solid, total solid, total dissolved solid, BOD, COD, and dissolved oxygen was analyzed on the influent and effluent of both the first and second MFC experiment. All the chemical parameters of the first experimental trail failed to meet the EPA limit. Only the total suspended solid of the second MFC experimental trail met the EPA limit of 50ppm, which had an influent of 96ppm and an effluent of 23.1ppm. In view of this, additional means of treatment needs to be used to help meet up the EPA discharge limit. The use of bio-sand filters, can be of consideration. According to (Primasari, B., et, al., 2020),

Bio-sand filter has a potential for organic removal from laboratory wastewater. The Bio-sand filter setup used in their experimental process was able to remove 76,9% of BOD (from an initial concentration of 161.58 mg/L) and removed 73.46% of COD (from an initial concentration of 202.4 mg/L) from laboratory wastewater.

4.1.3 Biological parameters

The biological parameter refers to the living organism present in the substrate. They are referred to as the bio catalyst that breakdown organic matters in the substrate and are responsible for the generating of energy in MFC. The proposed biocatalyst that was in our MFC experiment are reported exo-electrogen such as mycobacterium, Shewanella Oneidensis, Shewanellla (Pseudomonas) amongst others, found in solid waste water. Test was made on both the influent and effluent waste water to and from the MFC setup of the first and second experimental trails to ascertain the presence of the microbes and the rate of reduction or increment from the MFC effluent outlet. The microbial standard limit was not satisfied for both the first and the second experimental trial but significant reduction in their concentration was observed. In view of this, additional treatment such as the use of chlorine can be recommended to improve the microbe concentration in the effluent.

4.2 Discussion

Wastewater underwent continuous treatment as the anode chamber was regularly replenished with fresh substrate. The treatment rate in the first experimental trial was faster compared to the second due to the loosely compacted salt bridge. Effluent wastewater of 1.5 – 2 liters from the cathode chamber was collected from the first trial within 3 hours (10:00 AM – 1:00 PM), while the same volume from the second trial required 8 hours (10:00 AM – 6:00 PM) owing to a more tightly compacted salt bridge. A key precaution taken during the replenishment of the anode chamber substrate involved loading the funnel on the inlet valve with wastewater and then gradually opening the valve to maintain anaerobic conditions.

A clearer effluent solution was obtained from the second trial, indicative of lower suspended solids compared to the first trial's effluent. It was noted that allowing the effluent water to remain undisturbed for an extended period led to a clearer solution as particulate matter settled at the bottom, suggesting that incorporating a settling tank into the setup could further enhance effluent purification. The first trial experienced a rapid initial burst of energy generation as the volume of wastewater in the cathode chamber increased, creating more surface area contact with the electrode and oxygen. Energy generation rose steadily for about 15 minutes before stabilizing. This level was maintained for approximately 10 minutes before a gradual decline was observed. Two hours into the experiment, energy levels were minimal due to the salt bridge becoming supersaturated and losing its essential salinity.

In contrast, the second trial exhibited minimal energy levels initially, as the salt bridge released treated wastewater into the cathode chamber at a slow rate, limiting contact with the electrode. After 1 hour and 45 minutes, a gradual and more significant increase in energy generation was observed, correlating with heightened bacterial activity in the anode chamber, which was stimulated by the addition of fresh substrate..

4.3 Multi-meter readings

The positive terminal of the multi-meter was connected to the electrode in the anode chamber and the negative terminal of the multi-meter was connected to the electrode in the cathode chamber of the MFC setup.

4.3.1 First experimental trail result

In the first experimental trail, there was a continuous and initial burst of energy generation as the waste water in the cathode chamber rapidly increase and thus had more surface area contact with the electrode in the cathode chamber and air (that is oxygen). A steady increase in energy was observed and the highest reading recorded of 18.9m.V was recorded at a period of 15mins into the experiment from zero before an equilibrium energy generation was attained. This equilibrium energy generation was maintained for about 10mins at 13.2m.V, before a gradual and steady reduction in energy was observed. At 2hrs into the experiment, there was very trace energy level observed as the salt bridge was super saturated.

4.3.2 Second experimental trail result

In the second experimental trail, there was no initial burst of energy generation as the waste water entering the cathode chamber was very slow thus there was less surface area contact between the waste water and the electrode in the cathode chamber and air (that is oxygen). A steady increase in energy was observed and the highest reading recorded of 38.7m.V was recorded at the time of ending the experiment. A continuous gradual increase in energy was observed during the period of the experiment.

4.4 Removal of metals

Result from the second experimental trial showed that MFC are efficient in removing metals. Metals such as Cr. Mn. Pb, and Zn where satisfactorily reduced to meet the EPA surface water effluent discharge standard limit. According to (Zixuan, C., et al., 2018), MFC experimental conclusion, heavy metal ions were removed as solids, and transformed into non-toxic state. For example, toxic Cr(VI) was reduced to less toxic Cr(III) and Ag(I) ion was reduced to Ag (0) as solid in his MFC setup. Continuously generated electrons transfer facilitated current generation in the MFC setup while heavy metal pollutants were removed (Zixuan, C., et al., 2018).

5. CONCLUSIONS

Results from the first trial failed to meet the EPA surface water discharge standard primarily due to the fact that the salt bridge was not tightly compacted. The physical parameters such as the temperature, colour, odour, electrical conductivity and turbidity were analyzed on the influent and effluent of both the first and second MFC experiment. It failed to meet the EPA surface water discharge limit hence additional means of treatment needs to be used to help meet up the EPA discharge limit.
All the chemical parameters of the first experimental trail failed to meet the EPA limit. Only the total suspended solid of the second MFC experimental trail met the EPA limit of 50ppm, which had an influent of 96ppm and an effluent of 23.1ppm.

The microbial standard limit was not satisfied for both the first and the second experimental trial but significant reduction in their concentration was observed. In view of this, additional treatment such as the use of chlorine can be recommended to improve the microbes concentration in the effluent. A steady increase in energy was observed in the first experimental trial and the highest reading recorded of 18.9m.V was recorded at a period of 15mins into the experiment from zero before an equilibrium energy generation was attained. This equilibrium energy generation was maintained for about 10mins at 13.2m.V, before a gradual and steady reduction in energy was observed. At 2hrs into the experiment, there was very trace energy level observed as the salt bridge was super saturated. In the second experimental trail, there was no initial burst of energy generation as the waste water entering the cathode chamber was very slow thus there was less surface area contact between the waste water and the electrode in the cathode chamber and air (that is oxygen). A steady increase in energy was observed and the highest reading recorded of 38.7m.V was recorded at the time of ending the experiment. A continuous gradual increase in energy was observed during the period of the experiment.

Result from the second experimental trial showed that MFC are efficient in removing metals as Cr, Mn, Pb, and Zn where satisfactorily reduced to meet the EPA surface water effluent discharge standard limit. The microbial fuel cell setup for the continuous treatment of solid waste water in this thesis report did not met the EPA surface water discharge standard limit satisfactorily, but a continuous waste water treatment setup was successfully achieved and the generation of energy. The edge microbial fuel cell for the treatment of solid waste water and energy generation has over other waste water treatment processes is its potential for energy generation.

6. RECOMMENDATION

This research can be recommended for use in rural areas with high drought conditions, where water for irrigation is required and farming is the predominant economic activity. According to the compendium of standards for wastewater reuse in the Eastern Mediterranean Region compile by World Health Organization in 2006, our MFC setup can be adopted for the continuous treatment and supply of irrigation water as the minimum limits are well satisfied. (World Health Organization, 2006) This research thesis can be recommended for the treatment of domestic house hold kitchen and bathroom waste water given that domestic house hold kitchen and bathroom waste water is of lesser toxicity concentration compared to that of domestic solid waste water (Zhang J., et al. 2015).

An inoculation was done temporarily with the MFC setup with domestic house hold kitchen and bathroom waste water and it was observed to produce better effluent as because domestic house hold kitchen and bathroom waste water is relatively clearer and has lesser sludge and hence gave poor energy generation. This research thesis can also be recommended for the Treatment of domestic solid waste water effluence before final disposal to surface water bodies. According to (Zeng et al., 2010.), who in his work demonstrated the reduction of an inlet COD of 3000 mg/L to 243.67 mg/L COD by using a set of two-chamber MFC setup in series thus possible for discharge to a municipal sanitary sewer. Seconding this experimental research by (Zeng et al., 2010.), it is evident that this research thesis using doubled chambered (MFC) setup can be recommended for use in Further treatment of domestic septic tank effluence before final disposal to surface water bodies (Zeng Y., et al., 2010).

This research thesis can also be recommended for the treatment of hard water. Hard water is **water that has high mineral content and example of such water is common place with underground water source. The water in question to be treated** may not necessarily be of waste water origin, but can be of other origin such as underground water in contact with rocks that are high in minerals. Places such as Abakaliki, Eboyi state – Nigeria is known to face challenges of hardness of water thus MFC technology could prove helpful.

This research thesis can be recommended from the removal of metals such as **Manganese (Mn), Lead (Pb), & Chromium** (Cr), given that there was a significant decrease and total removal in the case of lead and **Manganese** in effluent water of the cathode chamber from the result of our experiment. According to (Zixuan, C., et al., 2018), heavy metal ions were removed as solids, and transformed into non-toxic state. For example, toxic Cr(VI) was reduced to less toxic Cr(III) and Ag(I) ion was reduced to Ag (0) as solid in his MFC setup. Continuously generated electrons transfer facilitated current generation in the MFC setup while heavy metal pollutants were removed (Zixuan, C., et al., 2018).

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