Research Article

Experimental characterization and identification of cell parameters in a BPL electrochemical device

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Abstract

Still, a large area in the islands and coastal regions of Bangladesh are out of getting the facilities of electricity. *Bryophyllum pinnatum* (Goethe Plant) is a perennial herb of 3–5 feet tall and has fleshy dark green leaves. This plant can be grown everywhere easily without any special husbandry. As these leaves contain some organic acids which are used as the electrolyte in BPL cells for low-level electricity production and it has found economically efficient considering current perspective at the off-grids. There are some parameters through which we can measure the performance of the BPL cell such as the variation of V_{OC} and I_{SC} with the electrode gaps, surface area of the electrode, leaf juice and water ratio, effect of secondary salt ($CuSO_4 \cdot 5H_2O$), different juice specimens, anode–cathode area ratio and the performance of the older juice. Information carried out through our studies will help to optimize the cell performance.

Keywords BPL cell · Electrochemical cell · Off-grid electricity

1 Introduction

Global warming has now become one of the biggest problems for us, as it is the rise in the average temperature of the Earth. The direct result of the global warming is the melting of ice at the polar regions which are melting rapidly as the increase of temperature is about 0.8 °C (1.4 °F) in the global air and sea surface at the early twentieth century and it is about two-thirds of the increase occurring since 1980 [1]. Scientists showed that the combustion of fossil fuels like- gas, oil, and coal releases carbon dioxide (CO_2) into the atmosphere are the major reasons for this hazardous situation that has occurred in recent decades [2]. But as fossil fuels are cheaper, the reduction of their use in a very short time is not economically suitable. Moreover, the abundance of fossil fuels is dwindling fast. Alternate sources are essential to meet the future demand. Extraction of the energy from the sun, wind, waves, tides, and biological elements and convert it into more useful forms of energy, such as electrical energy, that is also environment-friendly has now a key issue. Generating electricity from renewable sources rather than fossil fuels offers significant public health benefits.

Besides, searching for alternate renewable sources to provide electrical energy at rural and remote areas-islands and coastal zones in developing countries, like Bangladesh has become a major issue too. A possible solution at a very small scale is to convert electrical energy from a plant leaf. It is well known that plant leaf contains some organic acids. The use of *Bryophyllum pinnatum* leaf (BPL) to produce electricity has been developed considering those cases because it can be grown anywhere without special treatment. *Bryophyllum pinnatum* is tender, succulent plants that have stiff, straight, rounded stems ranging in height from 3 to 10 feet [3]. They are clothed with fleshy, green, ovate, oblong or lance-shaped leaves with wavy margins. Their flowers are greenish-white or red and they daintily hang from a top of the stems [3]. These plants are natives of Asia and tropical and South Africa. Their leaves are

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rich with chlorine and also contain a large portion of water and organic acids like amino acid, syringic acid, caffeic acid, ascorbic acid, malic acid, isocitric acid, etc. The herb is a good source of mineral elements such as Na, Ca, K, P, Mg, Mn, Fe, Cu, Zn [3–14]. This acidic leaf juice is used as the electrolyte with zinc and copper as electrodes in a cell, we call "BPL electrochemical device" which is a unit system and a technical piece of equipment utilizing electrochemical processes. In this paper, we shall show some investigated results on different parameters which determine the output performance of this kind of electricity generation process.

2 Materials and methodology

The blended juice of fresh *Bryophyllum pinnatum* leaves was used as an electrolyte in the BPL electrochemical device. Copper and Zinc metal sheets were collected from the local market to use as electrodes. The shape and dimensions of each electrode for all the following studies were kept the same (Fig. 1).

To keep the study, continue, we used a rectangular glass box, which is rectangular in shape and made of glass. The cell was 10 cm long, the width was 6 cm and height 12 cm and the inner volume was 720 cm^3. We called this a test unit cell because for producing larger energy, we use the cell whose several parameters and dimensions are the integral multiples of this kind of cell. With the complete arrangement of this cell forms a BPL electrochemical device. We used this device throughout all the studies. Before each study or reading, we have washed and dried this cell, used new electrodes and kept each specimen in separate containers/bottles (Table 1).

It is to be noted here that this specified dimension was also used to determine the electrical output parameters of this kind of device in other studies [6–8, 12, 13].

Table 1 Dimension of electrodes of BPL Electrochemical Device

Properties	Anode	Cathode
Element	Zinc	Copper
Average height	105.56 mm	105.39 mm
Average length	53.1 mm	53.26 mm
Average thickness	0.71 mm	0.17 mm
Average mass	27.71 g	6.77 g

3 Chemical reaction in the BPL electrochemical device

In this device, the anode is Zn plate and Cu plate is the cathode. The used electrolyte was BPL juice with an addition of secondary salt ($CuSO_4{\cdot}5H_2O$). Thus, the reactant ionic species present in solution are H^+ and Cu^{2+} ions. The overall reaction taking place is considered as follow:

$$Zn(s) + Cu^{2+}(aq) + H^{+}(aq) \rightarrow Zn^{2+}(aq) + Cu(s) + H_2(g) \uparrow$$

In such kind of arrangement, the zinc plate comes in contact with acidic BPL juice and goes into the solution and thus generates +0.762 V relative to the standard hydrogen electrodes; in equilibrium, and copper ions from the solution come in contact with the copper plates and generates -0.345 V. And the generating net e.m.f. of these reactions in the cell or a copper-zinc pair electrode in an acidic solution is 0.762 V – (–0.345 V) = 1.107 V [15] (Fig. 2).

The acidity of these leaves was responsible for the production of electricity via an electrochemical process. The addition of secondary salt stabilized the reaction process. This was ensured by determining the standard potential of this device, identification of the evolved gas from the device and finally the cell representation related to the electrochemical mechanism of this cell reaction in other studies [10, 11]. However, we had to investigate different parameters associated with a highly efficient BPL electrochemical device to build green batteries in the cheapest way following the easiest technique.

(a) (b) (c)

Fig. 1 **a** Apparatus- juice, electrodes, secondary salt, blender, multi-meter, rectangular glass box, **b** RECTANGULAR glass box, **c** pH meter

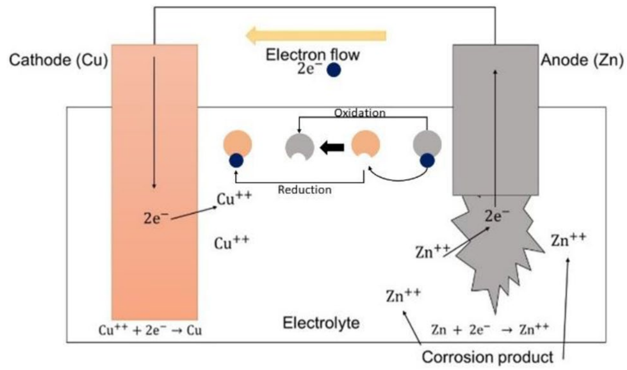

Fig. 2 Schematic reaction in the BPL Electrochemical Device

Fig. 3 Experimental set-up; plastic separator and holder inside the rectangular glass box holding the electrodes

The performance of this device is an important issue. There are some parameters through which we can measure the performance of the BPL electrochemical device. Brief outlines of key parameters used to characterize this device are discussed below. Also, it is shown how these parameters vary with the operating conditions.

4 Variation of V_{oc} and I_{sc} with the distance between electrodes

Open circuit voltage (V_{oc}) is the voltage which is not connected to any load in a circuit. While the short circuit current (I_{sc}) is the current flow through a circuit when there is no load on the circuit. At this condition, the current is considered to flow without any resistance although internal resistance is present there to valid Ohm's law.

4.1 Experimental set-up

The electrodes were immersed 120 mm deep in the juice inside the rectangular glass box. This depth was kept fixed throughout this experiment. The two leads of the multimeter were connected to the two electrodes to measure the voltage and current in absence of a load. The distance (space/gap) between the electrodes was varied and corresponding open circuit voltage and short circuit current readings were taken. We took reading ten times for ten different spaces. Spaces between the electrodes were 5 mm, 10 mm, 15 mm, 20 mm, 25 mm, 30 mm, 35 mm, 40 mm, 45 mm, and 50 mm respectively (Fig. 3).

4.2 Results and discussion

The variation of open circuit voltage and short circuit current with the distance between the electrodes is given below.

In the Fig. 4, we see the voltage is almost constant as we did not replace the electrodes and the current is decreasing linearly with the increase in the distance between both electrodes after the 10 mm gap. So, if we go inversely to the Fig. 4, we can say- by the decrease of the space between the electrodes, the short circuit current increases. Moreover, this direction of variation is almost similar to other experiments with different experimental specification [14]. By this information, we can conclude here that the distance between electrodes of this kind of device should be kept closed as much as possible.

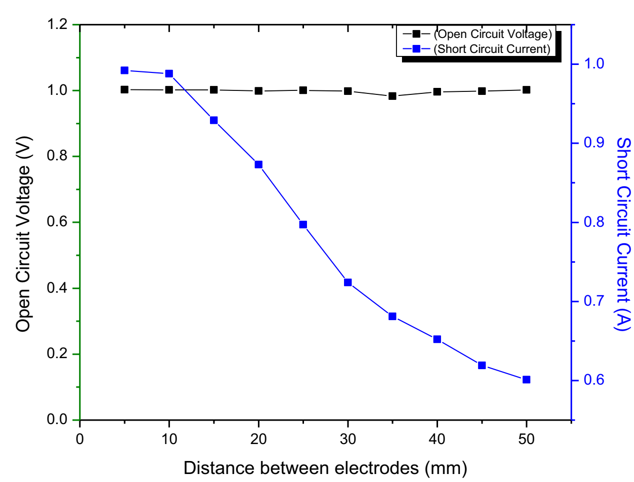

Fig. 4 Variation of V_{OC} and I_{SC} with Distance between anode and cathode

5 Effect of the surface area of the electrodes

5.1 Experimental set-up

In this study, the space between the electrodes was kept constant at 5 mm by placing a plastic separator to hold them. Black scotch tape was used at five positions to mark the percentage of the glass container. Each scotch tape was marked beforehand for 24 mm (20%), 48 mm (40%), 72 mm (60%), 96 mm (80%) and 120 mm (100%) distance mark from the bottom end of the glass container to the top. A 50 cc plastic syringe was used to pour the juice into the chamber initially for 24 mm mark. Corresponding readings of open circuit voltage and short circuit current were taken. More juice was poured gradually to reach the 48 mm mark and corresponding readings were taken. This process was repeated until the juice poured to 120 mm marks (Fig. 5).

5.2 Results and discussion

The variation of open circuit voltage and short circuit current with the percentage of the area of electrodes in the juice.

From Fig. 6, we see that the open circuit voltage is almost constant with several percentages of the area of electrodes immersed in the juice and the short circuit current is increasing linearly with the linear increase of the percentage of the area of electrodes immersed in the juice. So, we can conclude here that for a fixed pair of electrodes immersed in juice, there is almost no effect on the open circuit voltage on the area of electrodes in the BPL juice. This happens because of the generated electromotive force is the same for a fixed pair of electrodes due to redox reaction. But the current increases with the increase of the immersed area of the electrodes in the BPL juice. This happened because the more the area of electrodes, the more collision and the redox reaction as well as electron flow [16]. And this also showed a similarity to the previously done experiment but with dissimilar arrangements [14]. So, for better performance of this device we need the bigger surface area of the electrodes.

Fig. 5 Rectangular glass container with the marks

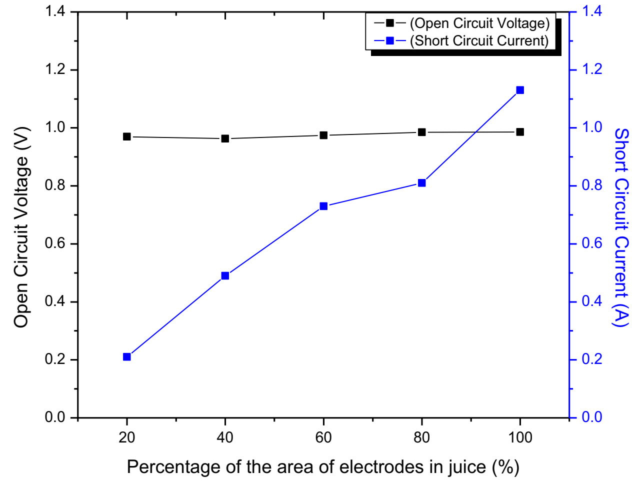

Fig. 6 Variation of V_{OC} and I_{SC} with the Percentage of the Area of Electrodes in the juice

6 Effect of the percentage of BPL with water

6.1 Experimental set-up

In this study, the space between the electrodes was kept constant at 5 mm by placing a plastic separator to hold them. We took our first reading of open circuit voltage and short circuit current where the percentage of BPL was 75, with 25% water. In our later readings, the percentages of BPL were 60, 50, 40, 30, 20 and 10. No secondary salt was added during this study.

6.2 Results and discussion

The variation of open circuit voltage and short circuit current with the percentage of the BPL in water.

From Fig. 7, we see that the open circuit voltage is almost constant with several percentages of BPL in the juice and the short circuit current is linearly increasing with the increase of the percentage of BPL in the juice. So, we can say here that for a fixed pair of electrodes immersed in juice, there is almost no effect on the open circuit voltage on the percentage of BPL in the juice. But the current increases with the increase in the percentage of BPL in the juice. This happened because of the more the percentage

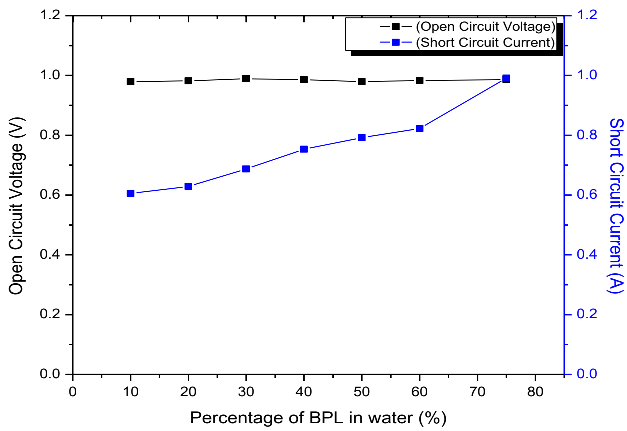

Fig. 7 Variation of V_{OC} and I_{SC} with the Percentage of BPL in water

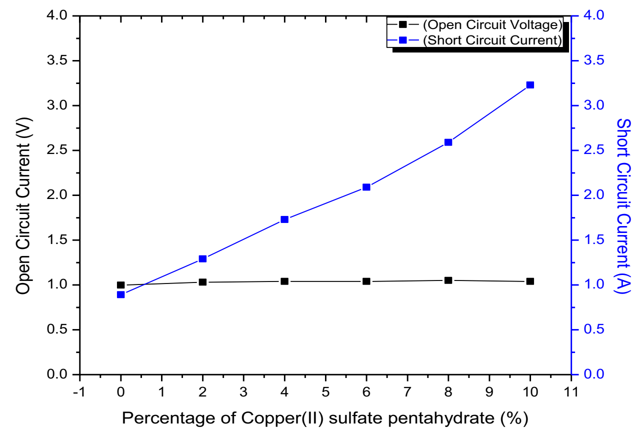

Fig. 8 Variation of V_{OC} and I_{SC} with the Percentage of $CuSO_4{\cdot}5H_2O$ in the BPL juice

of BPL in the juice, the more the concentration of the reacting ions, the more the redox reaction as well as electron flow [16]. And we can get the highest performance by the pure BPL juice i.e. no additional water in the juice.

7 The effect of $CuSO_4{\cdot}5H_2O$ in BPL

7.1 Experimental set-up

In this study, the space between the electrodes was kept constant at 5 mm. In the juice, BPL and water ratio was 3:1. We took our first reading without $CuSO_4{\cdot}5H_2O$. In our following readings, the percentages of $CuSO_4{\cdot}5H_2O$ in the solution were 2, 4, 6, 8 and 10.

7.2 Results and discussion

The variation of open circuit voltage and short circuit current with the percentage $CuSO_4{\cdot}5H_2O$ in the juice.

From Fig. 8, again we can see that the open circuit voltage is almost constant with several percentages of $CuSO_4{\cdot}5H_2O$ in the BPL juice and the short circuit current is increasing highly and linearly with the increase of the percentage of $CuSO_4{\cdot}5H_2O$ in the BPL juice. So, we can conclude here that for a fixed pair of electrodes immersed in juice, there is almost no effect on the open circuit voltage on the percentage of $CuSO_4{\cdot}5H_2O$ in the BPL juice and the current increases linearly with the increase of the percentage of $CuSO_4{\cdot}5H_2O$ in the BPL juice. This happened because of the more the percentage of $CuSO_4{\cdot}5H_2O$ in the juice, the more the concentration of the reacting ions, the more the redox reaction as well as the flow of electrons [16]. From the above discussions, we can say that we can improve the performance of BPL cell by adding $CuSO_4{\cdot}5H_2O$ as secondary salt. Moreover, we can get controlled improvement by adding $CuSO_4{\cdot}5H_2O$ in a nearly dead BPL electrochemical device.

8 Variation of pH, open circuit voltage and short circuit current with different BPL juice

8.1 Experimental set-up

In this study, we collected four samples of BPL came from Natore, Mohammadpur, Shantinagar, and Shiddhirganj. We made juice from those BPL where the percentages of BPL of all samples were 60. At first, we poured the glass container with the first sample and took the first data and then the rest were taken. We also measured the pH of all samples. In that experiment, the space between the electrodes was kept constant at 5 mm. We added no secondary salts in those specimens (Fig. 9).

8.2 Results and discussion

The variation of open circuit voltage, short circuit current and pH due to the change of the origin of BPL.

From the experimental data shown above, we can say that the characteristic of BPL is different for the different specimen. It is totally related to the soil where it is grown up. And we can also conclude here that the origin of BPL will be quite effective in electricity production. We also can see that the short circuit current depends on the pH of the juice. It also shows that the short circuit current increases with the decrease of the pH of the juice and the open circuit voltage has an ignorable impact on it (Fig. 10).

Fig. 9 **a** Different BPL sample juice and **b** calibration of pH meter

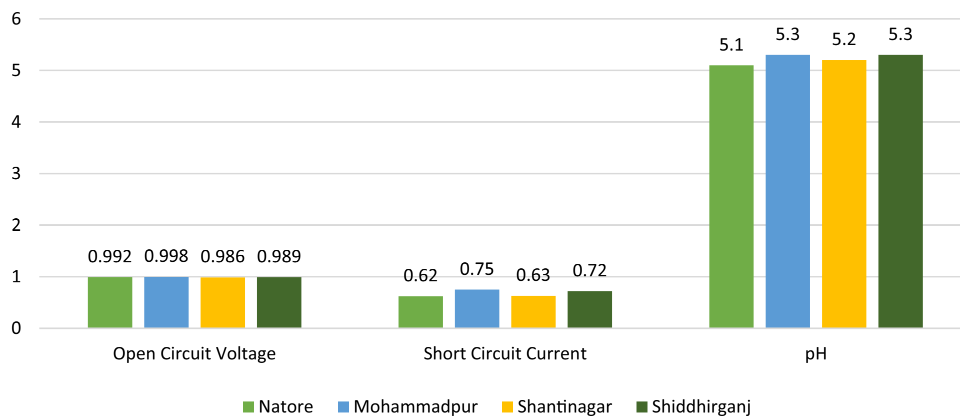

Fig. 10 Experimental data for different BPL specimen

9 Effect on decomposition of BPL

9.1 Theory

Decomposition is the first stage in the recycling of nutrients that have been used by an organism (plant or animal) to build its body, and are surrendered back to the ecosystem upon its death. It is the process whereby the dead tissues break down and are converted into simpler organic forms that are the food source for many of the species at the base of ecosystems. The species that carry out the process of decomposition and feed on the 'waste' products produced by it are known as detritivores, which means literally 'feeders on the dead or decaying organic matter'. Many of these decomposer species function in tandem or parallel with one another, with each being responsible for a specific stage or aspect of the decomposition process, and collectively they are known as the detritivore community [17].

When the plant decays the acidity of soil increases. The chemical reaction in the dead plant is quite responsible for this. So, we can say that the acidity of a dead plant increases with the passing of the day. This rate is higher when they are in direct contact with the soil [17]. As a result, if we take some *Bryophyllum pinnatum* Leaf in a plastic container, the acidity of the juice will increase; however, this rate will not be so rapid as we might observe with the soil.

9.2 Experimental set-up

In this study, we have collected BPL and made juice from those. At that time the percentage of BPL in the juice was almost 69. After making juice, we poured them in several plastic bottles. We took our first reading of open circuit voltage, short circuit current, and pH from the very first day. The space between the electrodes was 5 mm and kept constant for the next readings. Then we took the rest of the readings at day number 14, 29, 42, 60 and 72.

9.3 Results and discussion

The variation of open circuit voltage, short circuit current, and pH with the duration of the juice.

If we see the Fig. 12, we can see that the pH is gradually decreasing with the passing of days. This is an example of the decay of the organic matter of a leaf. Small pH has a great impact on redox reaction- the lower the pH the higher the redox reaction, the higher the current flow which can be observed in the Fig. 11. Figure 11 also shows that short circuit current increases with the increase of the duration of the BPL juice. Again, here we found that the

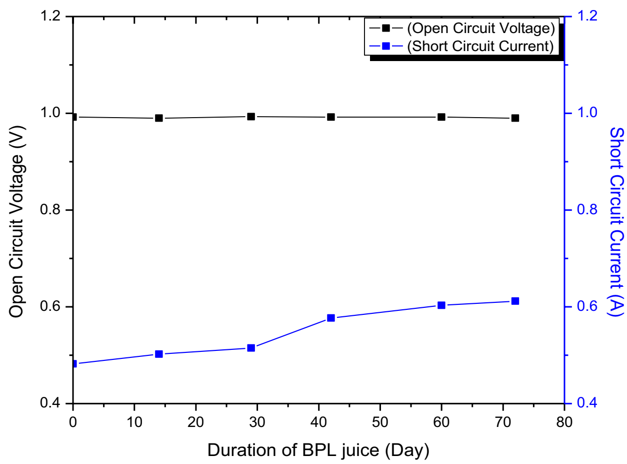

Fig. 11 Variation of V_{OC} and I_{SC} with duration of BPL juice

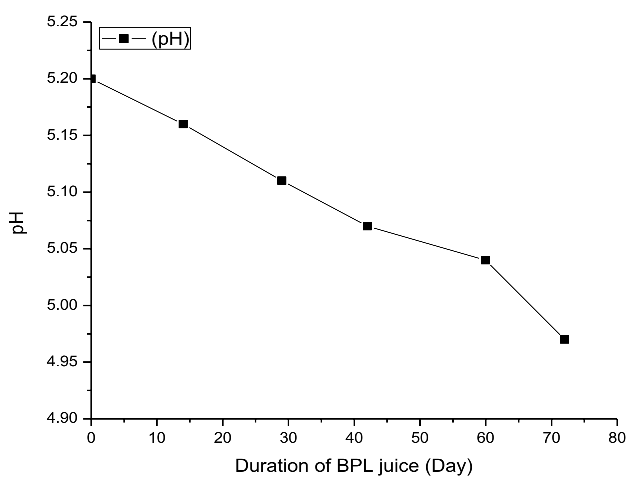

Fig. 12 Variation of pH with duration of BPL juice

duration of juice has no effect on the open circuit voltage on this pair of electrodes.

10 Effect of surface area of anode

10.1 Experimental set-up

In this study, we poured BPL juice in a glass container and placed a Zn plate and a Cu plate taking a 5 mm gap between them. In this calibration, we took our first reading. Then we placed another Zn plate and connected in series with the previous Zn plate which had a similar area as the previous one and took our second reading. We continued this until five Zn plate were connected in series with them and took five readings. Actually, by adding more Zn plate of the same area in the series, we increased the surface area of the anode. Adding an extra Zn plate means making the surface area of the anode double. In this process, we increased the surface area of the Zn plate by two, three, four and five times. While the area of the Cu plate or the cathode was the same.

10.2 Results and discussion

The variation of open circuit voltage and short circuit current with the surface area of the anode in the juice.

From Fig. 13, it is clear that the area of the anode has no effect on the open circuit voltage. And we also see the indistinguishable effect on short circuit current. So, if we increase the surface area of the anodic Zn plate, it will increase the current flow [18].

For given cell chemistry, increasing the surface area of the electrodes can increase the cell's current at a given current density and, thus, deliver more power.

The most efficient way to deliver a higher power density is to increase the effective surface area of an electrode while keeping the nominal area constant. It is important to consider any increase in parasitic reactions that may be enhanced due to the increase in the effective surface area. For example, in systems where corrosion is a concern, simply increasing the surface area may enhance the corrosion reactions while depleting the active material [19].

11 Conclusion

The BPL electrochemical device, we discussed here is subjected for the people living in remote places or off-grid. The demand for electricity for those people is not much. A small amount of electricity can fulfill their demand for

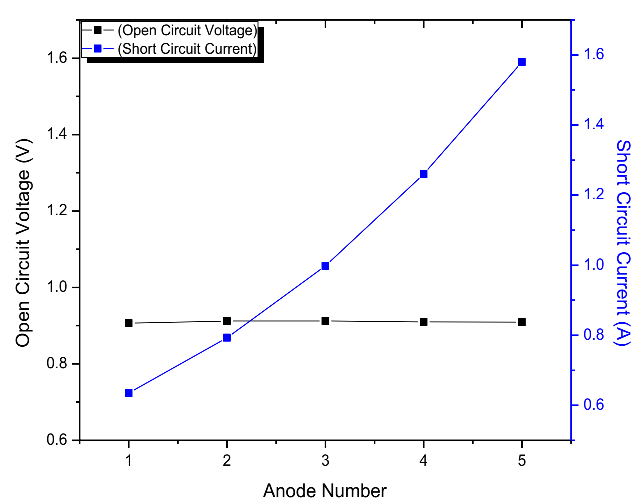

Fig. 13 Variation of V_{OC} and I_{SC} with the number of Zn anode

lighting a bulb of 3–10 W at night, charging mobiles and tuning radios. Considering the socio-economic condition of Bangladesh, they cannot be connected with grid electricity very soon. There are some places in the islands and coastal areas where the possibility of getting connected with the grid is very low. A low leveled power sources (20 W-100 W) based on the BPL electrochemical device can be a solution for those purposes. Device characterization is a must to determine and predict the output characteristics. In this paper, our studies show the output characteristics depend on the distance between the electrodes, surface area immersed in the juice, BPL-water ratio, secondary salt ($CuSO_4{\cdot}5H_2O$), the origin of the plant or leaf, duration of the juice and the ratio of anode–cathode surface area. Results have been discussed in this paper provides the information to construct a cell of such kind of optimum outputs. There are some other parameters yet to investigate- the effect of output on temperature, humidity, purity of electrodes, different electrode materials and cost per watt, secondary salts, and minerals in the water, reuse of the device, etc. The results also put a limitation on predicting the exact output of a cell. A good variation may observe while performing the same study because of the variation of device parameters. Further studies are ongoing to investigate the existence of some other parameters. While taking our readings we have found the currents were continuously changing, and we took the values which were stable for 3 s and considered that the average value. This puts another limitation on cell designing. Although there are limitations in cell designing, we are still working on some different models and found better performances. As the conventional resources are decreasing quickly, and feasibility to connect the people of off-grid in Bangladesh, the information of this device technique is surely providing a glance of hope for the near future.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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