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ELECTRICITY GENERATION FROM SEWAGE WASTEWATER IN A MICROBIAL FUEL CELL PILOT POWER PLANT USING ALUMINIUM CATHODES

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ABSTRACT:
Aluminium metal is a low-cost material which can be used as an alternative cathode to carbon-based electrodes, for oxygen reduction in microbial fuel cells (MFCs). This study showed the effect of using aluminium rods as cathodes and carbon rods as anodes in single chamber microbial fuel cells (SCMFCs) connected in series and parallel connections to form a pilot power plant for electricity generation. Each single cell generated an output voltage ranging between 0.5 to 0.7 V. The cells were arranged into two modules to increase the voltage and current in the system. Each module constituted of twenty-four cells connected in series. Module one generated a maximum output voltage of 13.72 V while module two generated 14.21 V. The two modules were then Connected in parallel to form the pilot power plant and increase the current in the system. The maximum output voltage obtained was 14.36 V and the maximum current was 3.5 mA when an external resistor of 815 Ω was connected in the system. The total working volume of sewage wastewater used in the system was 38.4 liters. The maximum power density obtained was 1281 W/m^3. The system was able to light DC bulbs, ranging from 3W and 5W. The results showed that SCMFCs using carbon rods as anode and aluminium rods as cathode can be connected in series to increase voltage and in parallel to increase the current, hence produce a good power output in watts.

KEYWORDS: *SCMFC. Aluminium cathodes, Sewage wastewater, Microbial fuel cell pilot power plant*

1.0 INTRODUCTION

Good sanitation and proper management of human waste (urine and faeces) is vital for a healthy and quality life [1]. Improper management of human waste causes environmental pollution, however, one sustainable approach of utilizing these wastes to improve the living conditions is through the use of microbial fuel cells (MFCs). Microbial energy generation technologies produce electricity from organic waste via a biochemical pathway followed by electrochemical reactions utilizing microbes and electrodes [2],[3], [4] . The microorganisms produce electrons from raw organic materials through microbial catalyzed oxidization/reduction reactions, which are then transferred from anode to cathode through an external circuitry to produce electricity [5]. Figure 1. illustrates a schematic of a microbial fuel cell while the reaction equations are presented in Eqs. (1) and (2) where acetate is taken as a satisfactory representative of the complex sewage substrate for the electrode reactions [6].

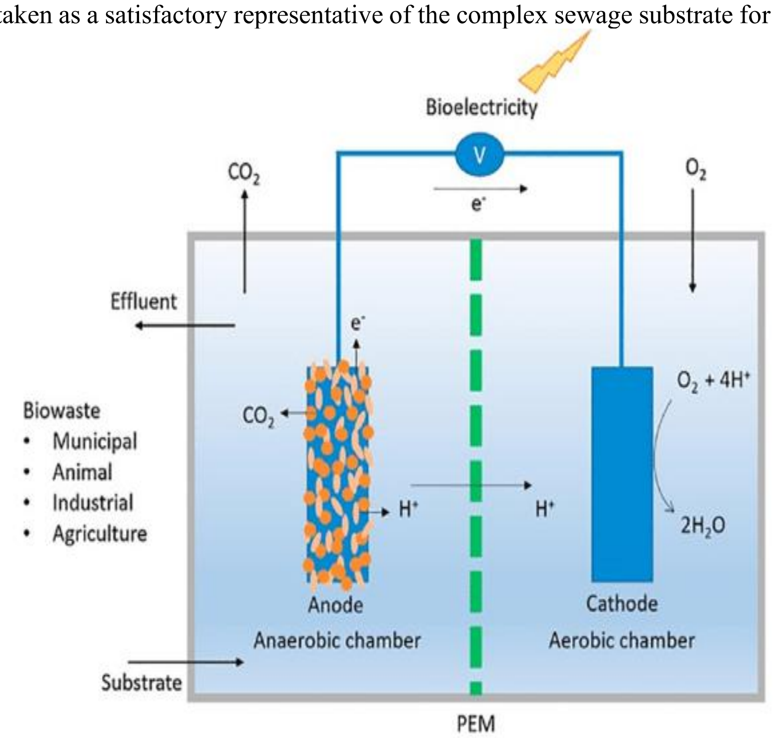


Figure 1. Typical configuration of MFC [7]

$$Anode: CH_3COO^- + H_2O \xrightarrow{Microorganism} 2CO_2 + 2H^+ + 8e^- \quad (1)$$

$$Cathode: O_2 + 4e^- + 4H^+ \rightarrow 2H_2O \quad (2)$$

A variety of organic substances can be used as substrates for microbial fuel cells, such as sewage, agricultural, dairy, food and industrial wastewaters [8].

The major issue with current laboratory scale MFC studies is the use of air cathodes with platinum catalyst or expensive, toxic and hazardous chemical agents such as ferricyanide for electron accepting mechanism. Use of catalysts was permissible for verification of principle feasibility of the method. However, these chemical substances are not sustainable and even impractical for large scale environmental applications [8]. Metals such as aluminium have shown a good potential as electrode materials due to their high conductivity. Bose [9] has reported using aluminium mesh as a cathode in MFCs used for treating food wastewater and the results indicated a 58% removal of dissolved solutes. While a study by Gadhave [10] indicated the use of aluminium electrodes for electricity generation from dairy farm waste such as cattle manure and yogurt waste.. The yogurt waste produced a maximum output voltage of 0.77 V on aluminium electrode compared to 0.173 V when graphite electrodes were used.

There has been substantial progress towards the scale-up and practical applications of MFC technology in the last decade [11]. A pilot scale by Jadhav [12] reported an output power density 1.3 W/m^3 while a scaled up system from Hiegemann [13] generated a maximum power density of 317mW/m^3. Cai [14] developed a pilot scale in the form of bioelectrochemical toilets (BETs) to treat fecal sludge and achieved a maximum power densityy of 465 mW/m^3. Despite these advances in the scaling up of microbial fuel cell systems, However, to date, there are still many obstacles to overcome low power output, which limits the performance to drive electronic devices [15]. Power density is heavily used as a key parameter for describing “electricity generation” in MFCs and is typically calculated in the “watts per square meter” (W/ m^2) as power output over the surface area of an anode electrode or “watts per cubic meter” (W/ m^3) of the reactor volume. Production of higher power outputs that can be expressed in watts is substantial for the commercialization of scaled up microbial fuel cell systems. This study investigates the performance of a modular stacked single chamber microbial fuel cell system using aluminium cathodes and carbon anodes for electricity generation to increase power output which can be quantified in wattage and power electrical appliances such DC bulbs.

2.0 MATERIALS AND METHODS

This section covers the geometry of the single chamber microbial fuel cell (SCMFC), the materials used and the design of the microbial fuel cell pilot power plant.

2.1 Geometry

The electrodes used in the system were carbon rods (diameter 0.8 cm and height 5.6 cm) and aluminium rods (diameter 1.3 cm and height 5.8 cm length) housed in a cylindrical polyethylene terephthalate (PET) casing with a height of 13 cm and diameter of 12 cm. The total volume of the casing was 1liter and the working volume was approximately 800 ml plus 200 ml headspace as shown in Fig 1. Sea sponge pieces approximately (11 cm x 11 cm) were used as separators between anode and cathode electrodes.

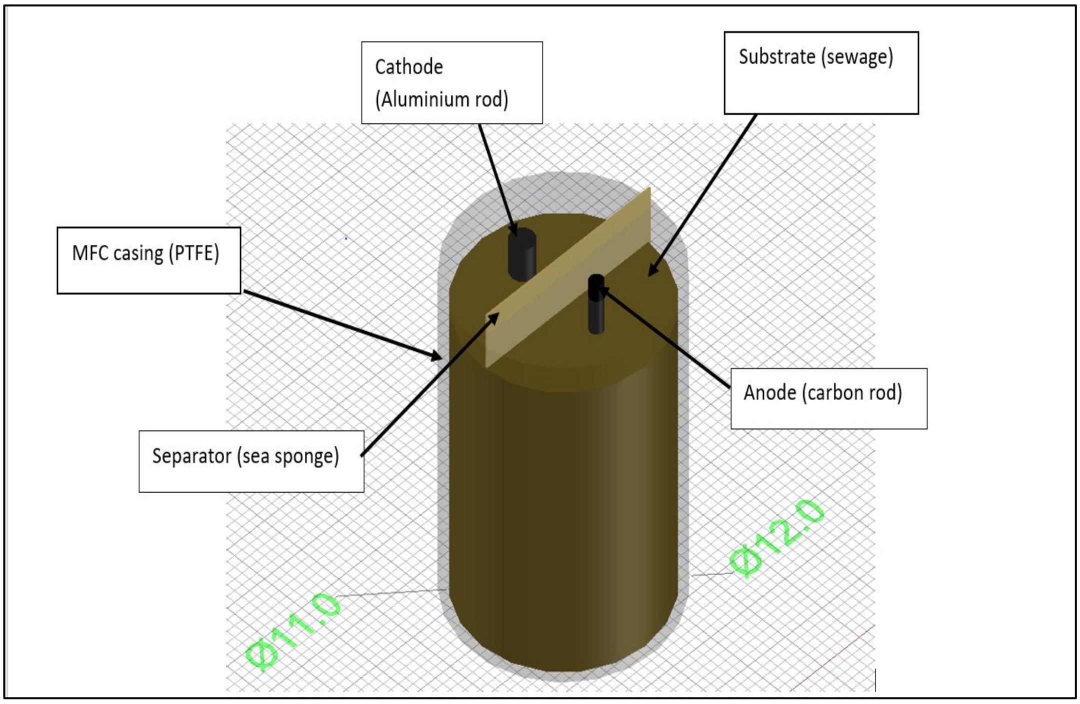
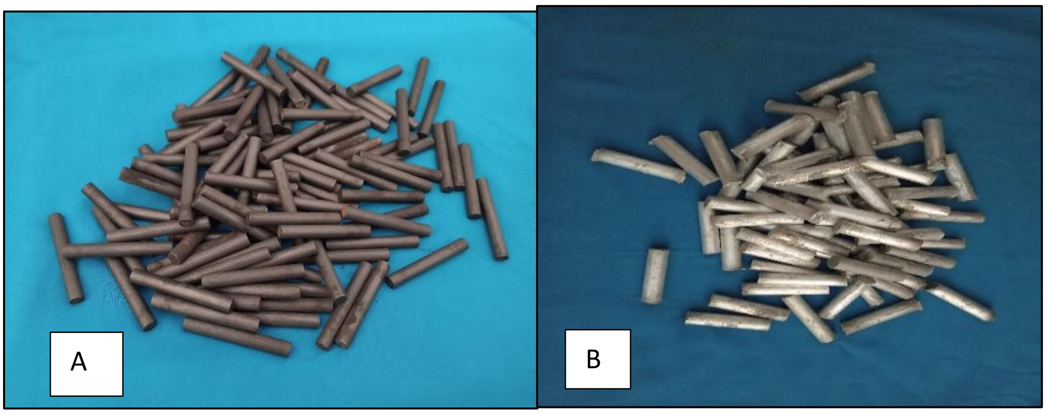


Figure 1: Schematic 3D drawing of a single chamber microbial fuel cell

2.2 *Materials*

Sewage wastewater was used as the substrate due to availability in any part of the world and also with an aim of providing electricity for domestic households. Carbon rods have good biocompatibility, long durability, good conductivity, and low cost. On the other hand, aluminium rods have excellent resistance to corrosion, and can be cast, machined and moulded quickly, exhibit low density and is non-toxic. PET was used for the housing material due to low cost and being non-reactive with substrate. They are readily available in the market or even from waste dumpsites, hence reducing environmental pollution from plastic. Sea sponge portrays good characteristics of a membrane/ separator for MFCs due to high porosity, robustness, chemical stability and good mechanical strength. They also have a wide range of bacteria which are biofilm forming and can be used in bioremediation processes of oil pollution in the oceans. Fig.2 below shows some of the materials used.



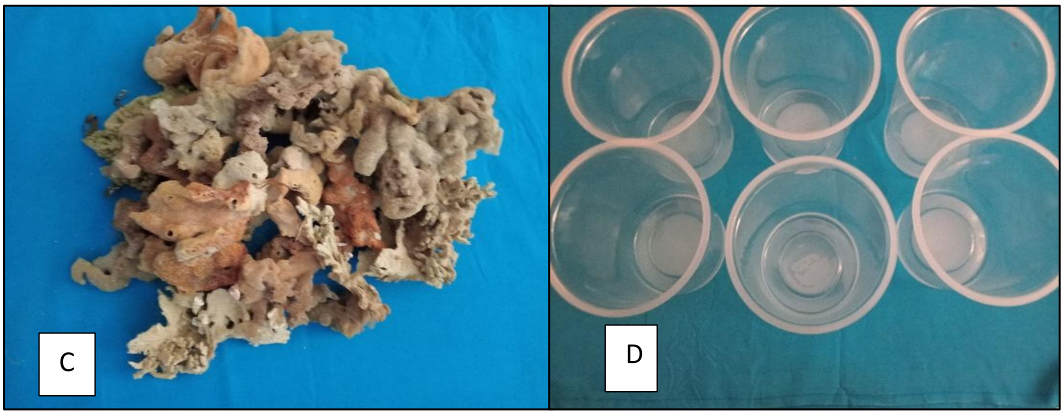


Figure 2: A) Carbon rods B) Aluminium rods C) Sea sponge D) Plastic reactors

2.3 *Experimental Section*

Twenty-four single chamber microbial fuel cells were connected in series to form one module. For the pilot power plant, two modules were connected in parallel to increase the current in the system hence a total of forty-eight cells were used. Sewage from septic tanks was used as the substrate collected from the Jomo Kenyatta University of Agriculture and Technology (JKUAT) staff residential area. The SCMFCs were all operated in a batch-fed mode. The pilot plant was operated to power a 5 Watts DC bulb. The readings for open circuit voltage (OCV) and current were measured for a period of 46 days. The current was measured across an external resistor of 815 Ω. The experiment was conducted at room temperature and pressure. The measurement of voltage and current was done using two digital multimeters, model UK 830 LN and INGCO DM 2002 ranging from 200mV to 600 V, while the current ranges from 20 mA to 10 A. Fig. 3 below shows a pictorial diagram of a 3 W and 5 W DC bulbs powered by the microbial fuel cell pilot plant.

Figure 3: A) 3 Watts bulb (B) 5 W bulb

The following Equations (1-3) were used for calculating power, power density and current density [Singh et al., 2021][15].

$$ID = \frac{I}{A} \qquad (1)$$

$$P = I \times V \qquad (2)$$

$$PD = \frac{P}{v} \qquad (3)$$

Where ID is the current density, I is the current, A is projected surface area of the anode electrode, P is the power output, V is the voltage, PD is the power density and v is the total working volume of reactor.

3.0 RESULTS AND DISCUSSION

3.1 *MFC pilot power plant performance*

The pilot power plant was able to generate a maximum output voltage of 14.36 V (14360 mV) and a maximum current of 3.5 mA and the calculated power output was 49.175 W (49175 mW). Table 1 below shows a summary of the results obtained.

Table 1: Pilot plant output parameters

Parameter	Results
Maximum voltage (volts)	14.36
Maximum current (mA)	3.5
Maximum power output (Watts)	49.175
Maximum current density (mA/m^2)	9.67
Maximum power density (W/m^3)	1281

The obtained results from using carbon rod anodes and aluminium cathodes demonstrated performance improvement in terms of power output obtained compared to other pilot scale projects in other studies which used other cathode materials. Table 2 below illustrate the comparison of power densities obtained from various microbial fuel cell scaled up systems. The highest power density obtained was 125 W/m^3 from the study by Liang et al. using artificial wastewater of 1000 liters volume using activated carbon anode. This study generated a higher power density of 1281 W/m^3, which is almost 10 times fold using sewage wastewater and a working volume of 38.4 liters.

Table 2: Power densities of pilot scale systems of microbial fuel cells

Configuration of MFC	Type of wastewater (WW)	Volume (L)	Anode	Power density W/m^3	Reference
Single chamber	Municipal WW	250	Carbon brush	0.47	[17]
Stack	Brewery WW	90	Carbon brush	0.12	[18]
Stack	Artificial WW	72	Activated carbon	50.9	[19]
Stack	Swine manure	94	Stainless steel mesh	2	[20]
Two chambers	Artificial WW	50	Activated semicoke	43.1	[21]
Stack	Municipal WW	1000	Activated carbon	60	[21]
Stack	Artificial WW	1000	Activated carbon	125	[21]
Stack	Diverse WW	1	Carbon veil	27.4	[22]
Stack	Septic tank sewage	38.4	Carbon rod	1281	This study

3.2 *Performance graphs of pilot power plant*

The output voltage and current produced for the period of 46 days was stable after day 3 onwards. Hence a stable power out can be produced from the microbial fuel cell pilot plant using aluminium cathodes. The open circuit voltage (OCV) on day one was 14.05 V while that on day 46 was 10.89 V. The current measured across an external resistor of 815 Ω on day one was 3 mA and on day 46 was 0.81. On the other hand, the power out on day one was 49175 mW while on day 46 was 8821 mW. The figures 4, 5 and 6 below show the graphs of voltage, current and power output with time. The reduction in voltage, current and power output are due to ohmic, concentration and overpotential losses in the system. The results from the graphs compare well with the study by Bose et al. who used aluminium cathodes in microbial fuel to treat food wastewater and also in the research by Gadhave et al. who used aluminium electrodes to produce electricity in a dual chamber microbial fuel cell.

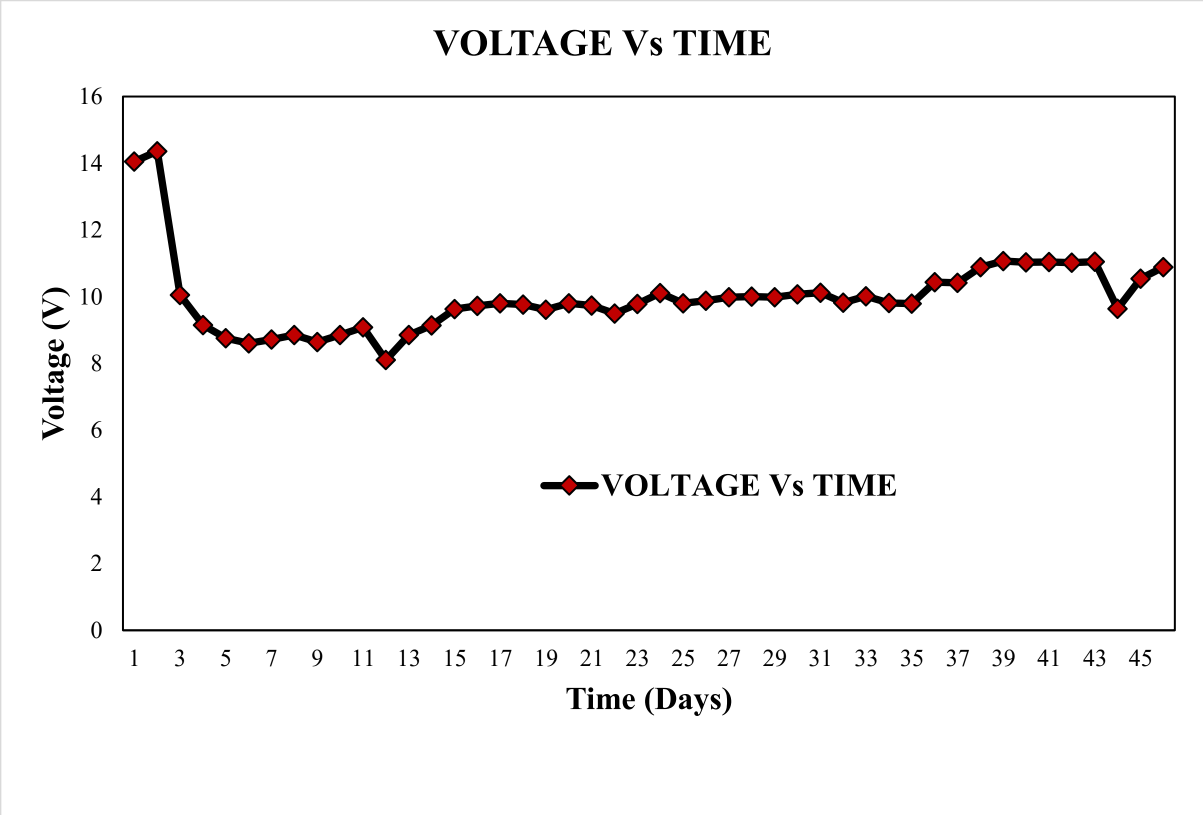


Figure 4: A graph of voltage versus time

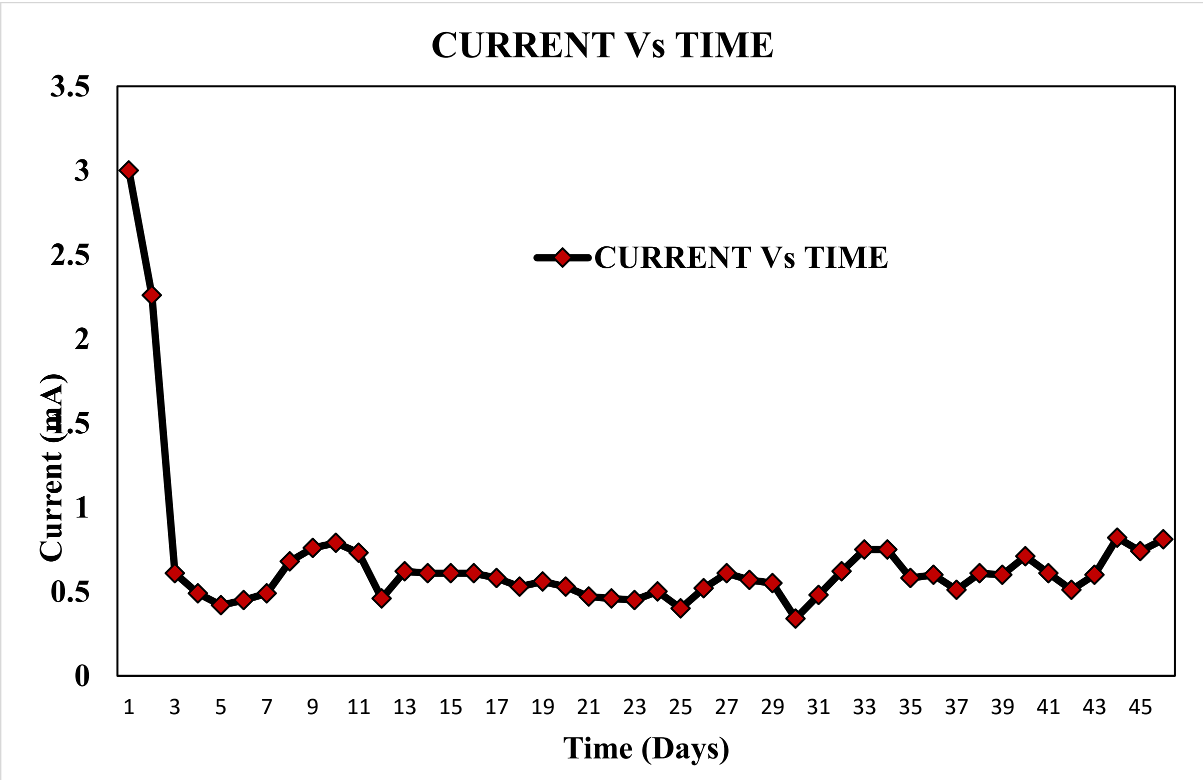


Figure 5: A graph of current versus time

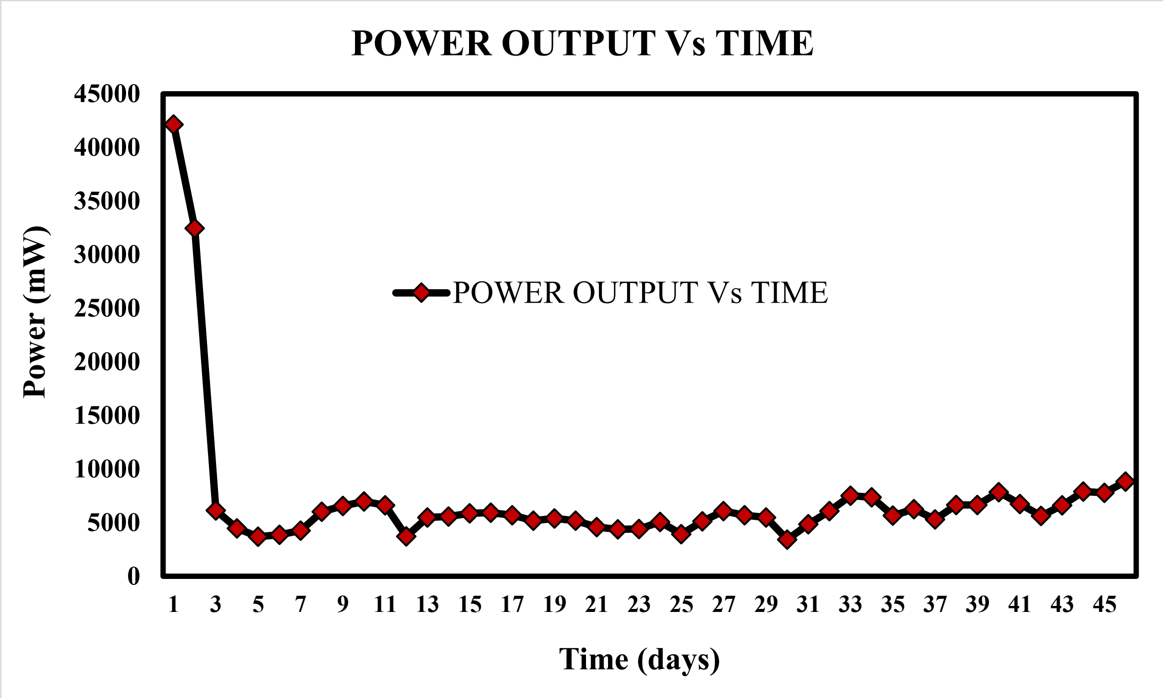


Figure 6: A graph of power versus time

3.3 Cost comparison between pilot scale MFC systems

The performance improvement of microbial fuel cell pilot scale systems does not become successful without taking cost into consideration. Stacking up several modules can increase the construction costs hence hinder commercialization. Table 3 below shows the construction cost of various microbial fuel cells [12]. From the table, the MFC system which costed the least was 720 US dollars from a study by Liang et al involving a single MFC with a volume of 20 liters, while this study demonstrated a lower cost of 40.32 US dollars which is almost 18 times less costly. In this study all the materials were obtained from waste (sewage, sea sponge, carbon rod), except the plastic reactor and aluminium rods. The SCMFC would cost approximately 0.84 USD, hence 48 SCMFCs would cost 40.32 USD for the pilot power plant.

Table 3 : Construction cost of various microbial fuel cell systems

MFC	Volume (L)	Cost (USD)	Reference
2 dual chambers in series	2000	288,910	[23]
1 dual chamber	10	1956.36	[24]
Single MFC	20	720	[21]
18 stacked MFCs	600	3300	[25]
50 module MFC	1000	36,000	[21]
48 stacked MFCs	38.4	40.32	This study

4.0 CONCLUSIONS

A microbial fuel cell pilot power plant was constructed by modularity and stacking of SCMFCs in batch operated mode. Two modules were used in this system, each consisting of twenty-four single chamber microbial fuel cells connected in series to increase the voltage. The modules were then connected in parallel to increase current output of the system. A SCMFC generated a voltage ranging from 0.5 volts to 0.74 volts. A total of forty-eight cells generated a maximum voltage of 14.36 V, current of 3.5 mA, power output of 49.2 W and a power density of 1281 W/m^3. The system was able to power various DC bulbs ranging from 3 Watts and 5 Watts. The impact of connecting several SCMFCs in series and parallel connection would increase voltage and current output of the system hence improving performance of the scale up design to power more devices. On the other hand, concentration losses of the substrate can be addressed by setting up a continuous flow system inside the septic tank chambers. Further research can be done to find ways of increasing the current output in the system for effective commercialization.

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DECLARATIONS OF COMPETING INTEREST

No conflict of interest exists.

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SUPPORT INFORMATION

Table 4: Experimental data for the pilot power plant for a period of 46 days (reactor volume V= 38.4 Liters=0.0384 m^3) and projected surface area of anode electrode for 48 cells (3619.2 cm^2)

Time (Days)	VOLTAGE (V)	VOLTAGE (mV)	CURRENT (mA)	POWER (mW)	POWER DENSITY (W/m^3)
1	14.05	14050	3.5	49175	1281
2	14.36	14360	2.26	32453.6	845.14
3	10.05	10050	0.61	6130.5	159.65
4	9.15	9150	0.49	4483.5	116.76
5	8.76	8760	0.42	3679.2	95.81
6	8.6	8600	0.45	3870	100.78
7	8.72	8720	0.49	4272.8	111.27
8	8.85	8850	0.68	6018	156.72
9	8.64	8640	0.76	6566.4	171
10	8.85	8850	0.79	6991.5	182.07
11	9.08	9080	0.73	6628.4	172.61
12	8.1	8100	0.46	3726	97.03
13	8.85	8850	0.62	5487	142.89
14	9.14	9140	0.61	5575.4	145.19
15	9.63	9630	0.61	5874.3	152.98
16	9.73	9730	0.61	5935.3	154.56
17	9.8	9800	0.58	5684	148.02
18	9.76	9760	0.53	5172.8	134.71
19	9.61	9610	0.56	5381.6	140.14
20	9.8	9800	0.53	5194	135.26
21	9.74	9740	0.47	4577.8	119.21
22	9.5	9500	0.46	4370	113.80
23	9.78	9780	0.45	4401	114.61
24	10.11	10110	0.5	5055	131.64
25	9.8	9800	0.4	3920	102.08
26	9.88	9880	0.52	5137.6	133.79
27	9.98	9980	0.61	6087.8	158.54
28	10	10000	0.57	5700	148.44
29	9.98	9980	0.55	5489	142.94
30	10.07	10070	0.34	3423.8	89.16
31	10.12	10120	0.48	4857.6	126.5
32	9.82	9820	0.62	6088.4	158.55
33	10.01	10010	0.75	7507.5	195.51
34	9.81	9810	0.75	7357.5	191.60
35	9.79	9790	0.58	5678.2	147.87
36	10.44	10440	0.6	6264	163.12
37	10.42	10420	0.51	5314.2	138.39
38	10.89	10890	0.61	6642.9	172.99
39	11.07	11070	0.6	6642	172.97
40	11.03	11030	0.71	7831.3	203.94
41	11.04	11040	0.61	6734.4	175.37
42	11.02	11020	0.51	5620.2	146.36
43	11.05	11050	0.6	6630	172.66
44	9.64	9640	0.82	7904.8	205.85
45	10.54	10540	0.74	7799.6	203.11
46	10.89	10890	0.81	8820.9	229.71