J. Inst. Eng. India Ser. B (October 2023) 104(5):1119–1131
https://doi.org/10.1007/s40031-023-00920-0

ORIGINAL CONTRIBUTION

Innovative Design and Development of Biological Fuel Cell-Based Energy Conversion System

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Received: 29 September 2021 / Accepted: 25 August 2023 / Published online: 23 September 2023

Abstract The article discusses a grass-root innovation in the form of a biological fuel cell (BFC) called the bio-dry cell. The main focus of this research is to address decentralized bio-compatible waste management and electricity generation from kitchen waste. The authors describe the operating concept of the BFC, which utilizes organic waste materials to produce low-level electrical power. The article explores four electrode designs and three BFC sizes to achieve its objectives. The authors conducted a 60-day measurement of the cell's output voltage and investigated the impact of room temperature changes on its performance. The authors have also tested the BFC by connecting multiple cells in serial-parallel configurations to power household appliances like table fans, solar panels, and LED lights. This clean and green energy conversion system aims to provide an alternative energy solution for off-grid areas in rural and urban settings where the electricity supply is limited. According to the testing results, the BFC utilizing organic kitchen waste has been successfully developed and tested. The research findings demonstrate that the BFC effectively manages organic waste and generates electricity for a lifespan of greater than 60 days. It is important to note that while this innovation shows promise for localized energy production and waste management, including considerations for economic viability, efficiency, and integration with existing energy systems. Nonetheless, this grassroots effort highlights the potential for decentralized renewable energy solutions using organic waste as a resource.

Keywords Biological fuel cell · Energy conversion system · Energy server · Green fertilizer · Lantern lamp · Organic kitchen waste · Renewable energy

Introduction

Traditional electrical generating technologies meet most of the 21st century's domestic and industrial energy demands.

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These conventional power plants emit a lot of pollutants, particularly greenhouse gases. Solar, wind, tidal, biomass, geothermal, and hydropower resources have been built to satisfy anticipated power needs. Non-conventional Energy Resources (NCERs) are being deployed without hurting the environment to enhance the power system's sustainability and the economic aspects of energy production. Most research on Renewable Energy (RE) has focused either on solar or wind, or hybrid RE for the dispersed generation with real-world validations [1–3]. This bio-energy uses wood, animal dung, charcoal, and crop waste in cookstoves to meet maintenance issues. However, serious worries exist about their expensive manufacturing, operating, and maintenance costs. As a result of the above, academics and entrepreneurs are focusing more on finding effective ways to generate clean and renewable energy to supplement or replace existing fossil fuels [4, 5].

To satisfy projected energy demand, there is always a need for technological development to capture organic waste's latent energy via the microbial fermentation process. In the Southern United States, [6] has accomplished bio-energy production and predicted a future with renewable energy. This energy uses timber-based bio-energy primarily as a social-technical future for energy and development projects. As a green energy source, soil-based fuel cells have also been created, according to [7]. As a result, organic waste, such as in landfills, where biogas is generated [8]. It is also utilized to maximize the electrical output of a traditional power station. Organic waste-based technology must be created so it can effectively generate electricity from organic waste, according to [9]. Then, given the benefits of an economic and biological approach, it is critical to preserve the efficiency of the generated electricity [10, 11]. The use of biological microorganisms to create significant amounts of renewable energy has been documented. Over the past two decades, Microbial Fuel Cell (MFC) technology has captivated the attention of the scientific and academic communities [12, 13]. This MFC can immediately convert organic waste into energy. It employs microbial-catalyzed anodic and enzymatic electrochemical processes, as mentioned in [14] during power generation by MFCs. To improve the electric-producing efficiency of MFCs, much research has been conducted [15].

The social sciences have successfully handled climate and electrical energy issues, according to [16]. In contrast to earlier suggested techniques, the MFC is regarded as a novel technology. It was created to use easily accessible bioenergy sources (or organic waste) throughout the globe [17]. During the day and at night, this MFC produces self-sustained energy. To be commercialized, MFC-based technology has developed considerable technological advancement in the past decade [18]. Due to its poor performance, the MFC must still be validated for optimum electrical power production [19, 20]. Despite MFCs' low performance, a method for producing self-sustaining electricity from algae growing in the MFC system was presented. The Benthic MFC for underwater sensors and the Floating MFC for signal transmission from water bodies have also been studied as energy harvesting devices.

Handling excessive wet waste generation in cities and towns is a global problem. As a result, [21] described power generation using municipal solid waste techniques while evaluating the value of food waste in biogas energy production. The government of the United Kingdom has made significant expenditures in "fourth-generation" biofuel technologies. The production of greenhouse gases such as methane and carbon dioxide produced by wet waste disposal is a significant issue. It was explained how several municipal solid waste management strategies may help decrease greenhouse gas emissions. By 2035, the electrical power demand is projected to increase to 18 billion tons of oil equivalents, up from the current requirement of 12 billion tons. The International Energy Agency has confirmed this increase in demand. Potter, a British botanist, suggested utilizing bacterial microorganisms to oxidize organic substrates to generate electrical power 1911. The information was provided on energy-efficient technology training and education. The program focuses on lowering energy usage and greenhouse emissions. [22] and [23] have focused on integrating bioenergy with carbon capture and storage to combat climate change.

During the 1980s decade, electron ($e-$) transfer and catalysts were reported to improve the production of electrical power from microbial activities. Researchers are particularly interested in this method because it offers a potential option for energy production that is both green and biocompatible. It has also recommended that enablers be used to help develop the waste-to-energy industry. In 1999, it was investigated that Synechococcus with glucose could be utilized to generate electrical power.

MISCAN, a modeling software tool, can also be used to assess the life-cycle performance of organic wastes. As a result, gasification outperforms power generation. An idea has developed into a technology that has opened a viable path for energy production using biodegradable wastes during the last 10 years, thanks to better electrode materials and techniques. The energy collected is measured in milliwatts per square centimeter, ranging from a few tens to hundreds per square centimeter. Despite its potential, today's realistic MFCs are costly to produce, have low output power, and have long-term performance limitations.

Methodologies for producing electricity are described in the preceding literature. Wood, landfills, microorganisms, electrochemical processes, microalgae culture, and other materials are often used in these methods. The current study looks at the problems of developing the architecture of manufactured BFC in easy stages. The authors substantially improved the output power of the BFC based on its cost-effectiveness and creative design. Furthermore, the research has developed a one-of-a-kind representation for a scalable and economical BFC stack for an autonomous renewable energy system. This article discusses a BFC-based lantern as an example of one of the created cells' applications. The applications are further developed, and BFC is used to power a tiny fan, charge mobile phones, and power street lights. The BFC's electrical power is reliable, clean, cost-effective, and available 24 h a day, seven days a week, as detailed in this article. The method as a whole offers a solution to the existing practical problems with solar-powered lanterns. In addition, the technique can potentially solve India's future energy issues [24] and resolve rare metals disputes to power green energy technologies such as wind turbines and electric cars [25]. Furthermore, as seen in Table 1, researchers have shown clean energy production with variations in the BFC.

The following are the major contributions of this work:

- Biological fuel cell is based on a green energy conversion system.
- A prototype of a Biological fuel cell is developed using organic wastes.
- Economic and technical comparisons are made between Biological fuel cells and Solar cells, and a 12-watt LED is lightened.
- An energy server (power bank) is developed using series and parallel connections of Biological fuel cells and implemented to lighten the street lights.
- The effect of cell size and temperature is observed on voltage developed by the prototype Biological fuel cell.

Figure 1 shows the existing workflow, and the remainder of the article is structured as follows. Section 1 depicts the technical features and research background of the Green Energy Conversion System (GECS). The BFC's prototype development and operating methods are detailed in Sect. 2. Section 3 covers the experimental elements of the BFC, such as organic waste collecting and processing, electrode technology with a catalyst layer, BFC constriction, and electricity measurement in produced BFC. Section 4 discusses the experiments on BFC using produced electrical energy. This section shows a BCD-based electric lantern lamp, a solar-BFC hybrid electric lantern, a series–parallel BFC configuration for generating improvements, and a street light system. The experimental findings, discussion, and general conclusion are given in Sects. 5 and 6, respectively.

Table 1 An overview of previously published work

S. No.	Electricity is generated using this medium	References
(1)	Sludge and waste from sewage treatment plants	[26]
(2)	Solid waste generated by municipalities	[27]
(3)	Woody biomass and yard waste	[28]
(4)	Biodegradable waste	[29]
(5)	Sewage from the dairy industry	[30]
(6)	Food waste and municipal wastewater	[31]
(7)	Kitchen trash that is organic	Proposed work

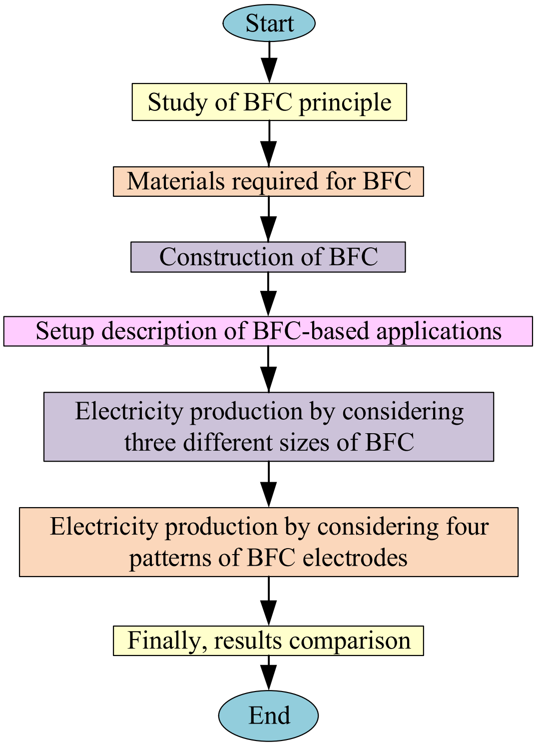


Fig. 1 Flow chart of research work performed

Biological Fuel Cell Electricity Production

The following subsections explain the basic operation, architecture, and mathematical notation of a BFC.

Basic Principle of Biological Fuel Cell

The BFC's operating concept is quite similar to that of the MFC. A BFC usually has a two-electrode design, with an anode and a cathode [32, 33]. The redox process occurs at the anode, where organic materials and biocatalysts like bacteria generate protons & e^-s. The reduction of atmospheric oxygen occurs as catalysts on the cathode, producing water and electricity. BFCs may extract metals and nutrients from industrial effluents and handle municipal or household waste. Two kinds of MFCs exist in the market [34].

1. Dual chamber MFCs and
2. Single chamber MFCs

Figure 2 depicts a schematic representation of the MFC for energy production. A simple sandwich arrangement is compromised by a cell in a microchamber. The anode, cathode, and potential difference cause the voltage the cell produces. In a Fuel Cell with Proton Exchange Membrane (PEMFC), a proton diffusion layer operates at low temperatures, typically below 90 °C, and is usually supplied with oxygen on the cathode electrode and hydrogen on the electrode surface. Other uses are being developed, including transportation and fixed and portable electrical power generation. As a result, researchers are drawn to this field to do study. The optimum theoretical potential for each electrode may be calculated thermodynamically using the Nernst Equation (1).

$$V^{\theta'} = V^{\theta} - \frac{R_g T}{zF_c} ln(\pi) \tag{1}$$

Where

- Under the experimental conditions, the theoretical voltage generated is $V^{\theta'}$
- V^{θ} is the standard voltage
- The ideal gas constant is R_g
- T denotes the temperature of the reaction
- The number of e^{-}s exchanged throughout the reaction phase is given by z
- F_c is Faraday's constant
- π is the product's chemical activity divided by the reactant's chemical activity

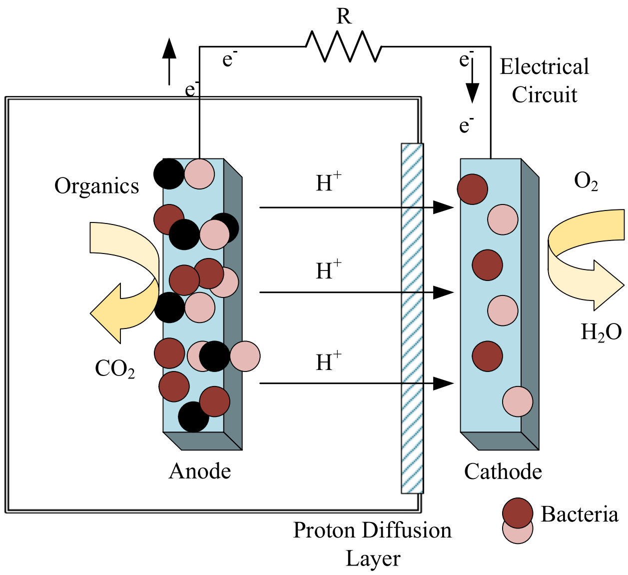


Fig. 2 A schematic representation of BFC for electricity generation

Due to the variation in experimental conditions, the estimated voltage $\Delta V^{\theta'}$ $(= V^{\theta'}_{cathode} - V^{\theta}_{anode})$ is lower than the theoretical value $(\Delta V^{\theta} = V^{\theta}_{cathode} - V^{\theta}_{anode})$ due to the variance in experimental circumstances. Due to irreversible reactions and processes, lesser voltage is produced in practice than is thermodynamically feasible $(\Delta V^{\theta'})$; thus, the actual cell voltage of a BFC may be calculated using Equation (2).

$$V_{cell} = \Delta V^{\theta'} - \sum \eta_i = \Delta V^{\theta'} - (\eta_c + \eta_{\Omega} + \eta_{\alpha}) \tag{2}$$

Where $\Delta V^{\theta'}$ represents expected voltage under real-world circumstances, η_c represents concentration loss, η_{ω} represents ohmic loss, and η_{α} represents activation loss. A high-energy catholyte with a high redox potential must be utilized to enhance bio-electrical efficiency. The improved BFC may also be designed to exaggerate the kinematics of the electrochemical processes.

Configuration of Developed Biological Fuel Cell

The BFC was constructed and tested using low-cost materials as part of the study. It is planned to test empty sweet box containers, stainless steel mesh with steel nut bolts as an air cathode, loose Granular Activated Carbon (GAC) as a catalyst, and aluminum mesh with nut bolts as an anode. To make a bio anode and biocathode, both the anode and cathode are covered with clay mud. During the six months of experimental testing, the cell generated stable voltage and current. Its price per watt of energy generated is excellent compared to high-cost membrane dual-chamber MFCs with the same rating. It's also worth noting that the BFC technology does not need the employment of any adhesives, such as Polyvinylidene fluoride, resins, chemical glues, or bonding materials, for the production of air cathodes and anodes, which are presently utilized by researchers and manufacturers all over the globe.

Figure 3 shows the blueprints of the various layers in the fabricated and fully completed BFC. The BFC is made up of five distinct functional layers that are encased in a brick-shaped microchamber. The granular activated carbon diffuser layer is the top fifth layer. The oxygen cathode, which is made out of stainless steel mesh, is the fourth layer. The third layer of GAC serves as a catalyst layer underneath this. Dry organic waste makes up the second layer of the developed BFC. The bottom layer comprises aluminum mesh that serves as an anode. In a sandwiched arrangement, all of the constituent layers are precisely aligned. Two terminal blocks, inserted into the holes of the microchamber, link the

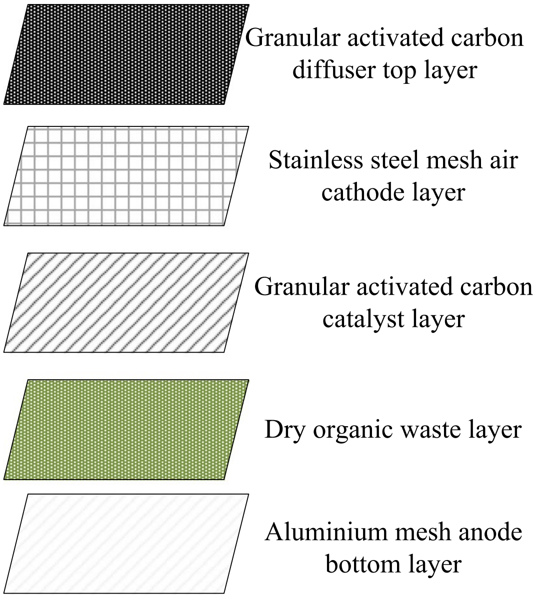


Fig. 3 Schematics of the individual layers used in the developed BFC

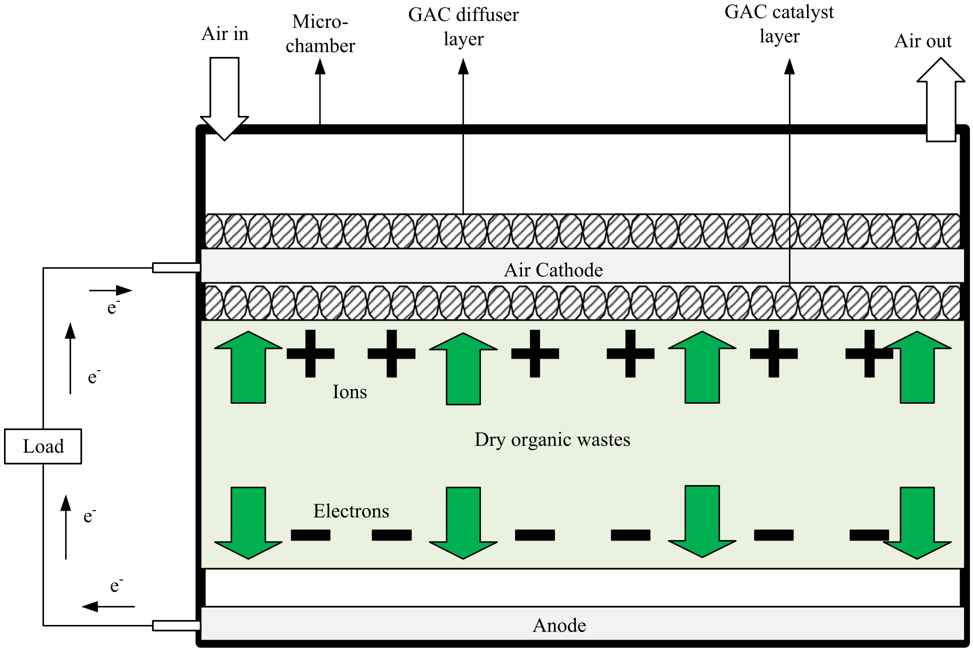
anode aluminum mesh and the air-cathode stainless steel mesh to create an electrical positive and negative output.

In the microchamber, the upper side of the air cathode has space for free oxygen. This design secures and maintains free air within the microchamber to sustain the chamber's moisture level. The oxygen trap can maintain the carbon dioxide, oxygen, and nitrogen metabolic activities produced. The generated air bubbles are designed to adhere to the lid of the micro-top chamber. Unlike other two-chambered MFCs, the BFC uses an air cathode. Free oxygen may serve as a e^- receiver at this cathode. This article develops a brick-shaped microchamber. The BFC is a single-chambered cell, unlike dual-chambered MFCs, bio-solar cells, or biological cells with a sandwiched configuration, as illustrated in Fig. 2.

The anode and cathode are positioned upright to maximize the collection or capture of microorganisms' energy (face-up). For bacterial attachment or e^- coupling, on the other hand, thin aluminum mesh materials, which are excellent conductors, may be used as the anode instead of expensive noble-based materials or graphite electrodes. The produced hydrogen ions (H^+) and protons (H^-) pass via GAC's catalytic layer to the air cathode stainless steel thin mesh, where oxygen is used as a e^- acceptor. Furthermore, the cell is built with a closed system to prevent air from leaving or contaminating it. The cell's open air must be confined to a designated region. A semi-transparent body is used to create an airtight seal. Through photosynthesis and respiration, the bacteria store the carbon dioxide and oxygen generated. These open-air bubbles provide for better gas exchange and moisture retention in the bacterial biofilm on the anode, allowing for long-term operation. Figure 4 shows the proposed BFC's operating concept.

The free air bubble is trapped, which improves device performance by adversely influencing power production. It becomes more helpful since it usually occupies much chamber space and obstructs bacteria development and subsequent e^- transmission. Low-cost technologies developed and innovated in the United States have substantially improved the power density of the BFC. With all this, a

Fig. 4 Principles of operation of biological fuel cell



fundamental step has been taken toward creating a generic BFC stack architecture.

Experimental Descriptions of Biological Fuel Cell

Biodegradable Waste

The biodegradable garbage from the homes was collected and treated with microbe inoculums in a domestic-sized pedal-operated trashcan. It was stored for 30–45 days for fermentation. After that, 0.2 kgs of dry biodegradable waste and 0.050 kg of wet biodegradable waste were used to make the low-moisture electrolyte. The anode is a thin aluminum sheet with a dimension of 10 cm × 15 cm × 0.02 cm. In comparison, the cathode is a stainless steel mesh with a thickness of 10 cm × 15 cm × 0.02 cm, and GAC of 0.4−0.7 cm diameter as a catalyst and diffuser layer has been chosen for the current collector [34]. Repeated fermentation processes under aerobic conditions were used to extract the liquid bio-fertilizer from the collected organic waste. For the collection of kitchen trash, a pedal-operated dustbin is utilized.

Electrodes with Catalyst Layer

The anode is made of aluminum mesh with a thickness of 0.02 cm, the cathode is made of stainless steel mesh with a thickness of 0.02 cm, and the catalyst layer is made of GAC with a 0.4−0.7 cm thickness. The aluminum mesh electrode, GAC, and stainless steel mesh electrode layers used in the recommended BFC-based GECS are shown in Fig. 5.

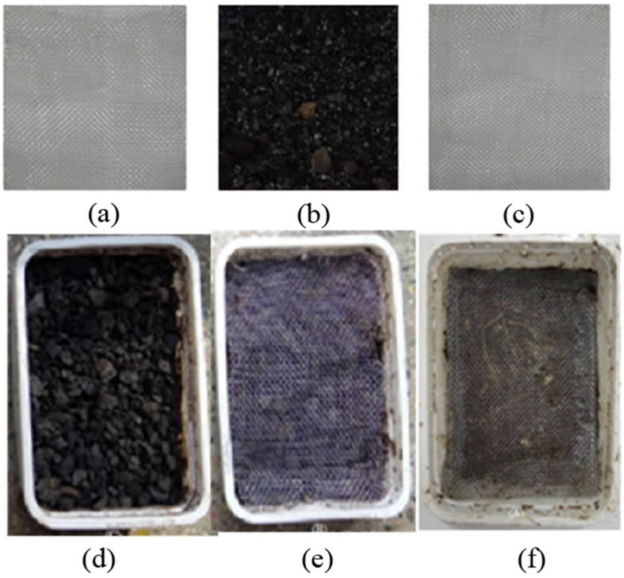


Fig. 5 **a** Aluminum mesh electrode, **b** granular activated carbon, **c** is a stainless steel mesh electrode for BFC development, **d** anode, **e** is a cathode and **f** granular activated carbon experimental configuration

Architecture of Biological Fuel Cell

A top cover or enclosure was included with the BFC, which consisted of a brick-shaped leak-proof microchamber. The experimental BFC measures 13 cm×10 cm×4 cm in size. In the microchamber, two electrodes of approximately 10 cm^2 each and a GAC layer of 1 cm thickness were inserted with terminals. Figure 5 depicts the experimental configuration of the anode, cathode, and GAC. 0.2 kg of well-degraded waste was prepared and placed in the small chamber. The specifications of the bottom layer of organic wet waste in the microchamber and the top layer of organic dry waste in the microchamber are examined during the tests.

Detection of Electricity in Developed Biological Fuel Cell

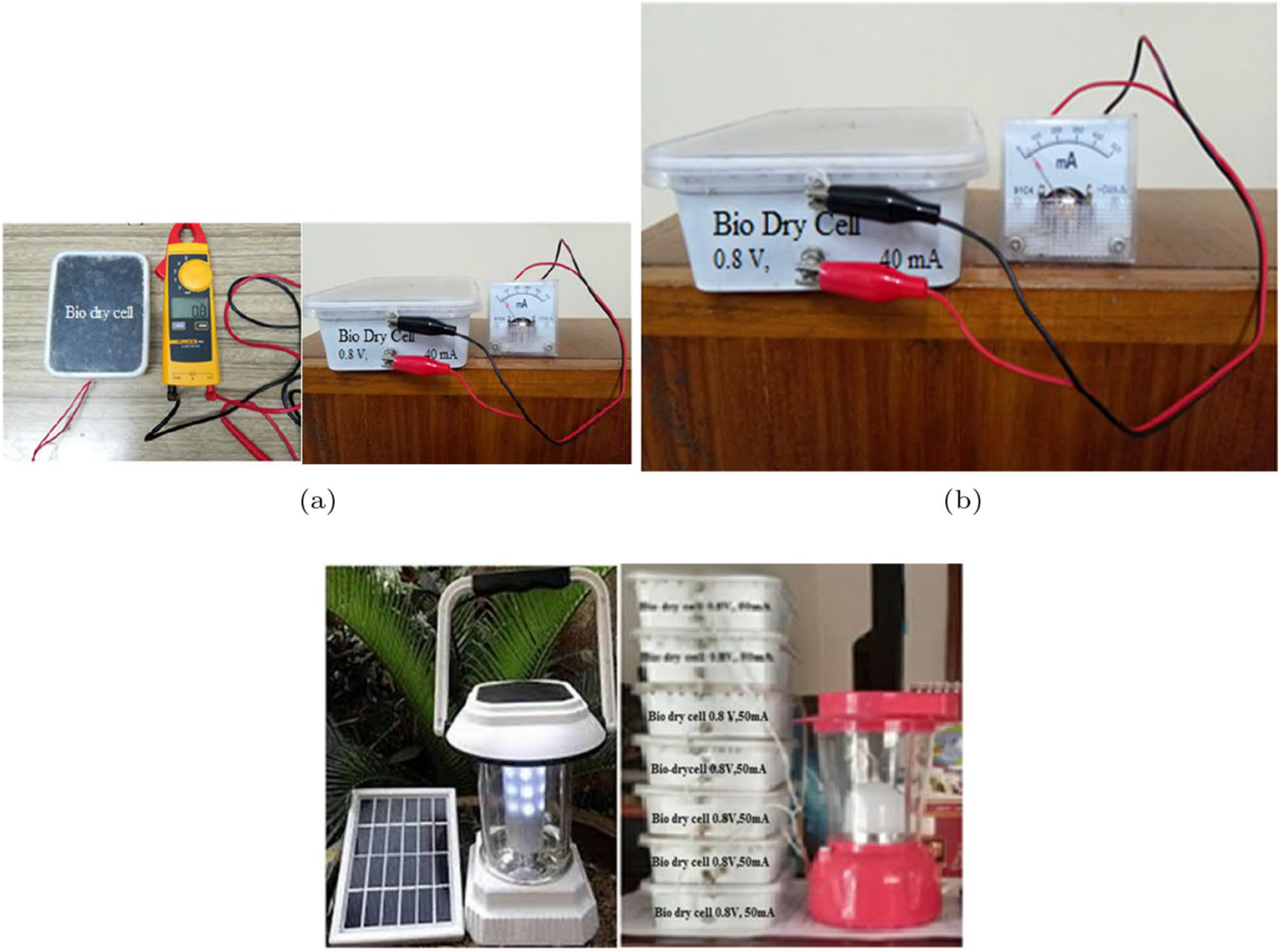
The test specimen (a well-sandwiched layer of BFC) is put in the brick-shaped microchamber. Measurements of electrical characteristics are used to evaluate the cell's bio-voltaic conversion capability under real-time environmental circumstances. Figure 6 shows the experimental setup and the measurement equipment. By collecting the energy produced, each cell of 13 cm × 10 cm × 4 cm size generates a maximum output power of 90×10^{-3} W. This energy comes from the naturally arising microbial decomposition of organic-rich materials like municipal hard waste, agriculture by-products, and so on. Section 4 addresses the produced and measured voltage and current values.

Experimental Analysis on BFC

Figure 6a depicts the developed BFC's no-load terminal and Open-circuit (OCV) Voltages' response. The OCV (V_{oc}) rises rapidly to 0.9 V in a fraction of a second after measuring the instrument selection knob at the voltage range. Figure 6a depicts the BFC's short circuit current (SCC) I_{sc} density response.

BFC-Based Lantern

The current invention pertains to a lantern light, specifically an LED lamp that uses a hybrid bio-solar energy source. This innovation offers an energy alternative for rural and metropolitan regions without access to power. A BFC-based lantern is a hybrid set with a primary BFC unit, a free energy producer or server, and an LED light



(a)

(b)

(c)

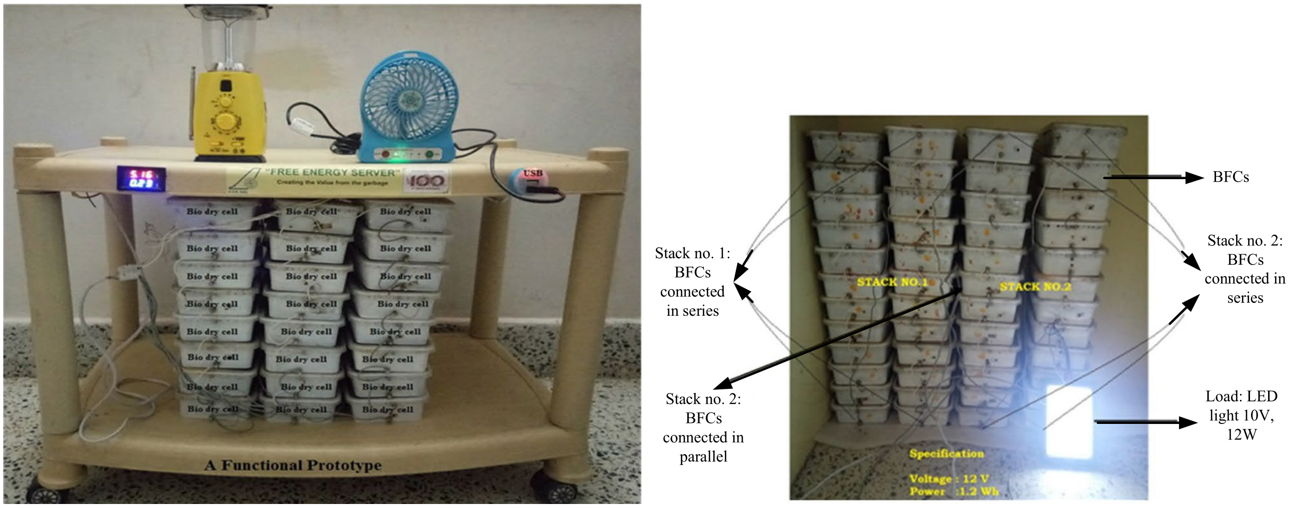
Fig. 6 The BFC was tested for **a** no-load terminal voltage (mV) and short circuit current density (mA), **b** the BFC-based Lamp, and **c** a comparability among solar and BFC-based energy servers and lantern lamps

with inverted solar cells. The suggested BFC-based lantern system gathers energy from organic-rich things such as wasted food, manure, plant waste, and other organic-rich materials and refills the lantern's lighted portion of light energy. This invention aims to provide those who live in poor, rural, or off-grid regions with reliable power. The BFC-based lanterns are best suited for isolated areas where there is no access to electricity. The schematic is shown in 6b.

Table 2 Comparison between solar and Biological Fuel Cell-based energy server and Lantern Lamp

S. No.	Comparisons	Solar-based Server	BFC-based Server
1	Voltage and Current ratings	Rating: 6V, 50 mA	5.6 V, 50 mA
2	Power	300 mWh	280 mWh
3	Cost	$3.96	$3.30
4	Placement	Only for outdoor	For outdoor and indoor
5	Time Interval	It provides energy for 8 hours each day	Serves energy for 24/7

There are eight BFCs in the established system. Each BFC has a capacity of 0.8 V, 0.12 A and generates a maximum output power of 90×10^{-3} W in each cell of 13 cm × 10 cm × 4 cm dimension. The microchambers are linked in a stack known as the Free Energy Server. The accessible energy server and the inverted solar cell-based LED lantern are electrically connected to form a hybrid set, as shown in Fig. 6c. The comparison between a solar and BFC-based energy server and a Lantern Lamp is seen in Table 2. Furthermore, to generate 1 kWh of energy for a living room, a succession of BFCs was necessary. However, since the series connection is impractical for many BFCs,



(a) (b)

Fig. 7 **a** Series–parallel BFC configuration for increased generating capacity; **b** Series–parallel BFC configuration for LED load

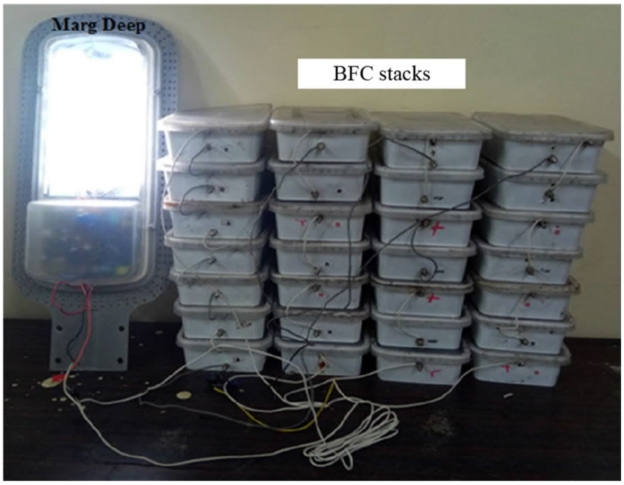


Fig. 8 Series–parallel arrangement of BFC for a power bank to supply street lights

the series–parallel hybrid is used, as described in the next paragraph.

Biological Fuel Cell Powered Domestic Appliances

For generating capacity improvements, the series–parallel configuration of BFC is illustrated in Fig. 7a. High power is required for residential uses. BFC is linked in series to improve voltage output, and three such series strings are connected in parallel to boost current density to accommodate household loads for output power increases. As illustrated in Fig. 7b, 12 BFCs are linked in series to enhance the output voltage, and four series strings are connected in parallel to boost the energy server's current supply capacity. This designed server provides a 12 V, 10 W LED load for residential applications.

Biological Fuel Cell-Based Street Light Systems

The evolved BFC's series–parallel configuration is also utilized for street lighting, as illustrated in Fig. 8. To provide a steady supply to the street light system (labeled "Marg Deep" in this work), seven BFCs are linked in series, and four similar strings are connected in parallel in this application. Figure 8 depicts the power bank of the series configuration of BFCs. There are 28 BFCs in this configuration. Figure 8 illustrates that this method is prepared for street light delivery.

BFC Versus Photovoltaic System

When comparing the scalability and bulkiness of BFCs with solar panels and inverters, there are the following factors to consider:

1. Scalability

- BFCs can be relatively scalable, allowing for the addition of more cells to increase power output. However, scaling up BFC systems may require significant space and resources to accommodate larger volumes of organic waste and microbial cultures.
- Solar panels are highly scalable. Multiple panels can be connected in an array to increase power generation capacity. Solar farms can cover large areas

and generate substantial electricity by adding more panels.

2. Bulkiness

- BFCs typically have a bulkier design due to the need for chambers, electrodes, and other components. The brick-shaped microchamber mentioned in the previous discussion may have a compact form factor compared to some other BFC designs, but it may still be relatively larger and require space for installation.
- Solar panels are generally thin and flat, with a slim profile. They can be mounted on rooftops, installed on open land, or integrated into building materials, minimizing the physical footprint.

3. Base Rating

- The base rating of a BFC depends on factors such as the size, number of cells, and specific design and configuration. BFCs typically operate at lower power levels compared to solar panels and inverters. The base rating of a BFC may range from a few milliwatts to a few watts.
- Solar panels and inverters are commonly used in photovoltaic systems. The base rating of a solar panel and inverter combination can range from a few watts to several kilowatts or even megawatts, depending on the system size and requirements.

Further, the BFCs generally have scalability and power output limitations compared to solar panels and inverters. Solar panels offer greater scalability and higher power generation potential, making them suitable for various applications, from residential to utility-scale installations. However, BFCs may still have their niche applications, especially for decentralized energy generation and waste management in specific contexts where organic waste is abundant and easily accessible.

Results and Discussion

The BFC is a simple technology that solves two major societal issues: organic waste management and cost-effective green, renewable, and green energy production. BFC, created and developed in India, is a grass-roots innovation and unique Indian technology that benefits Indian society. In contrast to conventional MFCs, the unique BFC does not need any maintenance. Compared to traditional MFCs, the BFC is simple to assemble, disassemble, repairable, and recyclable. A novel scientific and technological idea, energy conservation, and environmental preservation are all essential frugal aspects of innovation.

For the serial-parallel configuration of the Plant-MFC array, the OCV, and SCC were 1.75 V and 5.6 mA (producing a maximum power of 9.8 mW), respectively. SCC rapidly rose to and steadied at 100 mA within a fraction of a second after measuring the instrument selection knob set at the current range in the current study. The highest OCV ranged from 0.6 V to 0.9 V in repeated tests. The discharge current density rose from 10 to 110 mA with a direct short circuit route connection. A series–parallel combination of the experimental BFC is suggested for future development to increase power production capacity. The following three sizes of the created BFC were observed experimentally.

- Size A: 130 mm × 100 mm × 40 mm
- Size B: 150 mm × 150 mm× 80 mm
- Size C: 200 mm× 150 mm× 100 mm

Table 3 shows the fluctuation in output voltage during 60 days of trials with various BFC sizes.

Figure 9a shows characteristic curves and electricity generation as a function of voltage in mV and current in mA. Table 4 presents the findings of the constructed BFC for four different designs. The considered patterns are as follows.

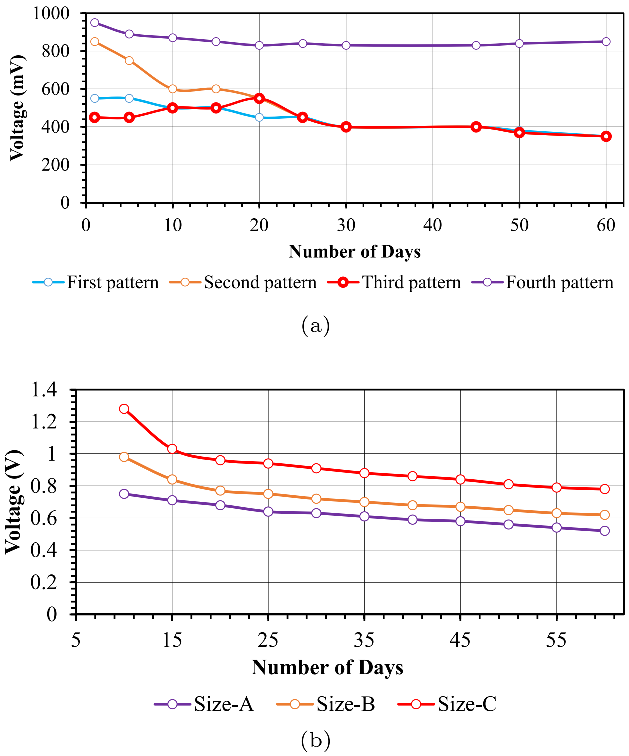
- Copperplate is the first pattern air cathode and carbon fiber fabric as anode
- Copperplate for the second pattern air cathode Anode: A thin metal mesh is used as an anode
- Third Pattern Anode: Carbon Fiber Cloth Air cathode: Stainless steel mesh
- Fourth Pattern Anode: thin aluminum sheet Air cathode: stainless steel mesh

Table 3 The output voltage varies as the BFC size changes

S. No.	Days	Size A (V)	Size B (V)	Size C (V)
1	10	0.75	0.98	1.28
2	15	0.71	0.84	1.03
3	20	0.68	0.77	0.96
4	25	0.64	0.75	0.94
5	30	0.63	0.72	0.91
6	35	0.61	0.70	0.88
7	40	0.59	0.68	0.86
8	45	0.58	0.67	0.84
9	50	0.56	0.65	0.81
10	55	0.54	0.63	0.79
11	60	0.52	0.62	0.78

Table 4 Measured OCV (V) with different electrode materials

Patterns	Duration in Days with corresponding voltage (V)									
	1	5	10	15	20	25	30	45	50	60
First	0.55	0.55	0.50	0.50	0.45	0.45	0.40	0.40	0.38	0.35
Second	0.85	0.75	0.60	0.60	0.55	0.45	0.40	0.40	0.37	0.35
Third	0.45	0.45	0.50	0.50	0.55	0.45	0.40	0.40	0.37	0.35
Fourth	0.95	0.89	0.87	0.85	0.83	0.84	0.83	0.83	0.84	0.85



(a)

(b)

Fig. 9 Graph between measured open circuit voltage versus time (days) **a** for four patterns and **b** for three different sizes

Table 5 Power output for all four patterns and three sizes in mW

BDC design	P_{avg}	P_{min}	P_{max}
First pattern	45.3	35	55
Second pattern	53.2	35	75
Third pattern	44.2	35	55
Fourth pattern	85.8	83	95
Size A	61.9	52	75
Size B	72.82	62	98
Size C	91.64	78	128

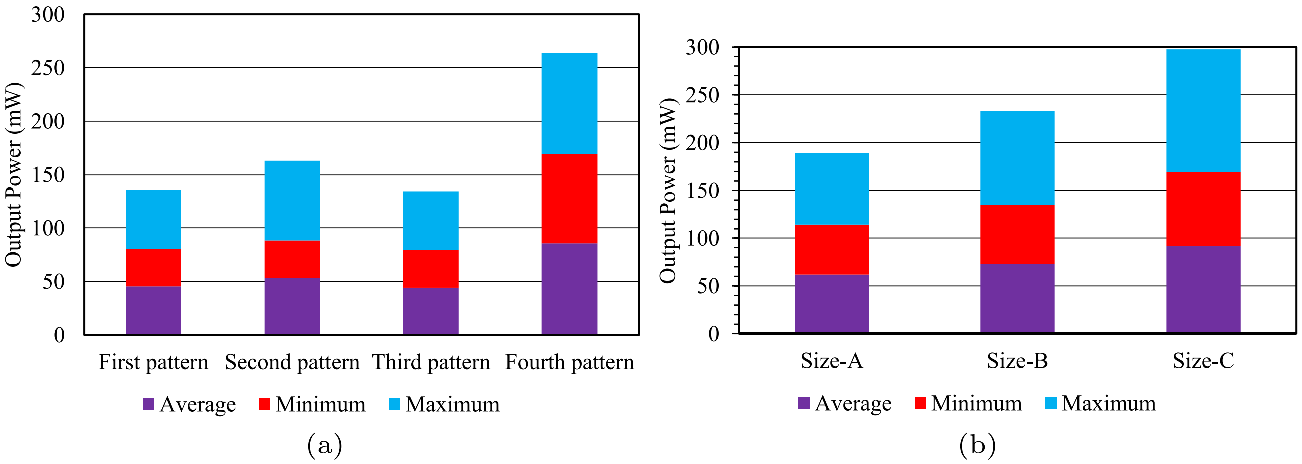
Figure 9b depicts a graphical representation of all possible patterns. During the 60-day experiments, the fluctuation in output voltage is monitored. It has been found that the output power progressively diminishes over time. Table 5 shows the average output power (P_{avg}), minimum output power (P_{min}), and output maximum power (P_{max}) for four patterns and three sizes, respectively, as shown in Fig. 10a, b.

As shown in Table 4 and Fig. 9a, the created BFC produced the OCV by utilizing various anode and cathode material combinations. According to similar findings, the researchers observed that the air cathode stainless steel mesh and anode thin aluminum plate provided a certain voltage output after seven days of testing, i.e., 0.85 V. Both are excellent conductor electrodes for bacterial adhesion or e^- coupling. The produced H^+ and H^- flow towards the free air cathode stainless steel thin mesh via the GACs catalyst layer. As a result, existing oxygen may be used as a e^- acceptor. Furthermore, the created cell is built in a closed configuration to prevent air from leaving or to reduce contamination. A specific region is created for the free air trapped in the cell due to a natural bacterial activity. As a result, we discovered that the aluminum plate anode was effective in enzyme fixation. Furthermore, it was confirmed that using stainless steel mesh on the air cathode side may result in substantial OCV. Table 6 and Fig. 11 illustrate the features of OCV production.

Table 7 graphically depicts the change in output voltage as a function of temperature. The temperature fluctuation in the proposed BFC system is 40 °C (summer season in India) to 10 °C (winter season in India). Figure 11 shows a graphical representation of the change in output voltage for Size A as a function of temperature. Due to the faster chemical reaction, BFC tests at higher room temperatures provide greater output voltage. Also, an extended analysis on obtaining the designed BFC's power density is performed, illustrated in Table 8.

Electrochemical Analysis of Electrodes

During tests, the three aluminum anodes, sheet, and mesh types are used; mesh-type aluminum showed higher reduction-oxidation activity than sheet-based anodes. The power density for all three anodes was calculated for corresponding voltages. Performance expressed as power density at 450 mV cell voltage decreased in the order Mesh vs. Sheet as shown in Fig. 12. The Mesh type of 200 × 150 × 100 and Sheet type of 150 × 150 × 80 anodes exhibited high power densities, both approximately 2 × and 3 × larger than the power densities of the 130 × 100 × 40 anodes, respectively.



(a)

(b)

Fig. 10 **a** Power output for all four patterns (mW) **b** Power output for all three sizes (mW)

Table 6 Measured Stability of the OCV (mV)

Days	15	20	25	30	40	50	60
Pattern IV	850	830	840	830	830	840	850

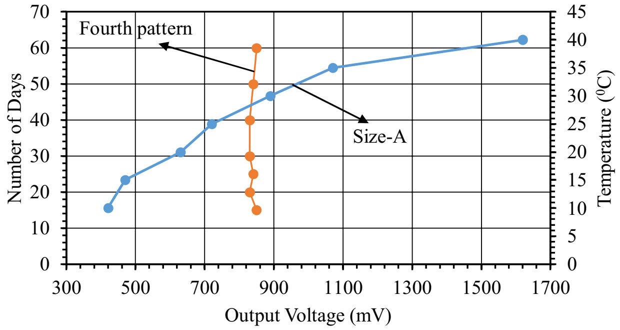


Fig. 11 Stability curve of the OCV versus number of days and Graph between measured OCV versus temperature

Table 7 Temperature-related changes in output voltage for Size A

S. No.	Room Temperature (°C)	Output Voltage (mV)
1	40	1620
2	35	1070
3	30	890
4	25	720
5	20	630
6	15	470
7	10	420

Table 8 Power density of the designed BFCs

Size	Area (m^2)	Power (mW)
A	0.0130	8.84
B	0.0225	15.30
C	0.0300	20.40

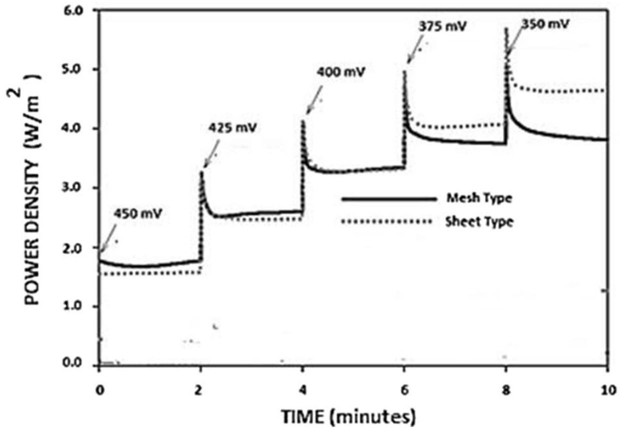


Fig. 12 Power density performance of the cell concerning time

The power density of the mesh type anode was remarkably higher than that of the sheet type anode, almost 3-fold. During tests, the mesh-type anodes produced comparable current densities, up to three times larger than the sheet-type current densities.

Conclusions

The article focuses on energy conversion characteristics and developing a BFC within a brick-shaped microchamber. This new cell design enables the creation of a single-chambered device, enhancing bacterial cell adhesion and overall device performance. The BFC described in the article has a capacity of approximately 0.25 ls. It consists of an anode aluminum mesh, an air cathode stainless steel mesh, and GAC layers as a catalyst and diffusers. The utilization of GAC allows for readily available oxygen as an electron acceptor. A BFC with dimensions of 200 mm × 150 mm × 100 mm achieved a maximum output power of 128 mW by harnessing the electricity generated through microbial metabolism in organic-rich materials. The researchers successfully tested the BFC using organic kitchen waste as the fuel source. To provide reliable green energy, the researchers created a BFC-based free energy server consisting of seven series-linked cells, producing a voltage of 3.7 V and a current of 100 mA DC. The primary objective of this innovation is to develop a BFC-based lantern that can serve as an energy-efficient light source, addressing environmental pollution concerns while offering energy-saving features for Indian society. The researchers also tested the BFC in a series–parallel configuration for various household applications. The research described in the article is considered innovative as it overcomes barriers and leads to breakthroughs in BFC technology. The developed BFC exhibits improved power density, energy efficiency, a lifespan of greater than 60 days, and self-sustainability. However, further advancements in BFC technology are necessary for practical, real-world applications to overcome research-related limitations and improve efficiency and cost-effectiveness. Future research could focus on the continued development of BFC designs to achieve even more efficient and economically viable electrical power production.

Acknowledgements This paper's experimental BFC is fabricated at Renewable Energy Lab, Electrical Division, CSIR−NAL, India. The authors acknowledge the support extended by CSIR−National Aerospace Laboratories, Bangalore, Karnataka, India, for providing the fabrication facilities. The authors would also like to thank the Department of Electrical Engineering, Indian Institute of Technology (Banaras Hindu University) Varanasi, Uttar Pradesh, India, for providing the research grant to complete this work on Biological Fuel Cell−based Energy Conversion System.

Author contributions Conceptualization and Methodology by Anand Kumar Kyatsandra; Draft writing, Review, and Editing by Sachin Kumar and Kumari Sarita; Mathematical formulations and Proof Reading by Aanchal Singh S Vardhan and Akanksha Singh S Vardhan; Supervision, Investigation, and Results validation by RK Saket.

Funding Not applicable.

Data availability Not applicable.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare no conflict of interest.

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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