P-MFC " Plant Microbial Fuel Cell "

Abstract: Energy crisis is a great challenge in our world. The usage of non-renewable resources causes pollution and hazardous effects on public health. The consumption and demand for energy is currently growing far greater than the amount of energy produced. To solve this serious problem, microbial integrated cell (MIC) is used. M.I.C is a plant microbial fuel cell (P-MFC). It harvests energy from bacteria, which is used as a catalyst to oxidize organic matters, through anaerobic fermentation. With the developing of traditional MFCs, there will be clean, available and suitable energy sources. Besides achieving our requirements of being efficient, eco-friendly and cheaper than the other resources, it can utilize the wastewater to generate green & renewable energy and produce clean drinkable water. MIC can also use byproducts of these reactions to produce not only electric current, but also hydrogen and methane gas. As a practical step, a prototype with locally available materials has been constructed for the project. Through tests conducted on the prototype to ensure that it meets our previously mentioned requirements, the results were positive in all these requirements. In conclusion, results' analysis represents the project's ability to provide sustainability and be applicable and centralized - can be implemented on large scales - in the future. The centralization process is regulated with an Arduino system.

Keywords: P-MFC (Plant Microbial Fuel Cell) – MEC - PEM – H_2 - CH_4 Fuel – Wastewater – Arduino System – MnO_2 - Electrodes – TiO_2 Photocatalyst - Electrogensis

1. Introduction

Most countries mainly depend on nonrenewable energy resources such as Fossil fuels (crude oil, coal and natural gas) which are extremely harmful for the environment. In most recent years, the rising demand and falling output of these resources have forced most of these countries to import sufficient amounts of energy for their needs, a shift that poses a substantial threat to their economy. Also, population growth and misuse of energy have escalated the energy problem. So, Renewable sources of energy such as wind, solar, biochemical energy, and hydroelectricity are required. In order to find a solution for this problem, prior solutions in this field were investigated, such as traditional microbial fuel cells (MFCs). After understanding the pros and cons of these solutions, our idea of the developed Microbial Integrated Cell (MIC) was set. MIC uses redox reactions to turn waste water into electricity. CO_2 gas produced from the reaction will react with a photocatalyst to produce methane as shown in the following equation: $CO2 + H2O \xrightarrow{TiO2\text{-}Cu(I)} CH4 + O2$. MIC is not affected by environmental factors, so producing of electricity will be constantly. The manufacturing of it is easy, and it can produce hydrogen and methane fuels beside electricity. Clean water is also produced from sewer or salty water. Our prototype was constructed using inexpensive materials, tested with accurate measurements and the analysis of tests' results concluded that we achieved our requirements and solved most critical challenges facing P-MFCs, all these things are shown in detail later in the upcoming sections below.

2. Related Works

Sucrose is used as a substrate for the bacterial field due to its inertness towards alternative microbial conversions (fermentations and methanogenesis) that lead to high efficiency and power output [9]. Although platinum coated electrodes are more efficient, Ferricyanide (K_3 (Fe (CN) 6) is frequently used as an electron acceptor (catalyst) in the MFCs due to its good performance, low cost, high efficiency and low over potential [8]. "Recently, some students from Harvard University experimented MFC device and they produced enough electricity to power a LED bulb for up to a year" [11]. P-MFC (plant-microbial fuel cell) was made in tubular system (Logan.2006), (Helder, 2012). And this system reduces the efficiency of (P-MFC) and increase the internal resistance of it according to (Plant-e, 2013). Exploiting micro/nano-structured anodes in micro-sized MFCs; CNT and CNF are emerging nano-materials with higher mechanical strength and electrical conductivity than conventional carbon-based materials [12]. But we will use better system to overcome these problems which is the flat system. the materials which was used as Proton Exchange Membrane (PEM) may be Nafion or Teflon. In our working, we discover new material which was Nylon that is considered the best choice.

3- Materials

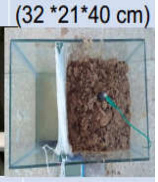
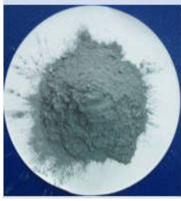
Wastewater Including Bacteria	Graphite rods (2*10*15 cm)	Sodium chloride (125 g)	Gelatin (250 g)	Glassed containers (32 *21*40 cm)
				
Titanium dioxide	Wires (50 cm)	Multimeter	Potassium permanganate	Arduino system
				

Table 1. *Shows the materials used in building the prototype*

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4. Methods of Building the Prototype

Step1: Making a design for the Container on Sketch up 3d program and then, sending this CAD design to a glass workshop to make the container.

Step2: preparing the graphite electrodes in an acidic potassium permanganate solution, as a catalyst.

Step3: Preparing a low-cost proton exchange membrane (PEM) with 300ml agar, gelatin, 75g table salt solution, 200ml water to make a membrane solution. Then, it was boiled, put in Petri dish and let to get dried in the fridge.

Step 4: Filling the anode chamber with the wet plant (Sugarcane) with its soil and making space between the soil and the wall of the glass container around 2cm to 2.5cm to irrigate the plant.

Step 5: Assembling our fuel cell, and making the external circuit using crocodile wires to make the electrons move through. The prototype is shown in figure 1 and figure 2:

Figure 1. *Shows the design of the container.*

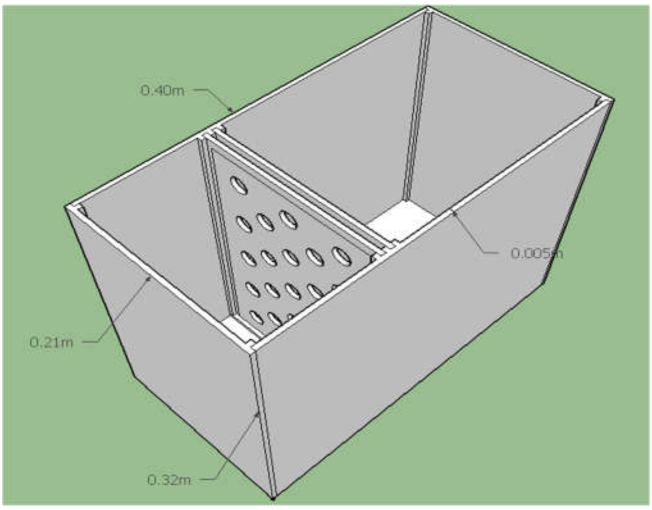
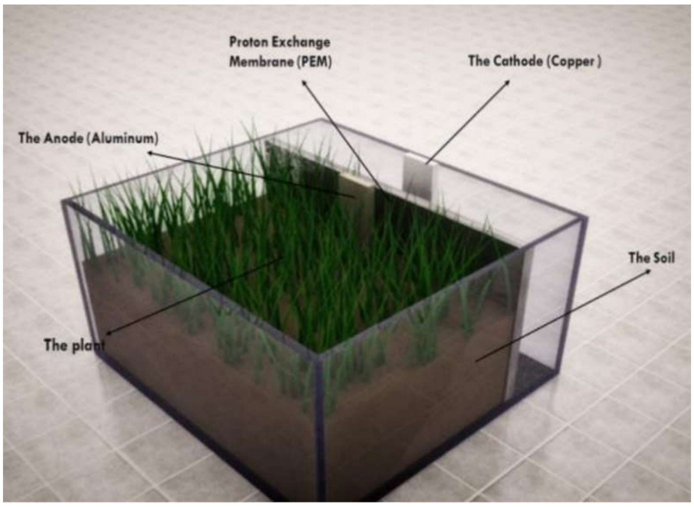


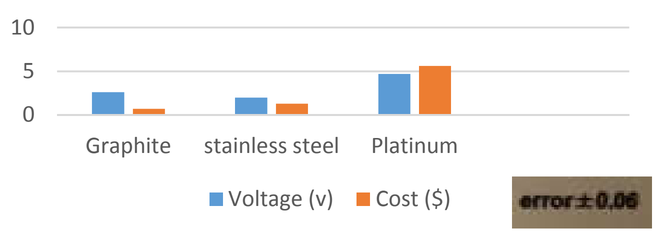
Figure 2. *Shows the final shape of the prototype (3d)*



5. Experiments and their results

Experiment 1: The objective of this experiment is to select the efficient and cheaper anode type from (Graphite- Stainless steel- Platinum). The results were observed as shown in Graph 1:

Graph 1. *Shows the output voltage and the cost of different anode electrodes.*



From these results, it was observed that graphite anode is the best choice as platinum has high cost although it has the highest output voltage. Stainless steel has higher cost than graphite and less output voltage.

Experiment 2: This experiment had been conducted to examine different substrates and find the best one. By collecting the data, it was found that sucrose can provide the highest power density, so P-MFC will depend on it in its soil [9].

Table 2. *Shows the output voltage by different substrates.*

Substrate Type	I (current, mA) (Error ± 0.21)	P (mW/m^2) (Error ± 1.5)
Wastewater	4.85	26
Glucose	0.9	494
Sucrose	6.2	506
Acetate	1.27	23
Butyrate	0.46	305

The reaction that takes place in the anode chamber is as followed: $\boldsymbol{C_{12}H_{22}O_{11} + 13H_2O \rightarrow 12CO_2 + 48H^+ + 48e^-}$

Experiment 3:

The purpose of this experiment is to test different cathode electrodes to determine the best type. The electrodes that had been tested are the Aluminum, copper and stainless steel. The data was collected as shown in table 3:

Table 3. *Shows the output voltage by different cathode types.*

Stainless steel	Copper	Aluminum
1.9 volt ±0.02	1.4 volt ±0.02	1.5 volt ±0.02

The results show that stainless steel provides the highest output voltage of these electrodes, but we can still use the graphite electrode as a cathode in addition to being an anode as from Graph 1, we observed that graphite is better than stainless steel. P-MFC is a galvanic cell (voltaic) that allows the 2 electrodes to be the same. In contrast, MEC (depends on electrolysis) must have 2 different electrodes.

The reaction in the Cathode: $\boldsymbol{12O_2 + 48H^+ + 48e^- \rightarrow 24H_2O}$

Experiment 4:

Temperature also affects the efficiency of the project. To know the temperature that achieves the highest power density, the temperature of the prototype has changed inside a laboratory. The results have recorded in table 4.

Table 4. *Shows the output voltage and the power density at different temperatures.*

T ± 1 (C°)	OCV (V) (Error ± 0.15)
20	1.4
25	1.54
30	1.63
35	1.72
40	1.99
45	1.83

From these results, it is found that optimal temperature to be applied on the project is 40°C. Errors in measurements have been recorded.

Experiment 5:

The readings of the multimeter are recorded to determine the potential difference in our project to compare between it and the other projects such as traditional Microbial Fuel Cell (MFC). From Table 5, we see that our project is more efficient than traditional MFC [4]. There were some negative results like test 4, but the other tests had positive values.

Table 5. *Shows the output voltage of the M.F.C.*

	Old MFC (V)	P-MFC (V)
Test 1	0.9	1.7
Test 2	1.08	1.87
Test 3	1	1.99
Test 4	1.65	1.15

Experiment 6:

To get an eco-friendly project, the CO_2 omitted from the anode chamber will go to a recovery system (a chamber exposed to high pressure and temperature with TiO_2 [6], a photocatalyst applied to a copper panel) to produce methane as shown in the following equation:

$$CO_2 + H_2O\ (g) \xrightarrow{TiO_2\text{-}Cu} CH_4 + O_2$$

Table 6 shows the effect of the amounts of water vapor and CO_2 on the amounts of methane produced.

H_2O (ml)±5ml	CO_2(ml) ±5.2	CH_4(ml) ±4.9
322	80.5	199
645	161.25	390
976	244	585
1290	322	793

6. Discussion

❖ P-MFC

Plant-microbial fuel cell mainly depends on photosynthesis process, with the equation,

$$6CO_2 + 6H_2O \text{ ----sunlight----> } C_6H_{12}O_6 + 6O_2$$

to produce glucose ($C_6H_{12}O_6$), the substrate that bacteria (such as Shewanella and Geobacter) [1,2] feed on by anaerobic fermentation to obtain the energy. The plant consumes 30% of glucose and stores the 70% in the soil of the plant. Providing the substrate from the plant is also profitable instead of buying it with relatively high cost. Moreover, CO_2 that pollutes the environment will be reduced in this process beside being reduced in experiment 6 using TiO_2.

P-MFC is separated into two chambers, one for the soil and it contains the anode, made of Graphite, to attract electrons produced from the microorganisms and the other half contains the cathode made of graphite also [7]. There is PEM (proton exchange membrane) between them to let the protons pass to the cathode while the electrons don't pass [3,10].

As the plant we already use in the project is a watery plant, needs more water to grow (clay soil), so it prevents the electrons from reacting with the oxygen in the atmosphere. Otherwise, it goes in the circuit from anode to cathode.

Sugarcane is our chosen plant. It's available in all seasons because it is planted all over the year. Sugarcane also has the highest photosynthetic efficiency (from 7% to 8%). The properties of its soil are also helpful:

o Has Good water retention capacity.

o Has Good amount of clay and organic matter.

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First property is needed as Existence of water in anodic half helps to prevent the electron from combining with the molecules of Oxygen from the air. The second property is also required as the organic matter is the nutrient of bacteria. The clay soil is a suitable environment for bacteria's life.

❖ The Design

The design of the real project affects its efficiency. Using PEM (proto exchange membrane) is more efficient than the salt bridge as its high internal resistance contributes to lower power output than of PEM. Our design consists of 2 huge chambers separated by PEM. The huge P-MFC is connected to a plant farm, where the substrates are provided as nutrients for Bacteria at anode chamber. Also, there are water drainages to water the plants and they are connected to Our P-MFC to be treated. The cathode is responsible for waste or salt water treatment as the electrons, protons and oxygen from the air combine together to form clean and drinkable water. Then, electricity produced is transmitted to the houses. All these steps are shown in figure 3 [13].

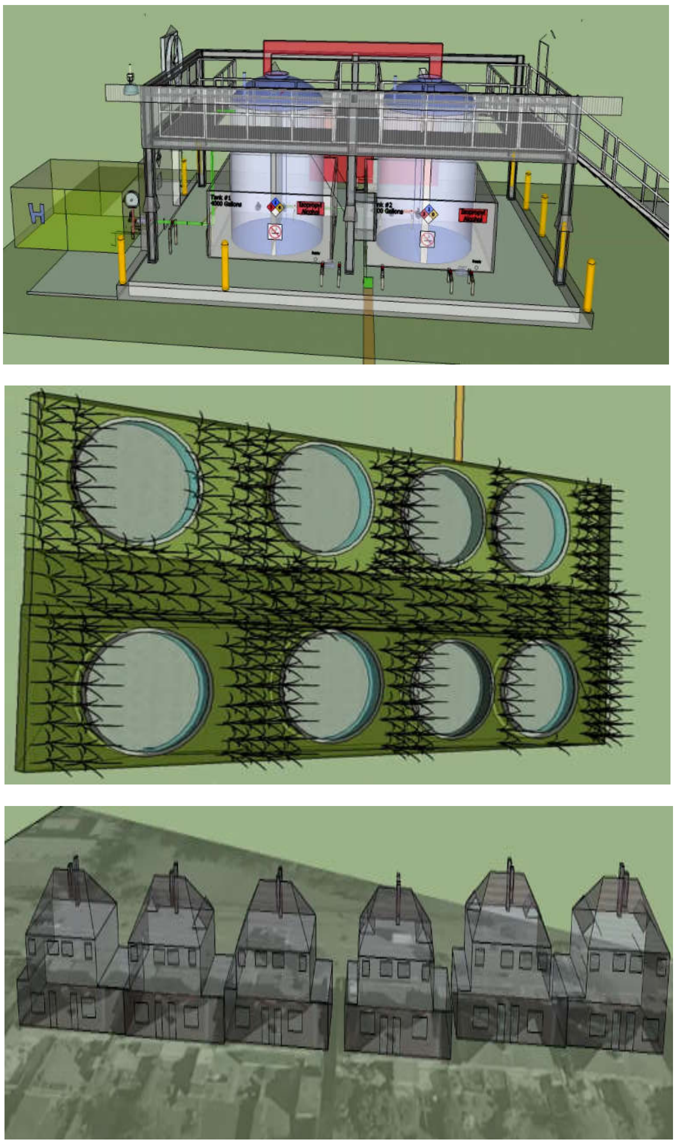


Figure 3. *Shows the design of P-MFC Factory.*

Our project requires some special conditions to be applied, one of them is obtaining relatively high temperature than in the surrounding area all the day. To provide this condition, the walls of the plant will be made from a material that can store heat energy all the day and release it at night. Thermstone is an example of this kind of materials which is made from cement bricks, sand and silica. This brick provides high thermal insulation than conventional bricks. We can coat the brick with transparent polymer film to help in this condition. The roof of the plant will be made from a special type of glass to let sun rays enter the system. This glass is called "Laminated Glass" and it is hard to be broken because it's made of layers of safety glass bound together with a transparent adhesive [14].

To provide the system with a sufficient amount of heat energy, the system will be with a tracking system to make the roof movable according to the angle of the rays of the sun.

7. Conclusion

we believe that our P-MFC is a high-efficiency, low emission solution to world's power needs and waste water systems. It's a centralized project to be applicable in the future and provide green environment. With our developments of traditional MFCs, we achieved the main goals as we produced efficient amounts of electricity with low cost and emissions.

8. Recommendations

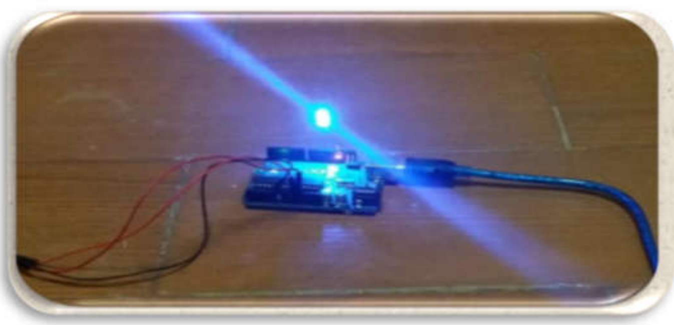
We recommend using high efficiency materials include CNF, carbon nano fiber, palladium and platinum electrodes, and (Nafion 117) and ionomers membranes. However, these materials are extremely expensive. A current method in development proposes a simple process to create carbon nanotubes at 70°C in an acidic solution, rather than the extremely high temperatures and pressure required for current procedures. This material costs less than currently available CNTs, but still quite expensive. MnO_2 provided from potassium permanganate (KM_nO_4) is the best catalyst for the electrodes as its high efficiency relative to its low cost and easy to be prepared in the laboratory as shown in Table 7.

Table 7. *Shows different catalysts; their performance and cost.*

	Efficiency (%)	Cost ($/g)
MnO_2	43.6±0.8	$20
Pt/C	39.8±2.6	$32.54

We designed an Arduino system as shown in figure 4 to demonstrate how a centralized unit would function. The system also provides feedback on power levels. The electric sensor on it lights blue when there's a huge waste of energy to inform people to reduce their usage to avoid blackouts. The system also distributes the current among houses.

Figure 4. *The Arduino System for Centralization*



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References

[1] Reece, J., & Urry, L. (n.d.). Campbell biology (Tenth ed.).

[2] Kelter, P., & Zumdahl, S. (2007). Chemistry, seventh edition, Zumdahl. Boston: Houghton Mifflin.

[3] A review on the role of proton exchange membrane on the performance of microbial fuel cell. (n.d.). Retrieved April 19, 2016, from http://onlinelibrary.wiley.com/doi/10.1002/pat.3383/full.

[4] Bruce Logan Research - Microbial Fuel Cells. (n.d.). Retrieved April 21, 2016, from http://www.engr.psu.edu/ce/enve/logan/bioenergy/research_mfc.htm

[5] Gude, V. (2016). Microbial fuel cells for wastewater treatment and energy generation. Microbial Electrochemical and Fuel Cells, 247-285. doi:10.1016/b978-1-78242-375-1.00008-3.

[6] Zhu, S., & Liang, S. (n.d.). Photocatalytic reduction of CO2 with H2O to CH4 on Cu(I) supported TiO2 Nano sheets with defective {001} facets. Retrieved April 12, 2016, from http://pubs.rsc.org/en/Content/ArticleLanding/2015/CP/C5CP00647C#!divAbstract peer reviews: 66

[7] P., & Quick, D. (n.d.). Plant-Microbial Fuel Cell generates electricity from living plants. Retrieved April 21, 2016, from http://www.gizmag.com/plant-microbial-fuelcell/25163/

[8] Logan, B. E., and Regan, J. M. (2006). Microbial Fuel Cells—Challenges and Applications. Environmental Science &Technology 40, 5172-5180.

[9] Pant D, V. B. G., Diels L, Vanbroekhoven K. (2010). A review of the substrates used in microbial.

[10] Prepare The Proton Exchange Membrane. (n.d.). Retrieved March 29, 2015, from www.instructables.com/id/Microbial-Fuel-Cell OfScience/step2/Prepare-The-Proton-Exchange-Membrane/

[11] Justa, Aditi. Harvard students harness electric power from bacteria in soil. Eco Friend, June 12, 2010. Web. Nov. 6, 2011. http://www.ecofriend.com/entry/harvardstudentsharness-electric-power-from-bacteria-in-soil/.

[12] McAveney, P., Pedersen, B., & Wong, J. (n.d.). Microbial Fuel Cell Using Inexpensive Materials. Retrieved April 10, 2016, from http://www.engr.psu.edu/ce/enve/logan/bioenergy/pdf/mcaveneyetal-mfc.pdf

[13] Schwartz, K. (2007). Microbial fuel cells: Design elements and application of a novel renewable energy sources. Basic biotech. ells. Enzyme and Microbial Technology 47, 179-188.

[14] M.Z. Açik and S. Tezcan. A Mathematical Model for the Behavior of Laminated Glass Beams. Computers and Structures, 83, 1742-1753, (2005).

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