

Performance investigation of Aloe vera plant-based microbial fuel cell using anode constructed of carbonized Ipomoea carnea.

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Abstract

The increasing trend in global atmospheric temperature caused by a spike in atmospheric concentrations of carbon dioxide must be addressed as soon as feasible to avoid approaching the point of zero return. Innovative technologies based on the concepts of plant microbial fuel cell (PMFC) may help in this direction by sequestering CO₂ while creating a massive amount of biomass. In the present study, the Aloe vera plant was employed to generate Cleaner and viable bioenergy in a PMFC. The carbonized *Ipomoea carnea* had a synergistic effect on power production and plant Growth. The highest power output of the PMFC with a carbonized *Ipomoea carnea* anode was 260 mW/m², which was 186.1 mW/m² more than the carbon rod anode. Within 35 working days, high biomass was identified in the carbonized *Ipomoea carnea* anode, allowing for increased generation bioelectricity.

Highlights

- Fabrication of Plant microbial fuel cell (PMFC) using waste material
- Low-cost anode composed of carbonized *Ipomoea carnea* was effectively integrated into a PMFC.
- Power density of 260 mW/m² is one of the best in PMFC studies..

1. Introduction

PMFC is a revolutionary method for producing renewable and sustainable bioelectricity through plant photosynthesis reactions [1–5]. Plants in the PMFC ecosystem use sunshine and CO₂ to make glucose via photosynthesis, a well-known mechanism. A percentage of the glucose produced by the plants is not consumed and is excreted into the soil via root exudates. In the rhizosphere, microbial communities breakdown these Lower-density organic carbon molecules, producing electrons, protons, and carbon dioxide [6–9]. Bioelectricity can be harnessed Place two electrodes over a membrane that is semi-permeable using the redox potential gradient. During PMFC functioning, three types of plants are used: artificial plants, wetland grasses, macrophytes (hydrophytes). Growth rate, microbial variety in the rhizosphere, density, collection, root system, rhizodeposition placement, location availability, and adaptability are all considered when selecting a suitable plant [6–8]. PMFCs operate by inserting anodes into the rhizosphere. Plant roots release a large number of rhizodeposits, which sustain a diversity of microorganisms, bacterial attachments and bacterial functions [8]. As roots differ within and between plant species, and microbial consortia vary in substrate or colonization environment and operational situations, rhizosphere bacterial populations range in PMFC. In PMFC action, a range of bacterial species like *Rhodobacter gluconicum*, *Natronocella*, *Beijerinckiaceae*, and *acetinitrilica*, *Rhizobiales* could be found in the rhizosphere [9–10]. PMFC technology could be a future source of alternative bioenergy that is clean, renewable, green and sustainable, as well as far less expensive than any other type of bioenergy [11–12]. In addition, PMFC has major advantages because it may be coupled with agricultural output without disrupting food production [7]. Furthermore, the PMFC has the ability to expand into innumerable plains that are not suitable for farming, wetlands and so can be transformed into a power plant [13–14].

In urban areas Rapid growth and expansion have led to a scarcity of green coverage, resulting in poor air quality [15–17]. Thus, the diversity of flora that grows in urban areas, particularly indoor and rooftop spaces, can serve as a source of stationary energy from PMFCs, generating live power while also saving the environment [18–20]. PMFC provides various advantages, including, hazardous pollutant removal, electricity recovery, significant biomass recovery from plants while simultaneously sequestering carbon. [19].

Right now, PMFC technology is in its early stages, and bioelectricity generation is extremely limited; nevertheless, due to its size, PMFC has the ability to be an environmentally friendly source of bioenergy in the future. As a result, researchers around the globe continue to work on the growth of PMFC bio-generating power, either through advances in the application of non-chemical catalysts, design, electrode alterations, or long-term energy production capacity. [21–24]. Nonetheless, using bio-based renewable materials as electrodes in PMFC, such as carbonized concrete, corncob, bamboo, rubber, scrap, tyres, and agricultural wastes, might drastically reduce the costs of their installation [25–26]. Wetser et al. [16] showed a A innovative design of a three-chambered flat porous-plate PMFC with one anode and two cathode chambers injected with *Spartina anglica* yields a very high power density of 679 mW/m². Sarma et al. [7] found power of 15 mW/m² using the plant *Epipremnum aureum* in the PMFC paired with the carbon fiber anode and bentonite clay membrane. The internal resistance was 200 Ω. Thakur and Das [8] improved the operation of microbial fuel cells (MFCs) by combining graphite with *Luffa aegyptiaca* anodes.

This work aims to: 1) demonstrate the simplified operation PMFC made from waste in order to demonstrates its viability in additional practical applications; 2) assess the effect of plant species *Aloe vera* with anodes made of carbonized *Ipomoea carnea* on PMFC performance; and 3) to reduce greenhouse gas emissions and boost the bioeconomy.

2. Material and Methodology

2.1. Anode Preparation

Ipomoea carnea, also known as a species of morning glory, was taken from Rajatalab near Varanasi (25.2602° N, 82.8466° E), India. The *Ipomoea carnea* wood was cut into 50 mm pieces and thoroughly cleaned with distilled water to eliminate dirt and contaminants. The cut *Ipomoea carnea* wood was first treated to sunlight drying for one week, and then dried cut *Ipomoea carnea* was carbonized in an air muffle furnace at a steady heating rate of 10°C per minute and a temperature slope of 100–550°C for two hours and after cooling off the carbonized *Ipomoea carnea* wood were stored in polyethylene bags for later experimentations. The *Ipomoea carnea* was chosen as an effective material for the production of the anode because of it being natural, cost effective, easily available, and highly porous with high surface area.

2.2. PMFC Design

Figure 1 depicts a graphical perspective of the PMFC, as well as the actual arrangement. Both PMFC installations were created with a 5-liter polyvinyl chloride box. PMFC was initiated by preparing a chamber with sand of particle size (1–2 mm) taken from the Ganga river, garden soil from Kashi Institute of Technology, and a little amount of dried buffalo dung in the ratio of 5:5:1. The experiment consisted of two configurations. The first used a carbonized *Ipomoea carnea* wrapped in stainless steel mesh as an anode (PMFC 1). The second had merely a carbon rod (85 mm length and 7 mm diameter) as an anode (PMFC 2). In all setups, an aluminum plate measuring 3.5 cm x 3.5 cm x 0.6 cm served as the cathode. Insulated copper wires were utilized to connect the cathode and anode. Aloe vera plants were taken from the Kashi Institute of Technology garden (25°28'4.3608"N and 82°79'25.784"E) and put in both the PMFC and an ambient environment for growth. All trials were carried out in triplicate, and the average values

2.3. PMFC Operation

A multimeter is used to measure open circuit voltage (OCV) and average power twice daily for 35 working days. The polarization experiment was carried out after 24 hours, when the steady state OCV was reached. Ohm's law was used to compute current across resistors from 30 k Ω to 10 Ω . The joule law has been used to define power. The current and power voltages are computed by dividing the current by the anode's overhead area. The plant's weekly growth was observed by measuring its height from the earth's surface to the top, as well as the chlorophyll concentration (A, B, and total) of the leaves. The chlorophyll was utilized to determine the greenness of the leaves, which is proportional to their nitrogen level. Chlorophyll is separated by combining acetone and water at a ratio of 80–20% by volume. Two grams of Aloe vera leaf tissue were put into a 25-milliliter solution of 80% acetone. Filtering was conducted, and the filtrate was placed to a 100 mL volumetric bottle wrapped with aluminum foil to avoid the oxidation of chlorophyll by light. A dual UV-VIS spectrophotometer beam (Perform: Systronics, Model: 2202) was used to measure absorption at 663 and 645 nm. The chlorophyll concentration (A, B, and total) was calculated as a new mg/g weight (F W). Chlorophyll A, B, and total were determined using Manolopoulou's formula [20]. FTIR methods were used to characterize *Ipomoea carnea*. The FTIR (Perkin Elmer) spectra of *Ipomoea carnea* was created in the 400–4000 cm⁻¹ region using potassium bromide pellets. The thermogravimetry analyzer (DTG-60H) with a constant air flow rate of 50 ml/min was used to examine the changes in the chemical and physical properties of *Ipomoea carnea* as the temperature increased at a rate of 10°C per minute. SEM was utilized to determine the surface structure of carbonized *Ipomoea carnea*. Samples are recorded using the FEI Verios 460L Scanning Electron Microscope, which operates at 2 kV and 50Pa. The following investigation (volatile matter, fixed carbon content, moisture quality, and ash content) of *Ipomoea carnea* was carried out in accordance with ASTM guidelines [23]. The final investigation, which included the oxygen (O), hydrogen (H), carbon (C), and nitrogen (N) content of *Ipomoea carnea*, was conducted at the Jagdamba Laboratories in Jaipur, India. A bomb calorimeter (Rajdhani Science - India) was used to determine the calorific value of *Ipomoea carnea*.

3. Results and discussion

3.1. SEM characterization

Surface Morphology of *Ipomoea carnea* was examined using a scanning electron microscope, as illustrated in Fig. 2. The micrograph of *Ipomoea carnea* is made up of thick, rough, heterogeneous, and a rugged morphological structure with no pores [24]. The surface shape of *Ipomoea carnea* provides a broad surface area for enhanced bacterial adhesion during operation[24].

3.2. Thermal analysis of *Ipomoea carnea*

TGA analysis explains *Ipomoea carnea*'s thermal stability (TG and DSC curves). The thermal degradation of biomass is greatly influenced by, functional group stability, crystallinity, amorphousness, particle size, structural behavior, and. The TG curve revealed three key stages of thermal deterioration, as illustrated in Fig. 3. Approximately 10% weight loss in the initial stage (24-92.38°C) suggested the elimination of moisture along with volatile chemicals linked with *Ipomoea carnea*. The breakdown of C-O bonds, C-C, and other core structures of the *Ipomoea carnea* including lignin and cellulose is responsible for approximately 35% of the weight loss of biomass acquired in the second stage of thermal degradation at temperatures ranging from 200 to 350°C. The third phase of thermal deterioration, which happened above 335°C, revealed carbonation reactions that resulted in the development of char residues [25]. The final weight % of carbonized residues in the end the breakdown was discovered to be 12%. The degradation temperature of *Ipomoea carnea* was approximately 480°C. The results were comparable to previous studies [25].

3.3. FTIR spectroscopy of *Ipomoea carnea*

Ipomoea carnea ligno-cellulosic material is made composed of lignin, hemicelluloses and cellulose with different Functional groups in the active region. The FTIR spectrum is utilized to determine the various functional groups (hydroxyl, sulfhydryl, aldehyde, ketone and carboxyl) Fig. 4 depicts the biomolecules of polysaccharides and protein found in *Ipomoea carnea*. The occurrence of amine (-NH) and hydroxyl (-OH) groups across *Ipomoea carnea* was portrayed by a broad band that appeared about 3,800–3,600 cm^{-1} [26]. The transmittance peak at 2,920 cm^{-1} was caused by symmetric and asymmetric C-H vibrations, as well as extending of the aliphatic functional regions of lignin [27]. The stretching vibrations of the nitroso (-N = O) and carboxyl (-C = O) on *Ipomoea carnea* were defined by a peak at 1,625 cm^{-1} and 1,380 cm^{-1} , respectively[25]. The existence of C-O-C functional groupings in the lingo-cellulosic *Ipomoea carnea*, which contains lignin, hemicellulose, and cellulose, was detected at 1,120 cm^{-1} [28].

3.4. Proximate and Ultimate analysis and Calorific value of *Ipomoea carnea*

The *Ipomoea carnea* examination (Table 1) showed a moisture content of 5.10%, volatile matter of 21.87%, fixed carbon content of 65.83%, and ash content of 7.20%. *Ipomoea carnea* contains volatile matter and fixed carbon, which can be utilized to make biochar and bio-oil. The fixed carbon/volatile matter ratio was 1:3. Based on ultimate analysis, components such as C (62.00%), H (8.20%), N (6.00%),

and O (23.80%) were calculated by weight in *Ipomoea carnea* anodes. The H/C and O/C ratios for the *Ipomoea carnea* anode were 0.383 and 0.13225, respectively. According to Sonu et al. [27], An extended lifespan of over 1000 years for this substance with an O/C ratio of 0.2 can be considered suitable for amendment of soil and carbon sequestration. Carbon sequestration occurs when the O/C ratio is smaller than about 0.4. The *Ipomoea carnea* anodes are also effective for soil stabilization. The calorific value of the *Ipomoea carnea* anode was 19.76 MJ per kilogram. As a result, the *Ipomoea carnea* anode is also an excellent solid fuel source.

Table 1
Proximate/ ultimate/ gross calorific value analysis of Ipomoea carnea as the dry weight

Analysis	Components	Quantity
Proximate analysis	Moisture content	5.10%
	Volatile matter	21.87%
	Fixed Carbon	65.83%
	Ash	7.20%
Ultimate analysis	C	62.00%
	H	8.20%
	N	6.00%
	O	23.80%
Calorific value	Gross calorific value (GCV)	19.76 MJ/kg

3.5. Electricity generation

Upon comparing the two systems, the PMC-1 generated greater power, with a peak output of 726 ± 15 mV. This provided that the PMC-1, which comprises carbonized *Ipomoea carnea*, provides a superior alternative to the usage of bacteria in the soil convert organic materials into electricity. The PMFC system took 15 days to adapt to the new surroundings, and power generation increased gradually after the 15th day, peaking at 455 ± 10 mV (PMC-2) on the 24th day. Figure 5 depicts the polarization curve, which is the most effective way to report PMFC performance. The PMFC The split curvature followed an identical pattern in all instances. The polarization curve revealed the PMFC's normal behavior, as its power output grew by lowering external resistance and achieving a higher value, after which Power intensity started to decrease with the present population rise. Table 2 displays the overall performance of the PMFC. The PMFC-1 achieved a maximum power of $260 \pm 5\text{mW/m}^2$ with an internal resistance of 1.44 ± 0.25 . This robust bioelectricity generation can be attributed to good bacterial adherence to the anode, resulting in Cytochrome bacterium form hydrogen bonds with the carboxyl group of carbonized *Ipomoea carnea*. As a consequence, electrogenic bacteria colonizing the anode's surface boost electron

transport through bacteria to the anode. Lower internal resistance is typically a crucial factor in enhancing bioelectricity [12].

Table 2
Electrical results for both PMFC systems.

Parameter	PMFC-2	PMC-1
Maximum Power Density (mW/m ²)	73.9 ± 0.05	260 ± 5
Maximum Current Density (mA/m ²)	0.89 ± 1.5	1.34 ± 0.5
Open circuit Voltage (mV)	455 ± 10	726 ± 15
Internal Resistance (kΩ)	1.75 ± 0.5	1.44 ± 0.25

3.6. The impacts of both light and dark phases.

The data was recorded at regular intervals between the light and dark phases. Regardless of how long the light and dark phases lasted, the amount of electricity produced was consistent. The results are positively associated as reported as Moqsud et al [5]. PMFCs were established demonstrated to be a type of a natural system that includes microorganisms and plants employ basic light and dark phases in an advantageous way to generate using energy sustainably.

3.7. Plant growth

Aloe vera grew well in both PMFCs, with plant length gradually increasing over time (Fig. 6). Plant growth was superior in PMFC 1 in contrast to PMFC 2. Good growth is caused by nitrogen availability, as shown by the presence of high quantities of chlorophyll. The plant in the PMFC-1 had normal chlorophyll A, chlorophyll B, and total chlorophyll levels of 0.05675, 0.08866, and 0.134711 mg g⁻¹ FW, as well as 0.084512, 0.165413, and 0.23085 mg g⁻¹ FW, respectively.

3.8. PMFC component biocompatibility and economy

Unlike standard MFC, The operation of PMFC does not require the use of poisonous, damaging, or hazardous chemicals, particularly during in situ activities. As PMFC materials like electrodes, membranes, and bioreactors are absorbed and do not degrade, They may be recycled following microwave treatment, hot exposure, and chemical treatment [6–10]. Perishable support matrix, electric circuits, and growing plants, however, are simply replaced, discarded and dried. Chen [29] showed that device prices alone accounted for 68.5 percent of MFC typical prices costs, proceeded by electrodes 10 percent, mediator 1.5%, 8.2%, collector and membrane 2.75%. PMFC, on the contrary, can be built simply by placing electrode in a rich biological environment, avoiding the need for costly pesticides and feeding systems. [8]. As a result, it can be predicted that PMFC can capture bioenergy for an additional amount period without the usage of substitutes, making PMFC technology cheaper than standard MFC.

Table 4 is a comparative evaluation of various PMFC under different conditions wherein the Low-cost carbonized *Ipomoea carnea* anode and *Aloe vera* plant were used for the first time in PMFC research.

The performance of this study is very much comparable with others in PMFC research considering the cost-effectiveness of the PMFC setup with a maximum voltage and power production of 726 ± 15 mV and 260 ± 5 mW/m², respectively

Table 4
Comparison of various PMFC performances

Plant Used	Operation time (days)	Membrane Used	Electrode used	Max. voltage (mV)	Max. power density (mW/m ²)	Max. current density (mA/m ²)	Reference
<i>D. braunii</i>	60	Bentonite clay	Carbon fiber	432	12.42	16.23	7
<i>E. aureum</i>	60	Bentonite clay	Carbon fiber	620	15.38	38.46	7
<i>S. anglica</i>	180	CEM	Graphite felt	NA	222	39	11
<i>I. aquatic</i>	40	Gravel	Granular activated carbon - Stainless steel mesh	650	23	NA	31
Rice Plant	110	Soil	Carbon fiber	400	22	31	30
<i>L. minuta</i>	45	Water filter	Carbon felt	700	380	1600	32
<i>Aloe vera</i>	35	Soil	<i>Ipomoea carnea</i> charcoal wrapped with the stainless steel mesh	726 ± 15	260 ± 5	1.34 ± 0.5	Present Study

4. Conclusion

Finally, the efficiency of *Aloe vera* in PMFC with carbonized *Ipomoea carnea* anode for bioelectricity generation was examined. The *Aloe vera* plant with a carbonized *Ipomoea carnea* anode produces a significantly higher output (726 ± 15 mV) than a carbon-powered anode. The carbonized *Ipomoea carnea* anode improves both current and durability significantly. *Aloe vera* growth under PMFC system has been shown to be decent, since the better generation of bioelectricity has no detrimental effect on plant growth. As a result, it is reasonable to expect that biomass and electricity can be produced simultaneously in a PMFC. To improve power output, the PMFC could be built and researched by

energizing individual systems of the PMFC using chemical modifications of carbonized *Ipomoea carnea* anodes in a series-like fashion.

Declarations

Declaration of author contributions

Kumar Sonu: Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Visualization. **Monika Sogani:** Conceptualization, Resources, Methodology, Validation, Writing– review, editing, Project administration, Supervision, Funding acquisition. **Zainab Syed:** Formal analysis, Writing – review, editing. **Karishma Maheshwari:** Formal analysis, writing – review, editing. **Jayana Rajvanshi:** Formal analysis, writing – review, editing. **Nishan Sengupta:** Formal analysis, writing – review, editing

Data Availability

All data, models, and code generated or used during the study appear in the submitted article.

Declarations of Interest

The authors declare that they have no conflict of interest.

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Figures

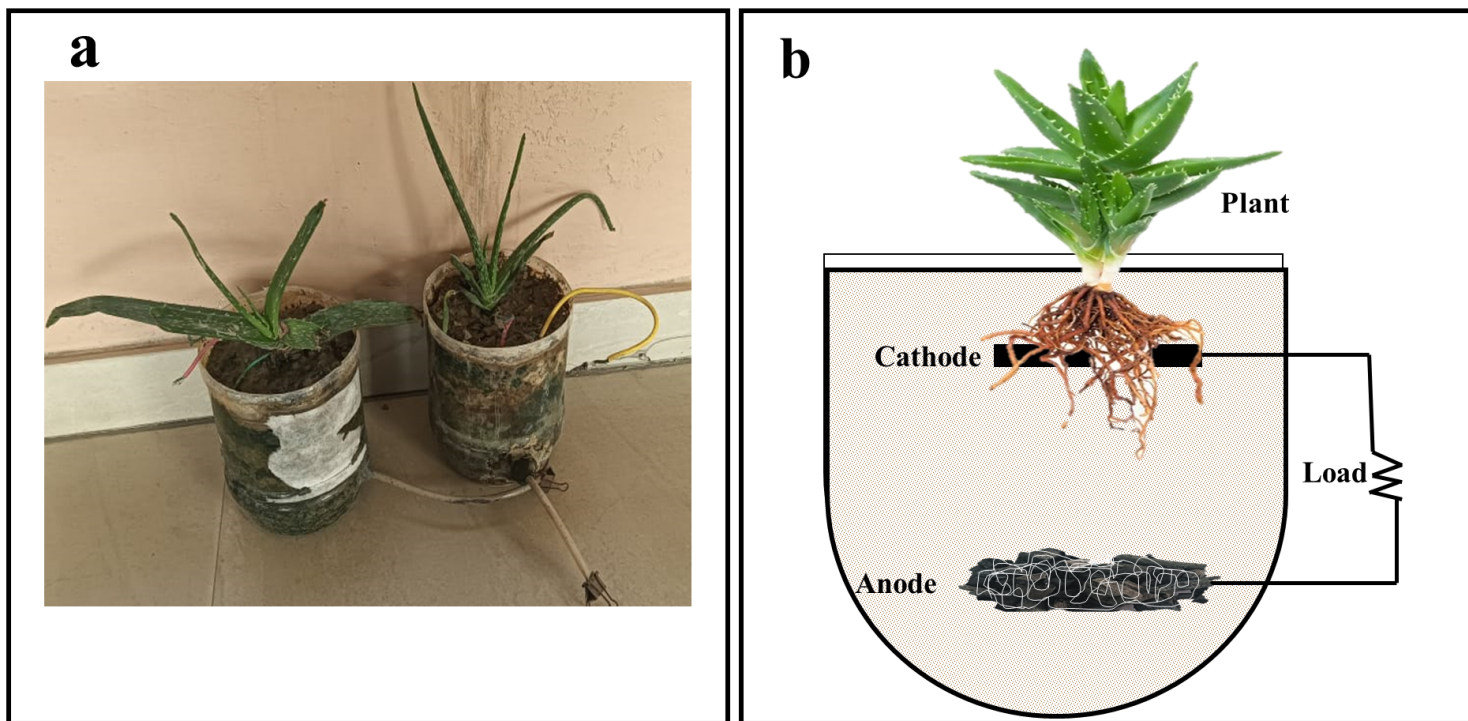


Figure 1

The experimental setup (a) Picture of the real experimental setup, and (b) Schematic diagram of single chamber PMFC setup

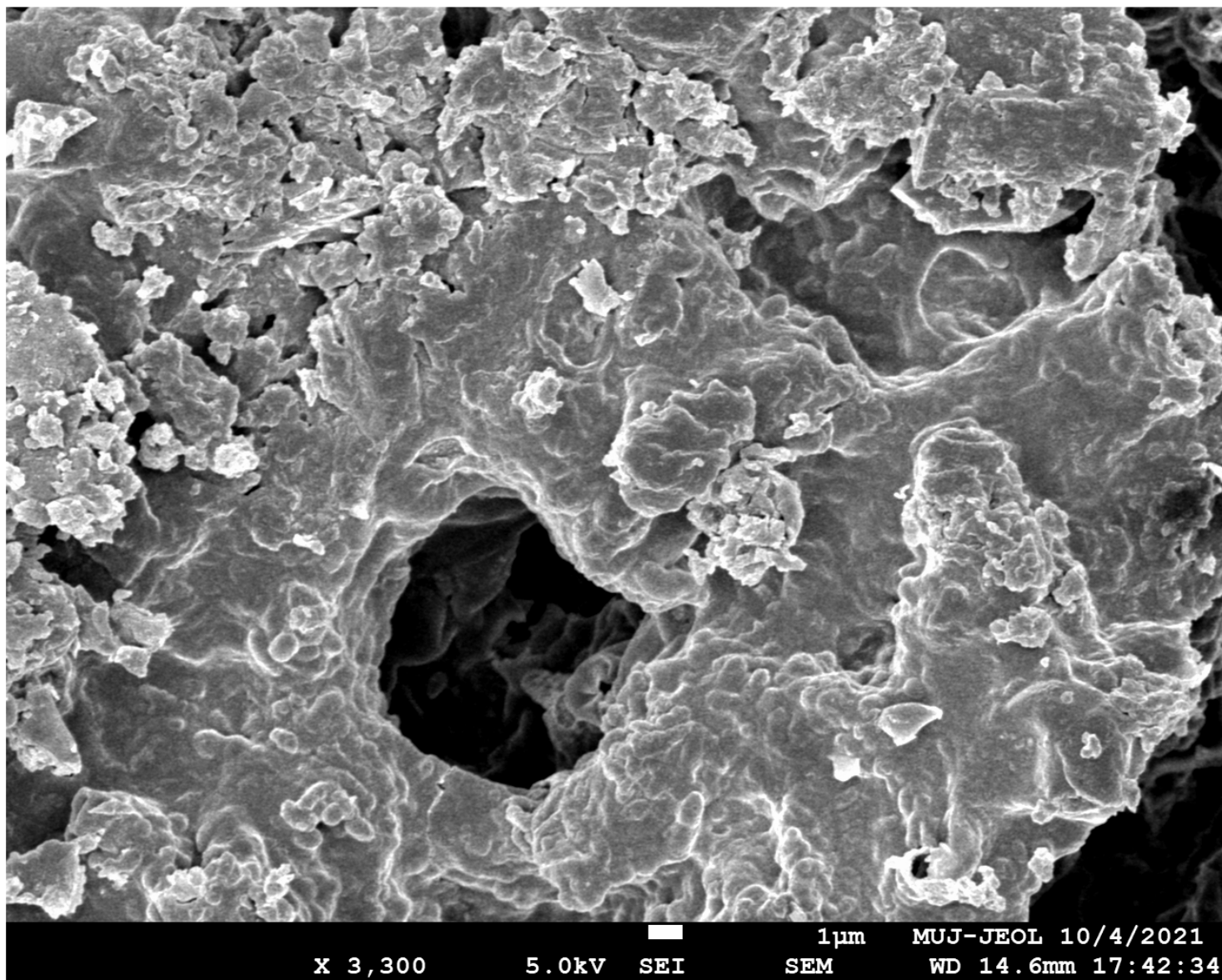


Figure 2

Surface morphology of *Ipomoea carnea*

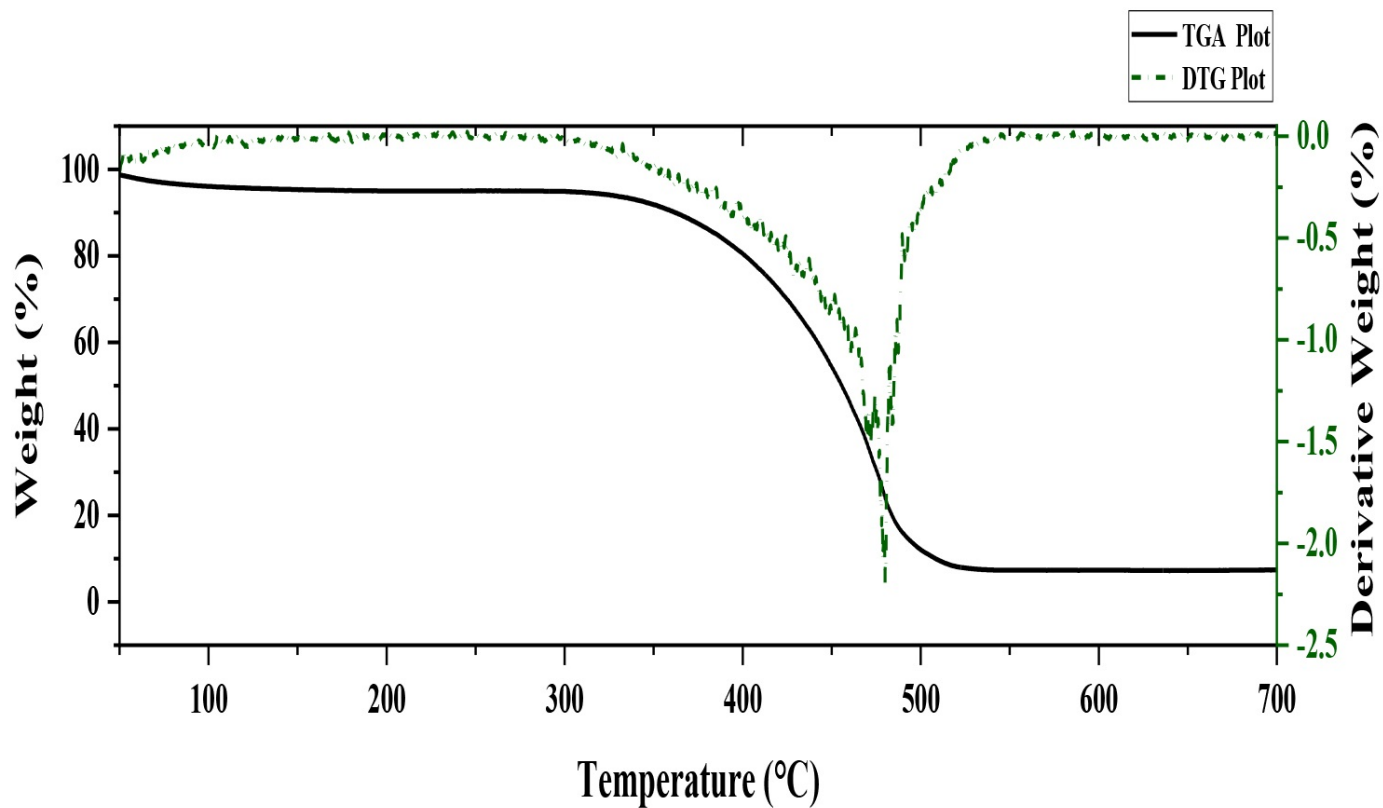


Figure 3

Thermo-gravimetric analysis for *Ipomoea carnea*

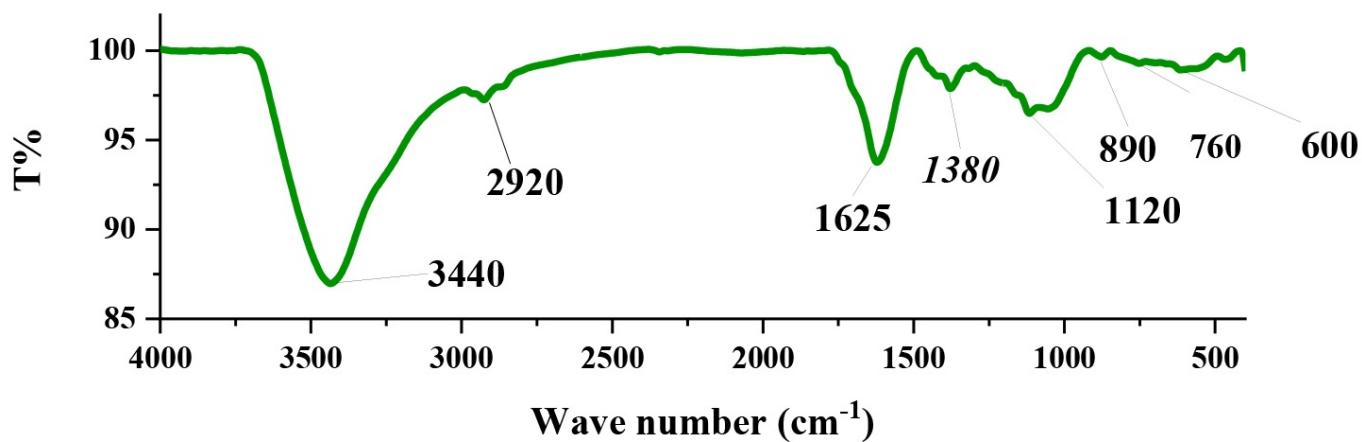


Figure 4

FTIR spectra for *Ipomoea carnea*

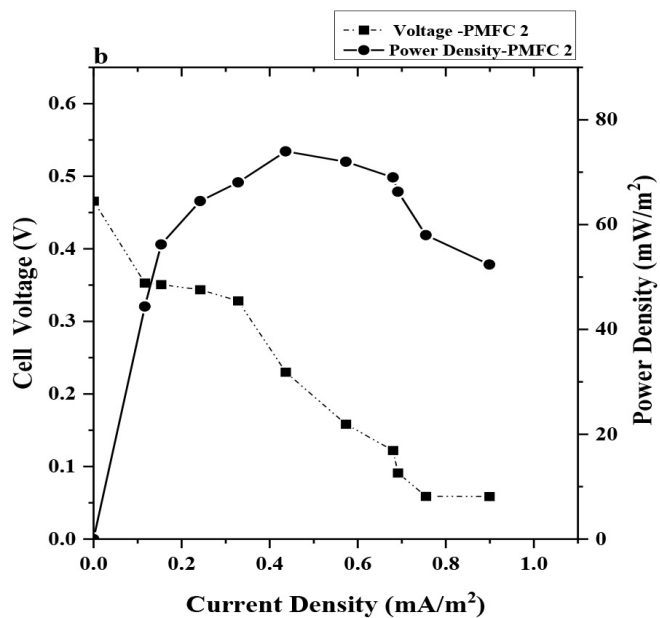
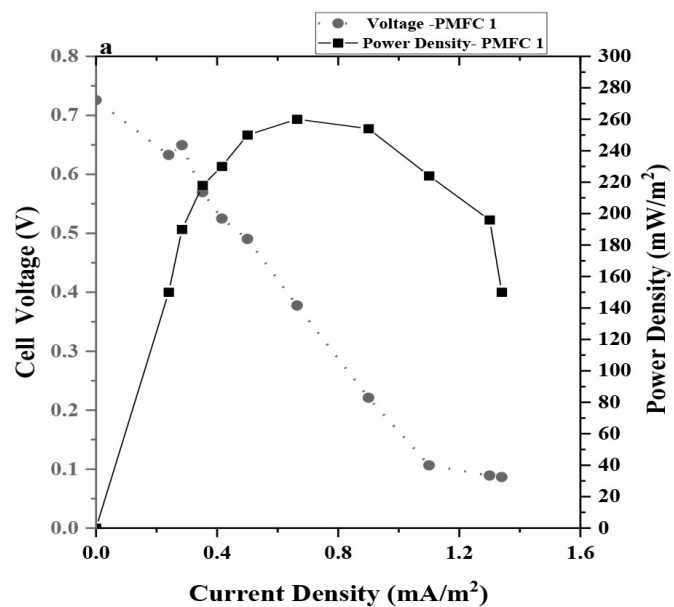


Figure 5

Polarization curve for (a) PMFC 1 (b) PMFC 2

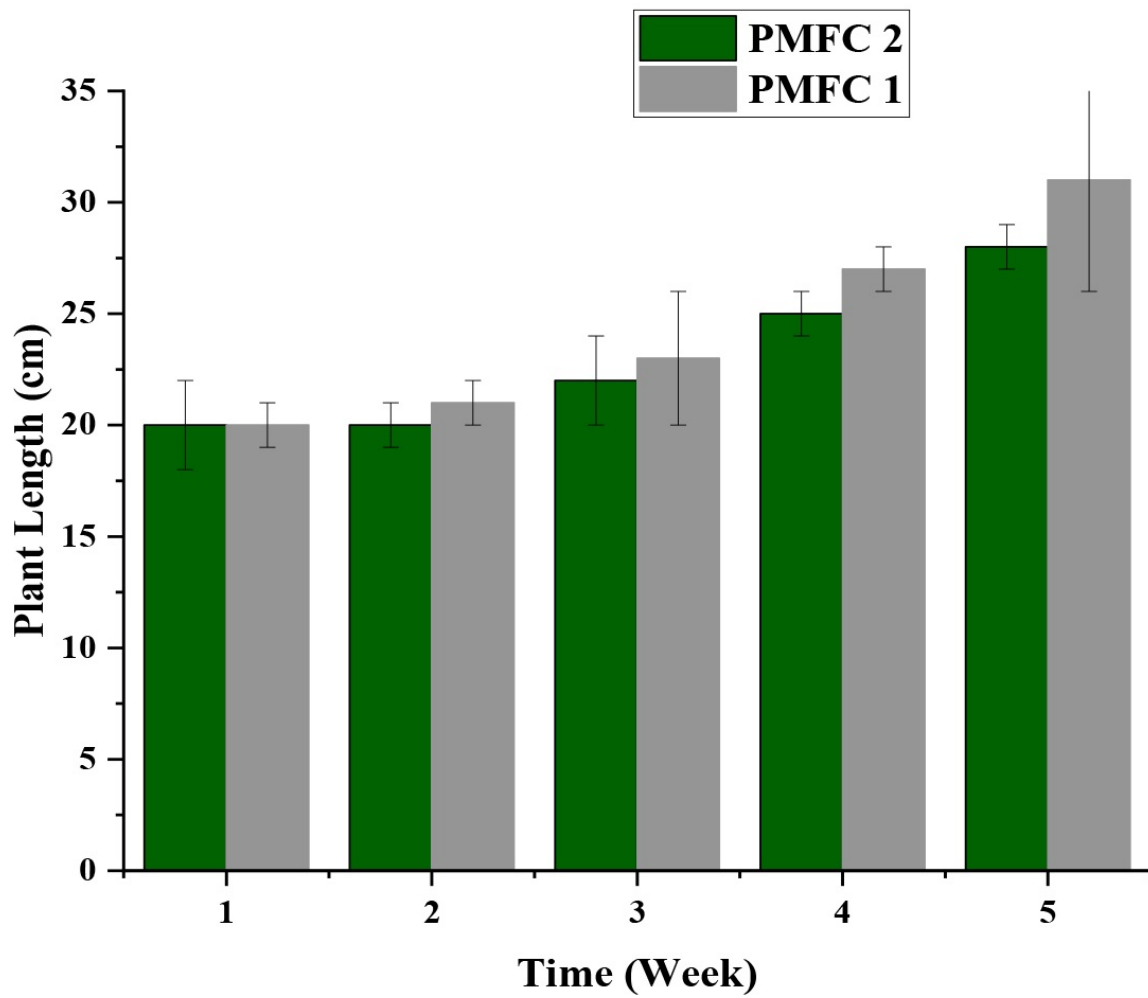


Figure 6

Plant length over time

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [GraphicalAbstract.jpeg](#)