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Analytical Estimation of plant power generation by PMFC (Performance, Limitations & Scope)

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***Abstract:*In this research paper we show that a carbon electrode can be replaced by a copper & zinc electrode in a plant microbial fuel cell PMFC with a new record power output. Some pair of electrodes was successfully integrated into the soil with rice paddy plants operated for 90 days. Paddy plants growth continued and the power density increased reaching a maximum power output as per plant growth area (PGA).The 90 days record peak output power density was 88.73 mW/m^2& 41.26 mW/m^2.These new records were reached due to the higher light intensity, temperature & solar radiation which are beneficial external parameters to the enhancement of voltage generation via Cu-Zn electrode.This resulted in a 2.54 V & 0.98 V higher voltages with the two different experiments by changing the position of electrodes. Also found that substrate availability in the anode eventual limits the current generation. This work is keen for PMFC applicability shows that could be a completely renewable, sustainable & affordable with an improved power output.**

***Keywords:*PMFC, Electrode Material, Rice Paddy Plants (Oryza Sativa),Photosynthesis, Microorganisms, Rhizosphere, Root Excudates,Soil pH, C/N ratio, Plant Growth Plant (PGA).**

I. INTRODUCTION

The urgency for new sustainable and reliable energy sources is required because of the global warming, depletion of conventional sources, environmental pollution and continuously growing energy demand [1]. Many non-conventional sources like solar, hydro, wind and bio-energy technologies are already performing very well and simply in modern life. The market share of all bioenergy is upgrading but it is not always sustainable. Deforestation for more food production and for arable lands these both reason responsible for occurring environmental pollution. Plantation is the only solution for overcome these sever problems. It can be explained easily by performing PMFC. A Plant microbial fuel cell (PMFC) is an emerging technology worldwide which can generate bioelectricity by living plants without disturbing the growth. PMFC is a sustainable technology because it is completely green, clean, renewable, affordable & 0% GHG emission technology and has beneficial to cultivation of crop with the electricity production at the same time same field [4].

In the PMFC, plant grows in the PGPA of anode where rhizodeposits are the substrates oxidized by electrochemically active bacteria to generate electricity in which PMFC can be integrated without extensive excavation of the soil [5]. PMFCs can also be implemented in green roofs, combining the advantageous of building insulation, biodiversity and electricity generation [8]. Even though PMFC is based on photosynthesis, it is expected to deliver electricity 24x7 day & night a year around in case of suitable conditions like temperature and plant growth [9]. The theoretical maximum electricity output of a PMFC is 3.2 W/m^2 plant growth area (PGA) [10], currently a long term output of 0.155 W/m^2 PGA is reached [11].

Rice paddy plant microbial fuel cells generate electricity from organic matter that is photosynthesized by rice plants and exudates from the roots. We examined factors that might affect cell performance and found that electrodes modification with material, sizes, position, and external load largely affected the power output.

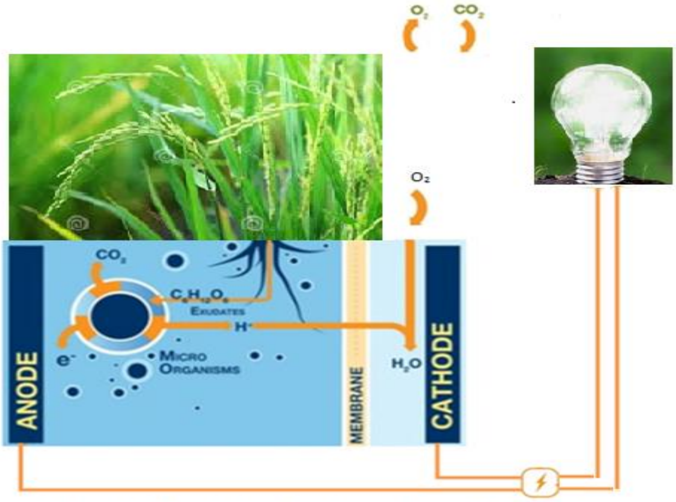


Fig. I - Working Principle of PMFC.

II. MATERIALS & METHODS

PMFC is the very recent surpassing concept has been proposed for onsite conversion of the energy conserved in photosynthesized organic matter present in the soil into electricity. To cite an instance we developed a project with 5 different size of pots culture system to generate electric power from organics exuded from the roots of rice paddy. In the system, 6 zinc anodes of 8 inch placed into the soil in the pots pairing with the copper cathode of same size to establish a plant microbial fuel cell (PMFC) with different numbers of rice paddy plants. Thus, electricity generation in a rice paddy plant has been demonstrated. Anodes were set in the rice rhizosphere and in flooded water, and it was observed that the voltage generation is as high as about normalized to the anode projection area was generated in a sunlight dependent manner. Cathodes were placed above the soil surface & just below the water level in the pots. Results had been taken by digital multimeter on daily basis which shows that the rice paddy plant electricity generation system by PMFC is an ecological solar cell in which plant photosynthesis can coupled to the microbial conversion of organic matter into electricity. Despite these so many efforts and taking care of the system, electric outputs from these systems are still low, and it is important to identify and examine the factors that affect them. In the present work, we examined factors that might affected PMFC performance, and discuss how electric output can be improved. We had used a residential area where rice paddy plantation had done in the pots.

While one electrode system was set as anode and cathode were connected via epoxy encapsulated wires, and the circuit was completed using an external resister. The voltage across the resister was monitored. Rice-plant seeding (Oryza sativa) were transplanted on March15, 2020. After which the voltage was monitored. In order to evaluate cell performance indices, open-circuit voltage (V), short circuit current density per projection area of the anode (I), and maximum power density per projection area of the anode (Pmax), were estimated.

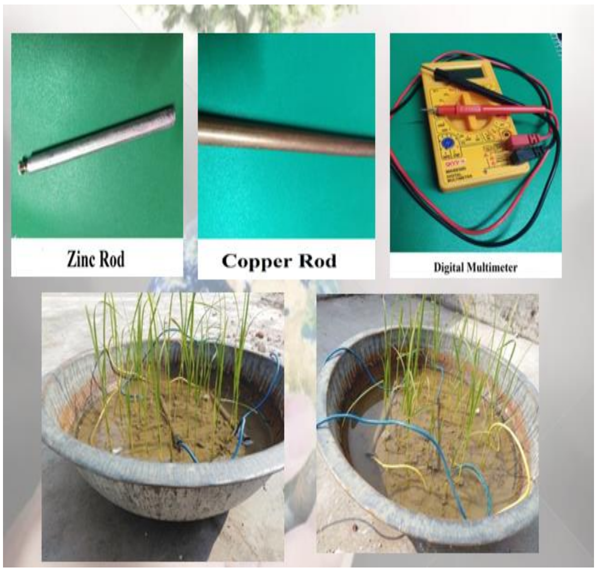
Table No . 01 Different parameters for all five pots at the starting of experiment. (Setup No.1& 2)

Parameters	Pot 1	Pot 2	Pot 3	Pot 4	Pot 5
Soil (kg)	0.5	1.0	2.0	5.0	5.0
Cow dung Compost (g)	50	100	200	500	100

Soil pH /Compost pH	7.2/7.4	7.2/7.4	7.2/7.4	7.2/7.4	7.2/
EC (m S/cm) of Cu/Zn	5.98x10^{7}/1.682x10^{7}	5.98x10^{7}/1.682x10^{7}	5.98x10^{7}/1.682x10^{7}	5.98x10^{7}/1.682x10^{7}	5.98x107/1.682x107
LOI (%)	9.2	9.2	9.2	9.2	9.2
Rice Paddy no.	5	15	20	25	20
Pair of Electrodes Cu/Zn	1	1	2	1	2
Density of Soil Particles	2.55 to 2.70 gcm^{-3}	2.55 to 2.70 gcm^{-3}	2.55 to 2.70 gcm^{-3}	2.55 to 2.70 gcm^{-3}	2.55 to 2.70 gcm-3
C/N (Soil & Compost)	20:1 & 25:1	20:1 & 25:1	20:1 & 25:1	20:1 & 25:1	20:1 & 25:1
Moisture Content (%)	40	40	40	40	40

In order to analyze factors that might affect PMFC performance, MFC systems were set under different parameters (Table 1). These parameters were set according to our knowledge of previous research case study, which affect the performance of PMFC. It was thus important to examine these operational parameters experimentally. Since we considered that more organic exudates from roots could be utilized for microbial anode respiration if the roots were contacted by more anode. The anode position (depth of the anode) corresponded to the distance between the anode and a cathode that was placed at the surface of the soil fig 5. The anode/cathode distance is known to influence MFC performance, since it affects proton diffusion from anode to cathode. We also investigated the effects of cathode modification. Finally, we examined output with external load during the operation, since it has been reported that external loads influence the electric output PMFC. In the experiment, double PMFCs were set for each experiment setup fig 2 & fig 3. After the start of the experiment, the electric output gradually increased. These daily observed values in our study the polarization and power curves were made for each PMFC (fig.7) and (fig.8) cell-performance indices were obtained from these curves (Table No. 4 & 5).

Construction of Setup No. 1



Construction of Setup No. 2

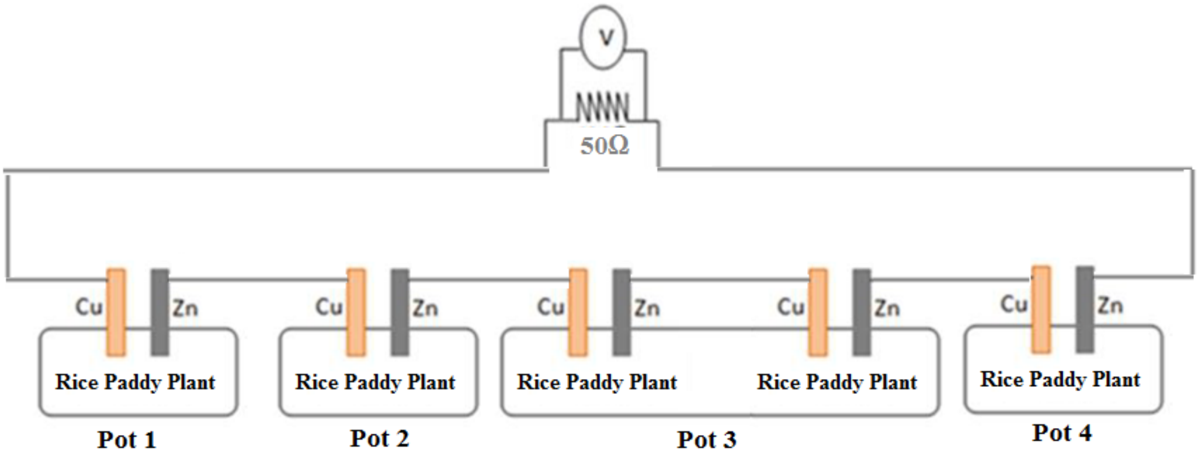


Fig. 4 - Schematic Diagram of PMFC Setup 1

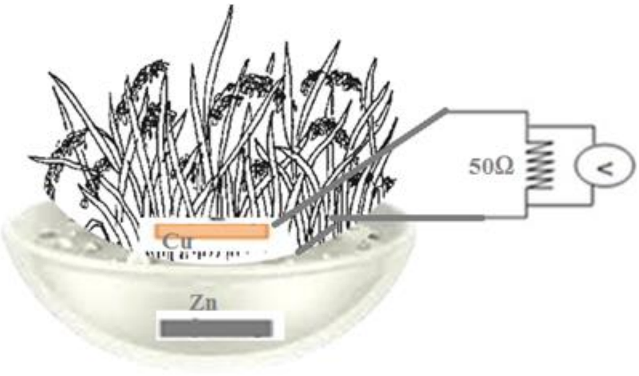


Fig. 5 - Schematic Diagram of PMFC Setup 2

III. RESULTS & DISCUSSION

By comparing the results for these different conditions, we were able to draw several conclusions. First, the number of electrode greatly influenced cell performance (compare the setup 1 and 2). This was checked by visual inspection after the experiment. Second, an anode depth of 5 cm was better than 2 cm (compare the setup 1 and 2). This suggests that proton transfer efficiency from the anode to cathode did not limit the electric output from PMFC.

Few reasons are conceivable for the high performance with the anode at a depth of 5 cm:

(1) The zone at a depth of 2 cm was not sufficiently anaerobic, resulting in the presence of oxygen, which served as an alternative electron sink;

(2) More rice paddy plant roots were associated with the anode at 5 cm than that at 2 cm, resulting in larger amounts of organics supplied for the anode at 5 cm. We think that the first explanation is unlikely, since the oxidation/reduction potentials (vs. a standard hydrogen electrode) for the zones at 2 cm and 5 cm in depth were not substantially different (158mV and 165mV respectively). This is consistent with data reported previously. For instance, Lu¨demann et al. documented for a rice paddy that oxygen was almost completely absent at a depth of more than 2mm from the surface. This suggests that cathode reaction efficiency is important for electric output from PF-MFC.

(3) The external load influenced performance. This large influence was surprising; in particular, it was unexpected that the high load would result not only in high Voc but also in high Isc. We assume that the operation of the MFC system at high cell voltages facilitated the activation of anode respiring microbes. Further studies are necessary for a deep understanding of this phenomenon, since this approach can relatively easily improve cell performance. In conclusion, this study examined factors that might affect the performance of PMFCs.

Table No. 02: Daily Basis Analysis and observation ofPMFC. (Setup No. 1 & 2)

S.No.	DAY NO.	SOLAR RADIATION (Wh/m^2)	HUMIDITY (%)	TEMPERATURE (Max/Min) ^{0}C	VOLTAGE GENERATION (V) Setup 1	VOLTAGE GENERATION (V) Setup 2
01	90	$7.14X10^3$	22%	28 ^{0}C/17 ^{0}C	1.58	0.98
02	86	$7.14X10^3$	39%	30 ^{0}C/13 ^{0}C	1.51	0.95
03	83	$7.14X10^3$	42%	36 ^{0}C/20 ^{0}C	1.46	0.89
04	79	$6.61X10^3$	62%	36 ^{0}C/21 ^{0}C	1.49	0.92
05	73	$6.61X10^3$	44%	35 ^{0}C/19 ^{0}C	1.43	0.87
06	65	$6.61X10^3$	27%	38 ^{0}C/20 ^{0}C	1.52	0.83
07	58	$6.61X10^3$	92%	38 ^{0}C/22 ^{0}C	1.51	0.81
08	51	$6.61X10^3$	35%	37 ^{0}C/21 ^{0}C	1.45	0.78
09	46	$6.61X10^3$	40%	40 ^{0}C/22 ^{0}C	1.38	0.80
10	37	$6.61X10^3$	68%	40 ^{0}C/24 ^{0}C	1.34	0.79
11	32	$6.61X10^3$	39%	38 ^{0}C/24 ^{0}C	1.53	0.74
12	29	$6.61X10^3$	95%	38 ^{0}C/22 ^{0}C	1.95	0.77
13	26	$6.83X10^3$	67%	40 ^{0}C/26 ^{0}C	2.35	0.78
14	24	$6.83X10^3$	49%	38 ^{0}C/24 ^{0}C	2.54	0.76
15	23	$6.83X10^3$	28%	41 ^{0}C/26 ^{0}C	1.46	0.79
16	21	$6.83X10^3$	27%	44 ^{0}C/31 ^{0}C	1.27	0.75
17	19	$4.59X10^3$	60%	39 ^{0}C/27 ^{0}C	0.99	0.73
18	11	$4.59X10^3$	97%	30 ^{0}C/22 ^{0}C	0.89	0.72
19	06	$4.59X10^3$	41%	34 ^{0}C/25 ^{0}C	0.83	0.69
20	01	$4.59X10^3$	28%	40 ^{0}C/28 ^{0}C	0.96	0.62

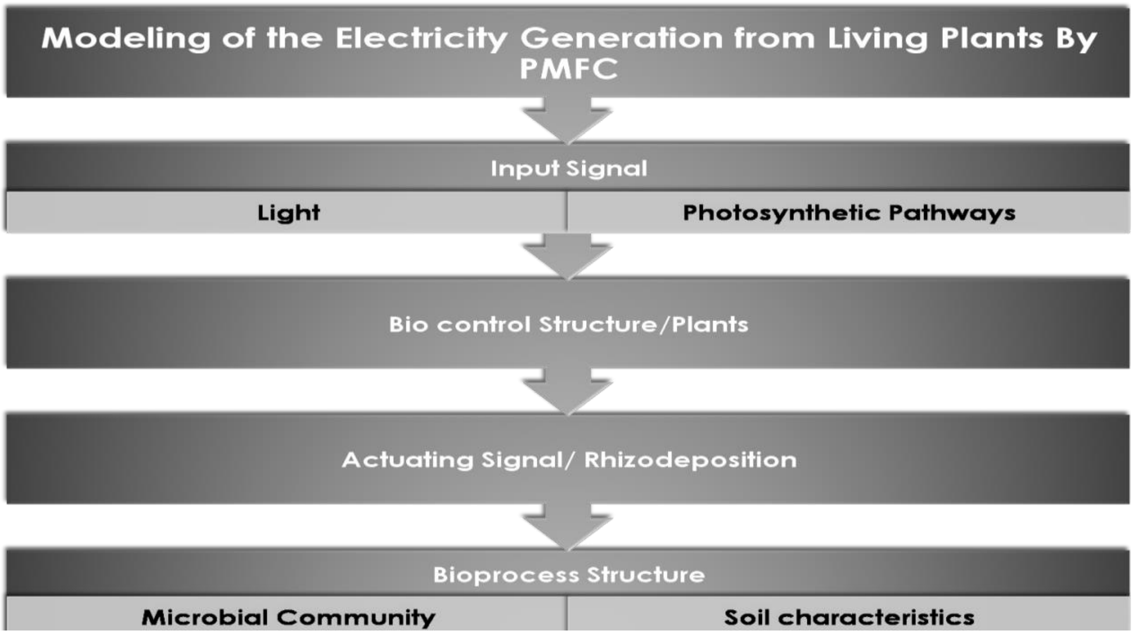


Table No. 03 :Daily Basis Analysis and observation of PMFC voltage generation (Setup No.1)

Sn.	Day No.	Pot 1 Cu_1-Zn_2 (V)	Pot 2 Cu_3-Zn_4 (V)	Pot 3 Cu_5-Zn_6 (V)	Pot 4 Cu_7-Zn_8 (V)	Pot 5 Cu_9-Zn_{10} (V)	Voltage ∑P=P1+P2+P3+P3+P4 (V)	Final Voltage Cu_1-Zn_{10} (V)
01	90	0.37	0.37	0.33	0.05	0.40	1.52	1.58
02	86	0.37	0.33	0.35	0.04	0.41	1.50	1.51
03	83	0.21	0.21	0.51	0.05	0.57	1.46	1.46
04	79	0.27	0.37	0.29	0.04	0.42	1.38	1.49
05	73	0.23	0.37	0.25	0.10	0.43	1.40	1.43
06	65	0.35	0.32	0.27	0.03	0.49	1.51	1.52
07	58	0.23	0.13	0.51	0.05	0.57	1.48	1.51
08	51	0.25	0.38	0.25	0.10	0.43	1.41	1.45
09	46	0.26	0.37	0.29	0.04	0.40	1.36	1.38
10	37	0.20	0.39	0.24	0.12	0.32	1.27	1.34
11	32	0.36	0.38	0.29	0.04	0.42	1.52	1.53
12	29	0.43	0.42	0.40	0.04	0.64	1.93	1.95
13	26	0.26	0.64	0.59	0.05	0.73	2.27	2.35
14	24	0.47	0.57	0.61	0.07	0.74	2.46	2.54
15	23	0.21	0.11	0.51	0.05	0.57	1.45	1.46
16	21	0.65	0.16	0.10	0.09	0.27	1.26	1.27
17	19	0.09	0.02	0.02	0.03	0.82	0.98	0.99
18	11	0.10	0.03	0.01	0.04	0.70	0.88	0.89
19	06	0.09	0.01	0.02	0.08	0.62	0.82	0.83
20	01	0.07	0.03	0.02	0.04	0.78	0.94	0.96

Table No. 04 : Calculation of Power Density (Setup No.1)

Resistance R (in Ω) = R internal + R external = 1.1+50 = 51.1 Ω

Total Area a = a1+a2+a3+a4 = 0.98 + 0.14 + 0.29 + 0.045 = 1.46 m^2

Where $a_1 = 2 \pi r_1 h_1 + \pi r_1^2$ (m^2) , $r_1 = 0.45$ m , $h_1 = 0.30$ m

$a_2 = 2 \pi r_2 h_2 + \pi r_2^2$ (m^2) , $r_2 = 0.075$ m , $h_2 = 0.23$ m

$a_3 = 2 \pi r_3 h_3 + \pi r_3^2$ (m^2) , $r_3 = 0.15$ m , $h_3 = 0.45$ m

$a_4 = l_4 \times w_4$ (m^2), l = 0.30 m , w = 0.15 m

S.no.	Day	Voltage Generation (V)	Current I = V/R (A)	Current Density I_D = V/a x R (A/m^2)	Power Density $P_D = I_D$ x V (mW/m^2)
1.	90	1.58	0.031	0.0212	33.55
2.	86	1.51	0.030	0.0205	31.03
3.	83	1.46	0.029	0.0199	29.00
4.	79	1.49	0.029	0.0199	29.59
5.	73	1.43	0.028	0.0191	27.42
6.	65	1.52	0.031	0.0212	32.27
7.	58	1.51	0.031	0.0212	32.06
8.	51	1.45	0.028	0.0192	27.81
9.	46	1.38	0.027	0.0185	25.52
10.	37	1.34	0.026	0.0178	23.86
11.	32	1.53	0.031	0.0212	32.49
12.	29	1.95	0.038	0.0260	50.75
13.	26	2.35	0.046	0.0315	74.04
14.	24	2.54	0.051	0.0349	88.73
15.	23	1.46	0.029	0.0199	29.00
16.	21	1.27	0.025	0.0171	21.75
17.	19	0.99	0.020	0.0137	13.56
18.	11	0.89	0.017	0.0116	10.36
19.	06	0.83	0.016	0.0110	09.06
20.	01	0.96	0.019	0.0130	12.49

Table No. 05 : Calculation of Power Density (Setup No. 2)

Resistance (in Ω)= R internal + R external =1.1+50 = 51.1 Ω
Total Surface Area of a hemisphere a = $3\pi r^2$, a = 0.456 m2
where r = 0.22 m,

S.no.	Day	Voltage Generation (V)	Current I = V/R (A)	Current Density I_D = V/aR (A/m^2)	Power Density ($P_D = I_D$ xV) (mW/m$^{2)}$
1.	90	0.98	0.0192	0.0421	41.26
2.	86	0.95	0.0186	0.0421	40.00
3.	83	0.89	0.0174	0.0382	33.96
4.	79	0.92	0.0180	0.0394	36.32
5.	73	0.87	0.0170	0.0372	32.43
6.	65	0.83	0.0162	0.0355	29.49
7.	58	0.81	0.0159	0.0349	28.24
8.	51	0.78	0.0153	0.0336	26.17
9.	46	0.80	0.0157	0.0344	27.54
10.	37	0.79	0.0155	0.0341	26.85
11.	32	0.74	0.0145	0.0318	23.53
12.	29	0.77	0.0151	0.0331	24.50
13.	26	0.78	0.0153	0.0336	26.17
14.	24	0.76	0.0149	0.0327	25.49
15.	23	0.79	0.0155	0.0340	26.85
16.	21	0.75	0.0147	0.0322	24.18
17.	19	0.73	0.0143	0.0314	22.89
18.	11	0.72	0.0141	0.0309	22.26
19.	06	0.69	0.0135	0.0296	20.42
20.	01	0.62	0.0121	0.0265	16.45

Table No. 06:Comparison of Voltage and Power Density at the two different setups of PMFC.

Setup No.	Peak Voltage (V)	Maximum Power Density (mW/m^2)
1	2.54	88.73
2	0.98	41.26

IV. CONCLUSION

We suggest that cathode modification with different materials, anode position, and external load affect power generation in Plant Microbial Fuel Cell (PMFC). Recently, we performed a simulation experiment on PMFC using pot cultivation of rice plants, finding that the incorporation of the suggested optimum conditions resulted in maximum power density increases of up to approximately 30mWm^2 (our unpublished data). Several studies have previously demonstrated plant associated MFC systems, while it is still unclear how the cell performance of these systems can be improved. We expect that the information reported herein will be useful for improving plant-associated Microbial Fuel Cell systems.

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