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Electricity Production Using Plant–Microbial Fuel Cell (P-MFC)

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The current climate change threat by green house gas emissions from the combustion of fossil fuels has necessitated a search for alternative non-polluting, reliable, renewable and sustainable sources of energy such as solar energy and it's derivatives. The present work focuses on power generation by Plant-Microbial Fuel Cell using Phragmitesaustralis (Reed plant). The plants were grown in fuel-cell, graphite as anode and carbon felt as cathode, separated by proton-exchange-membrane. During anaerobic microbial metabolism of carbohydrates in the roots, protons and electrons are released, the electrons are donated to the anode by the microbes. These electrons can be channeled through a circuit bearing a load to the cathode. In this work, carbon granules as substratum (control), red soil and carbon granules mixture (30:70) as substratum in varied condition was considered. For control substratum, the max.voltage measured was 0.327 V and power density of 2.06×10^{-3} mW m^{-2} was obtained. When red soil mixed with carbon granules in the ratio 30:70, the voltage measured was 0.6 V and the power density was found to be 3.78×10^{-3} mW m^{-2}. When graded red soil (0.0018 m) mixed with carbon granules in the ratio 30:70, the voltage measured was 0.623 V and the power density was found to be 3.98×10^{-3} mW m^{-2}. The result proves that the plant microbial fuel cell can be used for generating electricity and is a promising renewable energy technology.

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Keywords: Plant microbial fuel cells; sustainable energy source; phragmitesaustralis; cathode; anode.

1. INTRODUCTION

Worldwide electricity generation is mainly dependent on fossil resources. Over 67 % of the electricity produced is originating from coal, oil or natural gas. Other sources are nuclear (13.4 %), hydropower (16.2 %), wind, solar, biofuels and waste (3.3 %). The share of fossil fuels in the total electricity generation has decreased over the last 50 years and is expected to further decrease within the coming decades. It has been shown that energy is directly linked to economic welfare. In order to enable developing countries to actually develop their economy more energy will be needed [1-3].

To meet future electricity demand, alternative electricity generating technologies are needed. Latest trends in energy conservation include the use of renewable energy as a means to conserve the nonrenewable energy sources. Renewable energy is also called as green energy due to their pollution free nature [4-7]. There are different forms of renewable energy like solar, wind power, hydroelectric energy, biomass, geothermal power.

A new alternative electricity generation technology is the Plant- Microbial Fuel Cell (P-MFC). Earlier studies have considered plants such as Arundodonax, Spartinaanglica, Reed mannagrass and Arundinellaanomala [9]. In general, the P-MFC can generate up to 3.2 Wm^{-2}. Lijiao Ren et al. [9] conducted a study on 'A two stage microbial fuel cell and anaerobic fluidized membrane bioreactor system (AFMBR) for effective domestic wastewater treatment'. Authors observed that, total electrical energy required for the operation of the MFC-AFMBR system was 0.0186 kWh/m^3, which was slightly less than the electrical energy produced by the MFCs (0.0197 kWh/m^3). The energy in the methane produced in the AFMBR was comparatively negligible (0.005 kWh/m^3). Yuko Goto et al. [10] studied about 'The effects of Graphene Oxide (GO) on electricity generation in Soil Microbial Fuel Cells (SMFCs) and Plant Microbial Fuel Cell (PMFCs)'. Authors concluded that GO added to soil can be microbially reduced in soil, and facilitates electron transfer to the anode in both SMFCs and PMFCs. The GO containing PMFC displayed a greater generation of 49mW m^{-2} after 27 days. Santoro et al. [11] concluded that, microbes are extremely sensitive, specific and accurate'sensors'of their own environment, and the MFC is one of the very few technologies that can directly capture the microbial response and metabolism, and produce this as ananalogue electrical signal. This gives the technology inherent sensing capability, which can be used in any environment.

The present research work focuses on generating electricity using Phragmites Australis (Reed plant) in Plant Microbial Fuel Cell. The specific objectives are,

- Fabrication of the Plant Microbial Fuel Cell
- To generate electricity by using only carbon granules as substratum
- To study the feasibility of electricity generation using red soil and carbon granules mixture in the ratio 30:70 respectively as substratum

The components of P-MFC are anode, cathode, circuit and proton exchange membrane. The plants produce Rhizo deposits, mostly in the form of carbohydrates, and the bacteria produce electrons which are transferred to the fuel cell [12-16]. A plant produces organic matter via photosynthesis, part of which is excreted at the roots into the soil [17,18]. These Rhizo deposits are oxidized by microorganisms. In the oxidation process electrons are released by the microorganisms and donated to the anode of microbial fuel cell [19-24]. The reactions that take place in at anode and cathode are as follows,

Anode: $C_6H_{12}O_6 + 6H_20 \rightarrow 6CO_2 + 24H^+ + 24e^-$
Cathode: $6O_2 + 24H^+ + 24e^- \rightarrow 12H_2O$
Overall: $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$ + electricity

The plants use sunlight for photosynthesis and produces organic matter which get settled in the roots (David P.B.T.B. Strik et al**,** 2010). The bacteria consume this organic matter or exudates and convert this into electrons which are later then transferred to anode where oxidation takes place as shown in Fig. 1.

The advantages of Plant Microbial Fuel Cell are,

- Microbial Fuel Cells are a very clean and efficient method of energy production
- produce energy from plants without the destruction of the plant or the reduction of yield

- Plant-Microbial Fuel Cells capture solar energy which is renewable and will be available for an estimated 5.5billion years

Fig. 1. Mechanism of P-MFC
Source: http://en.wikipedia.org/wiki/Microbial_fuel_cell

2. MATERIALS AND METHODOLOGY

The PHRAGMITES AUSTRALIS (REED PLANT), belongs to the Kingdom: Plantae, Order: Poales, Family: Poaceae, Subfamily: Arundinoideae, Tribe: Arundineae and Genus: Phragmites. The Plant specimens (Plate 1) are collected from Mahadevapura, Mandya district which is 30km away from Mysuru. The coordinate range is 12.52 ^{0}N and 76.9 ^{0}E. The location and collection of the plant samples are shown in Fig. 2. The material specifications are given as below,

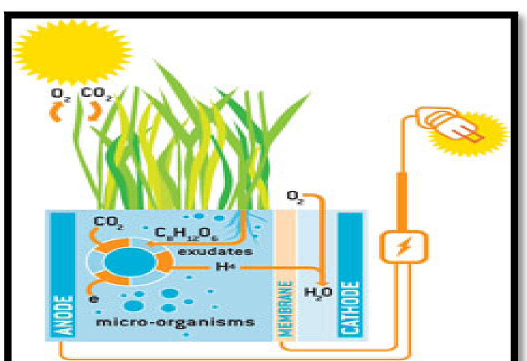

Plate 1. Phragmites Australis
http://www.cathylaw.com/APES/NPHSPlantList.html

Anode compartment – PVC pipe (0.3m x 0.09m):

This anode compartment (PVC pipe) acts as an outside compartment for substratum (Plate 2). It is procured from the local market, Mysuru.

Cathode compartment – Plastic container (0.2m x 0.15m):

Acts as an outside compartment for the anode compartment (Plate 3).It is procured from the local market, Mysuru.

Cathode–Carbon felt (0.11m x 0.11m x 0.002m):

Carbon felt is used as cathode material (Plate 4). Cathode is procured from M/s. Libra associates, Bengaluru.

Carbongranules (0.0015m):

Theroots of theplant are integrated in thecarbon granules to createananaerobiccondition (Plate 5). Carbon granules isprocuredfromM/s Rathnachemicals, Mysuru.

Anode-Graphite rod (0.4m x 0.005m):

It is inserted into the carbon granules placed within the anode compartment (Plate 6). Anode was procured from M/s.Libra associates, Bengaluru.

Proton exchange membrane of diameter (0.09m):

Proton exchange membrane is used for the effective transfer of protons and electrons. It does not allow any other solute to pass through (Plate 7).

Proton exchange membrane preparation:

Proton exchange membrane or polyelectrolyte membrane acts as a semi-permeable membrane for the transport of electrons. Proton exchange membrane is prepared using sodium chloride, agar and distilled water.

- 70mL of distilled water is taken and boiled
- 3g of agar is added to the boiling water
- 15g of sodium chloride is added to the boiling solution and heated
- The solution is then poured on a petridish and kept aside for 20 minutes
- It is then placed in a cooler for around half an hour until a solidified form is obtained

Hoagland solution composition:

The Hoagland solution is a hydroponic nutrient solution that was developed by Hoagland and

Arnon in 1938 and revised by Arnon in 1950 and is one of the most popular solution compositions for growing plants. The Hoagland solution provides every nutrient necessary for plant growth and is appropriate for the growth of a large variety of plant species. The solution described by Hoagland and Arnon in 1950 has been modified several times, mainly to add iron chelates, the constituents of Hoagland solution are given below. 2.5g of Hoagland solution was mixed with 1L of distilled water and 0.5ml of Hoagland solution was fed daily in P-MFC.

[Source:http://en.wikipedia.org/wiki/Hoagland_solution].

- Potassium nitrate(KNO_3)
- Magnesium sulphateheptahydrate, $MgSO_47H_2O$, and
- Potassium dihydrogen phosphate (Potassium phosphate monobasic), KH_2PO_4
- Iron EDTA or Iron chelate, Fe-EDTA
- Boric Acid, H_3BO_3
- Copper Sulfate, $CuSO_4$
- Zinc sulfate heptahydrate, $ZnSO_4•7H_2O$
- Manganese chloride, $MnCl_2•4H_2O$
- Sodium molybdate, $Na_2MoO_4•2H_2O$,
- Calcium nitrate, $Ca(NO_3)_2•4H_2O$

2.1 Methodology

The present research work was carried out using Reed plant (Phragmites Australis), an abundant grass species in Asia, America, Europe and with its roots placed in the anode compartment of the microbial fuel cell. P-MFC was setup in indoor conditions in the laboratory Carbon granules were alone used as a substratum for the roots. The cell voltage of plant- MFC's was recorded during a period of 27 days. An anode compartment setup was used. The cylinder was filled with carbon granules of 150 g. The plant-roots and carbon granules were cleaned with distilled water and afterwards the plant was planted in the carbon granules. The plant used was Phragmitesaustralis consisted of 2 stems of 0.54 m tall and a fresh weight of 25 g. The anode compartment was filled with modified Hoagland solution of about 0.5 ml. On top of the carbon granules soil was put to the level of the overflow point to prevent algae growth on the carbon granules. The anode cylinder was placed in the cathode compartment, which consisted of a container in which a carbon felt was placed at the bottom.

As a current collector for the anode, a graphite rod was inserted in the carbon granules which act as anode. For the cathode, an alligator wire was clipped through the carbon felt with an electrical wire attached to it. Anode and cathode wires were connected with an external resistance of 1000 Ω in between. The alligator wires were then connected to a multimeter to check the potential difference as shown in Plate 8. The anolyte consisted of modified Hoagland solution. The Hoagland solution served as a nutrient medium for the plants. The set-up was placed indoors under fairly constant conditions of temperature and light intensity [25,26].

The voltage was checked in the control setup initially using carbon granules as substratum. This was done by integrating the roots with carbon granules to maintain anaerobic conditions. The light intensity and temperature remained fairly constant during study period. The above parameters were then checked with red soil as substratum and the increase in the voltage was observed as soil is a nutrient medium and a good substratum for the growth of plants and inoculation of bacteria. The laboratory setup of Plant-Microbial Fuel Cell is shown in Plate 8.

2.1.1 Determination of voltage, power density and current

- **Voltage:** Voltage, electric potential difference, or electric tension (denoted ∆V or ∆U and measured in units of electric potential: volts, or joules per coulomb) is the electric energy charge difference of electric potential energytransported between two points. [http://en.wikipedia.org/wiki/Voltage]
- **Power density:** Electric power is the rate of energy consumption in an electrical circuit. The electric power is measured in units of watts. [http://en.wikipedia.org/wiki/Electric_power]

$$P = (V)/(\frac{R}{Membrane\ Area}) \longrightarrow \quad \text{Eq.(1)}$$

Where,

P= Power density in W m^{-2}
V= Voltage in Volts
R= Internal Resistance (1000Ω)
Membrane area= $0.0063m^2$

- **Current:** An electric current is a flow of electric charge. In electric circuits this charge is often carried by moving electrons in a wire.

[http://en.wikipedia.org/wiki/Electric_current]

$$I = \sqrt{\frac{P}{R}} \longrightarrow \text{Eq.(2)}$$

Where,

I= Current in milli Ampere
P= Power density from Eq (1)
R= Internal resistance (1000Ω)

Fig. 2. Plants are collected @ Mahadevapura, Mandya district

Plate 2. PVC pipe

Plate 3. Plastic container

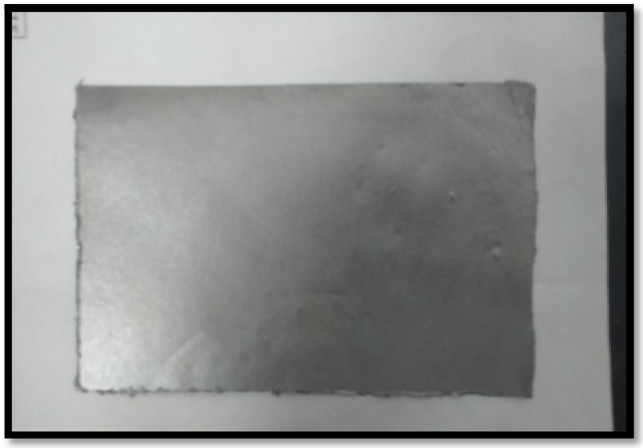

Plate 4. Carbon Felt

Plate 5. Activated charcoal

Plate 6. Graphite rod

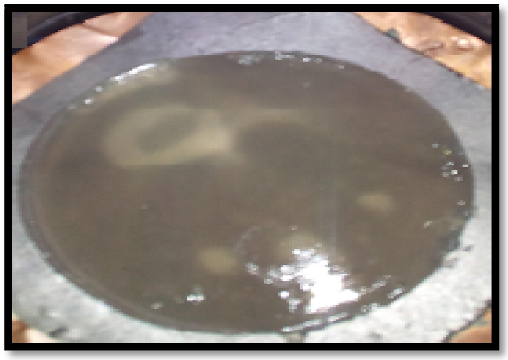

Plate 7. Proton exchange membrane

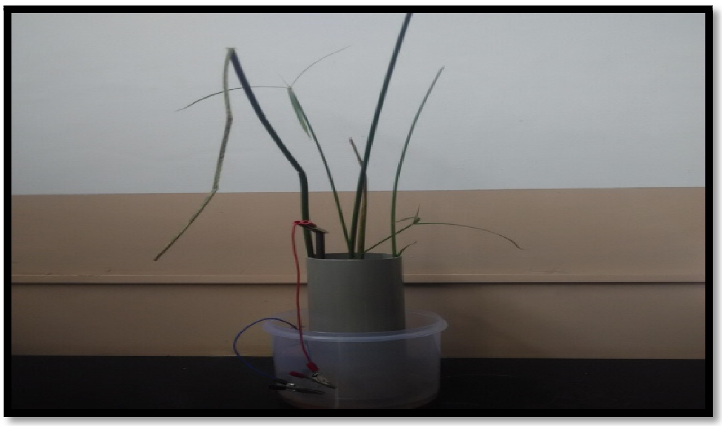

Plate 8. Lab Setup of Plant Microbialfuel Cell (P-MFC)

3. RESULTS AND DISCUSSION

3.1 P- MFC with Control Substratum

Figs. 3 & 4 shows the results of the controlled P-MFC. Period of 27 days proved to be necessary to obtain conditions favorable for electricity generation and hourly variation of the voltage was checked. The cell voltage of P-MFC increased steadily up to day 6 and because of the transportation of the P-MFC from one lab to another, disturbance was caused and a fair dip in the voltage was noticed on day 13. Then again the voltage increased from day 15 as the setup got acclimatized to the surrounding environmental conditions like temperature and light intensity. It produced a maximum voltage of 0.563V, power density of 3.546×10^{-3}mW m^{-2} and current of 0.0059mA. This was a control P-MFC under unvarying conditions of the substratum. In hourly observation of voltage in the controlled P-MFC substratum, the voltage is seen to be steadily increasing.

From present investigation for voltage, measured of 0.632V, a maximum power density of 3.98×10^{-3}mW m^{-2} was obtained using Phragmitesaustralis. Researchers David et al. [27] demonstrated using Reed mannagrassand achieved a maximal electrical power production of 67mWm^{-2} with carbon granules as substratum with one plant for three months. While a similar study conducted by Helder et al. [28] on three species of plants such as Spartinaanglica, Arundinellaanomala and Arundodonax, each species of two plants for around six months. The highest obtained power density was from Spartinaanglica of around 222mW m^{-2}. Sudrijo et al. [29] observed that, Plant-MFC outperformed the other plant-MFCs in terms of current density (16.1 mA/m^2 plant growth area) and power density (1.04 mW/m^2 plant growth area). Sudrijo et al. [30], concluded that the maximum current and power density of an acetate fed MFC reached 3 mA·m^{-2} projected surface area of anode compartment and 22 mW·m^{-3} anode compartment.

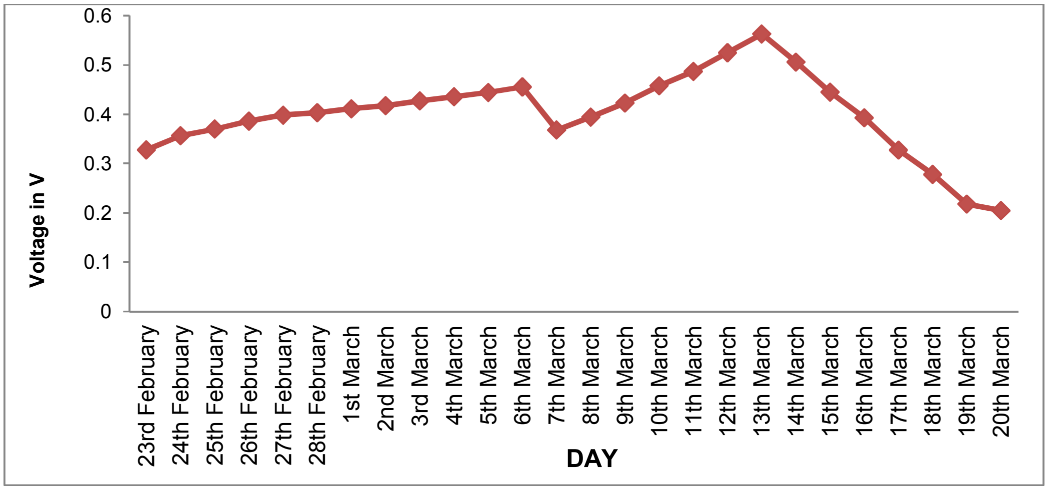

Fig. 3. Voltage daily variation in P-MFC control setup

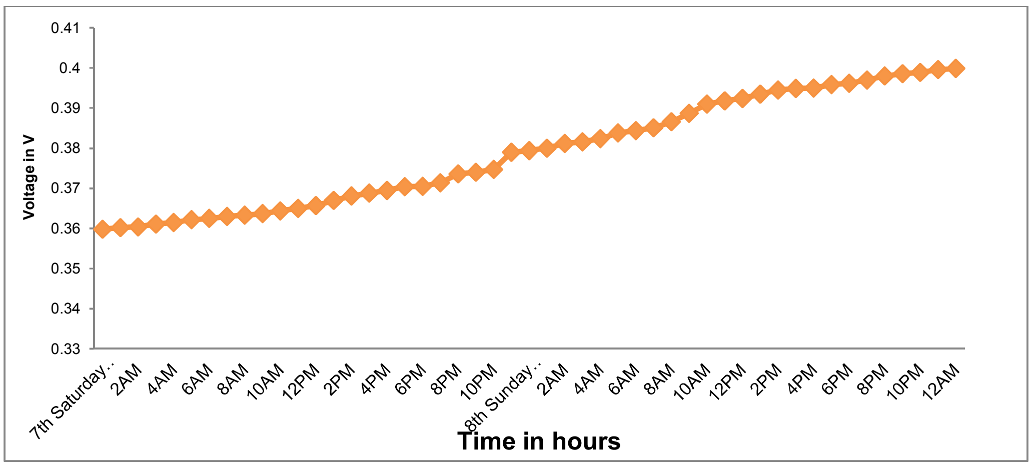

Fig. 4. Hourly voltage variation in P-MFC control setup

3.2 Red Soil and Carbon Granules Mixture as Substratum in P- MFC

The Plate 8 represents P-MFC setup in the laboratory using red soil and carbon granules mixture as substratum in the ratio 30:70. The readings of P-MFC were recorded for a period of 29 days as shown in Table 1 and soil largely helped in the growth of microorganisms and played a key role in the release of electrons and thereby increase in the voltage was observed. Fig. 5 shows the variation of light intensity on a daily basis. The characteristics of the soil is shown in Table 3. The red soil contained an electrical conductivity of 0.101mho per second. The soil contained potassium oxide of 19.165g m^{-2} and nitrogen of16.0025g m^{-2}which helped in the growth of plants. Fig. 6 shows the voltage variation in P-MFC mixed soil and carbon granules as substratum. Daily variation was then later calculated and found a maximum voltage of 0.592V, current of 0.00609mA and power density of $3.72x10^{-3}$mW m^{-2} on the 20^{th} day of the study. MohamedJaffer Gulamhussein et al. [31], observed that, the power output of the plant species, the *W. thyrsiflora* produced the highest, 1036 ± 59 mW/m^3 followed by *C. papyrus* with 510 ± 92 mW/m^3 and the lowest was measured in the control (no plant), 392 ± 67 mW/m^3.in the present study, the plant sustained for more than six weeks. From the above voltage, current and power density, it was investigated that red soil largely helped in the production of a higher power density when compared to the control substratum of P-MFC. Fig. 8 shows the variation of current with power density. From this graph, it was observed that as current increases, power density also increases. In other words, current is directly proportional to power density.

Table 1. Variation of Voltage, Power density, Current in red soil & carbon granules as substratum P-MFC

Day	Temperature (^{0}C)	Light intensity (LUX)	Voltage (V)	Power density (mW m^{-2})	Current (mA)
1	26	24	0.451	$2.82x10^{-3}$	0.0053
2	25	20	0.462	$2.91x10^{-3}$	0.00532
3	26	17	0.481	$3.03x10^{-3}$	0.0055
4	25	21	0.495	$3.11x10^{-3}$	0.0057
5	26	32	0.513	$3.23x10^{-3}$	0.0056
6	26	37	0.532	$3.35x10^{-3}$	0.0057
7	26	24	0.548	$3.45x10^{-3}$	0.0058
8	25	18	0.551	$3.47x10^{-3}$	0.00589
9	26	21	0.554	$3.49x10^{-3}$	0.00590
10	26	24	0.562	$3.54x10^{-3}$	0.00594
11	26	27	0.568	$3.57x10^{-3}$	0.00597
12	26	18	0.575	$3.62x10^{-3}$	0.00601
13	25	30	0.583	$3.67x10^{-3}$	0.00605
14	26	25	0.592	$3.72x10^{-3}$	0.00609
15	26	31	0.600	$3.78x10^{-3}$	0.00614
16	26	19	0.612	$3.85x10^{-3}$	0.00620
17	25	24	0.625	$3.93x10^{-3}$	0.00625
18	26	22	0.632	$3.98x10^{-3}$	0.00630
19	25	17	0.627	$3.95\ x10^{-3}$	0.00628
20	26	24	0.624	$3.93\ x10^{-3}$	0.00626
21	27	27	0.620	$3.906\ x10^{-3}$	0.00624
22	25	16	0.617	$3.88\ x10^{-3}$	0.00622
23	26	19	0.613	$3.861\ x10^{-3}$	0.006213
24	27	30	0.608	$3.830\ x10^{-3}$	0.006218
25	26	22	0.603	$3.79\ x10^{-3}$	0.006156
26	27	18	0.600	$3.78\ x10^{-3}$	0.006148
27	25	26	0.598	$3.767\ x10^{-3}$	0.006137
28	25	48	0.596	$3.754\ x10^{-3}$	0.006126
29	26	35	0.594	$3.724\ x10^{-3}$	0.006117

3.3 Graded Red Soil (0.0018m) and Carbon Granules Mixture as Substratum in P- MFC

The third setup of P-MFC was setup using graded red soil (0.0018m) and carbon granules mixture as substratum (30:70). The readings of P-MFC were recorded for a period of 45 days as shown in Table 2. The cell voltage in P-MFCs increased steadily from day 9. It produced a maximum voltage of 0.632 V,current of 0.0063 mA and power density of $3.98x10^{-3}$ mW m^{-2} as shown in Fig. 9. The cell voltage of P-MFC was recorded during a period of 45days as seen in Table 2. Fig. 7 shows the voltage variation in P-MFC graded soil and carbon granules as substratum Fig. 9 shows the variation of current with power density in 0.0018 m graded soil.

After few days the current generation decreased to about 10–20 % of the maximum value. From the start of the experiment the Reed plant were vital and showed normal root and leaf growth. After the peak in current generation, the plant vitality slowly declined until the end of the experiment. This followed the normal decline of plant vitality at the end of the growing season. The decline is not an effect of the conditions in the controlled P-MFC, but also plants in soil mixed with carbon granules and graded soil (0.0018 m) mixed with ratio 30:70 showed a similar decline in vitality. Eventually, all three setup of P-MFC showed electricity production for a period of more than six weeks.

Table 2. Variation of Voltage, Power density, Current in graded red soil (0.0018 m) & carbon granules as substratum P-MFC

Day	Temperature(^{0}C)	Light intensity (LUX)	Voltage (V)	Power density (mW m^{-2})	Current (mA)
1	25	11	0.497	3.13 X10^{-3}	0.0055
2	25	21	0.514	3.23 X10^{-3}	0.0056
3	26	26	0.522	3.28 X10^{-3}	0.0057
4	25	25	0.535	3.37 X10^{-3}	0.0058
5	26	24	0.549	3.45 X10^{-3}	0.00587
6	26	22	0.569	3.58 X10^{-3}	0.00598
7	26	20	0.580	3.65 X10^{-3}	0.006
8	26	18	0.592	3.72 X10^{-3}	0.00609
9	26	35	0.570	3.59 X10^{-3}	0.00599
10	25	38	0.551	3.47 X10^{-3}	0.00589
11	25	38	0.531	3.34 X10^{-3}	0.00577
12	26	21	0.517	3.25 X10^{-3}	0.00570
13	27	19	0.483	3.04 X10^{-3}	0.0055
14	25	23	0.459	2.89 X10^{-3}	0.0053
15	26	24	0.454	2.86 X10^{-3}	0.00534
16	26	23	0.449	2.82 X10^{-3}	0.00531
17	26	24	0.440	2.77 X10^{-3}	0.0052
18	25	20	0.432	2.72 X10^{-3}	0.00521
19	25	17	0.424	2.67 X10^{-3}	0.00516
20	26	21	0.421	2.65 X10^{-3}	0.00514
21	26	32	0.419	2.63 X10^{-3}	0.00512
22	25	37	0.4012	2.52 X10^{-3}	0.00501
23	25	24	0.4005	2.521 X10^{-3}	0.00501
24	26	18	0.3961	2.5 X10^{-3}	0.005
25	26	21	0.3934	2.501 X10^{-3}	0.0050009
26	26	24	0.3922	2.488 X10^{-3}	0.00497
27	25	27	0.3910	2.477 X10^{-3}	0.00496
28	26	18	0.3902	2.49 X10^{-3}	0.00498
29	26	30	0.3891	2.472 X10^{-3}	0.00497
30	26	25	0.3901	2.457 X10^{-3}	0.00495
31	25	31	0.3898	2.455 X10^{-3}	0.004954
32	26	19	0.3895	2.453 X10^{-3}	0.004952
33	26	24	0.3889	2.45 X10^{-3}	0.00494
34	26	22	0.3885	2.44 X10^{-3}	0.00493
35	25	17	0.3870	2.438 X10^{-3}	0.00493
36	26	24	0.3842	2.420 X10^{-3}	0.00491
37	27	27	0.3815	2.403 X10^{-3}	0.00490
38	25	16	0.3795	2.390 X10^{-3}	0.00488
39	26	19	0.3762	2.370 X10^{-3}	0.00486
40	27	30	0.3739	2.355 X10^{-3}	0.00485
41	26	22	0.3712	2.338 X10^{-3}	0.00483
42	27	18	0.3681	2.319 X10^{-3}	0.00481
43	25	26	0.3655	2.302 X10^{-3}	0.00479
44	25	48	0.3623	2.282 X10^{-3}	0.00477
45	26	35	0.3602	2.269 X10^{-3}	0.00476

Table 3. Physico-chemical characteristic of soil

Sl. No.	Parameter	Concentration
1	pH	7.65
2	Electrical conductivity	0.101 m mho s^{-1}
3	Organic carbon	0.210 %
4	Nitrogen	16.0025445 g m^{-2}
5	Phosphorous oxide	2.409277 g m^{-2}
6	Potassium oxide	19.165493 g m^{-2}

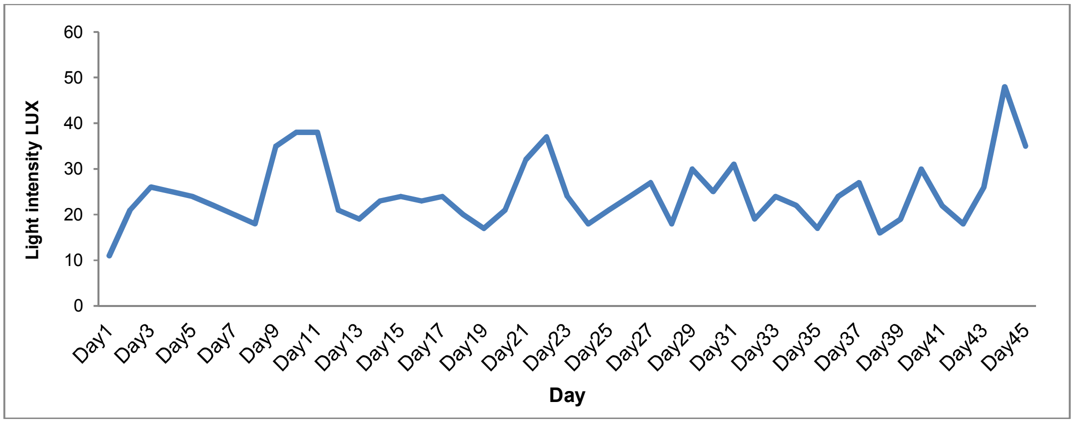

Fig. 5. Variation of light intensity during study period

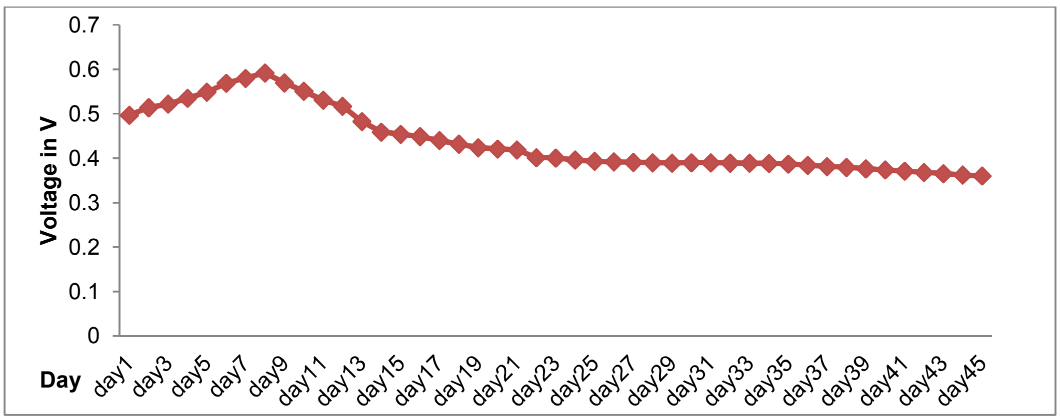

Fig. 6. Voltage variation in P-MFC mixed soil and carbon granules as substratum

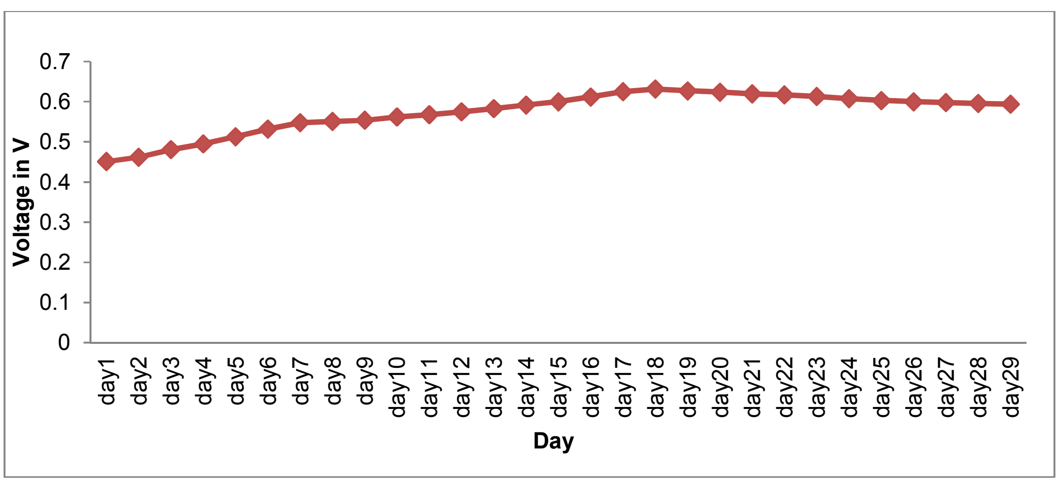

Fig. 7. Voltage variation in P-MFC graded soil (0.0018 m) and carbon granules as substratum

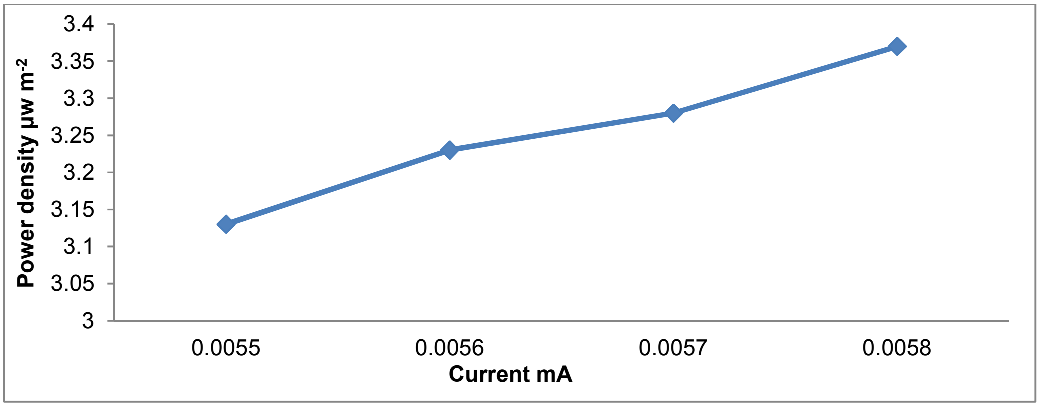

Fig. 8. Variation of current and power density for mixed soil in P-MFC

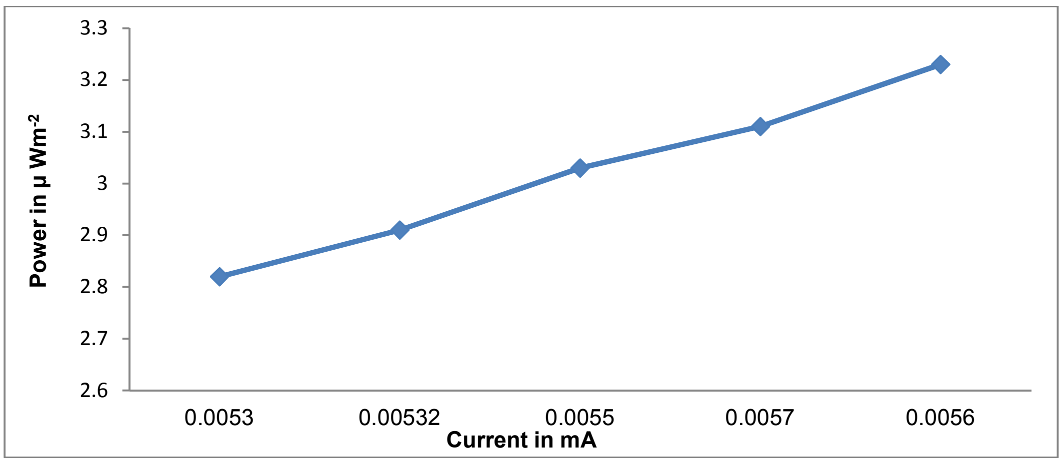

Fig. 9. Variation of current and power density graded soil (0.0018 m) in P-MFC

4. CONCLUSIONS

In the present work, carbon granules as substratum (control) and soil as substratum(30:70) was carried out in varied condition.

- For control obtained a power density of 3.546×10^{-3} mW m^{-2}(0.563 V)
- When soil was used as substratum power density produced was around 3.72×10^{-3} mW m^{-2} (0.592 V)
- When graded soil (0.0018 m) size mixed with carbon granules in a ratio 30:70, obtained a power density of 3.98×10^{-3} mW m^{-2} (0.632 V)
- The power density obtained was higher for soil and carbon granules mixture compared to control setup, as carbon granules are involed in electron exchange
- The result proves that the plant microbial fuel cell can be used for generating electricity and is a promising renewable energy technology.

DISCLAIMER

The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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