Full Paper

MODELLING OF THE ELECTRICITY GENERATION FROM LIVING PLANTS

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Graphical abstract
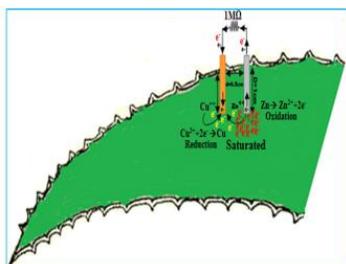
Abstract

Electricity can be harvested from living plants by generating reaction between the plant and a pair of different metals. It has great potential in sustainable energy production because it offers a green approach to harvest energy from sources that are abundantly available. Previous investigation has shown that electrochemistry process is accountable for its mechanism of energy production. In this paper, the behavior of the ions flow in the electrodes-plant system is modelled and illustrated. For this purpose, energy harvesting system consists of Zn-Cu electrodes and aloe Vera was used where the electrodes were immersed in the aloe Vera leaf. It was hypothesized that during the energy harvesting process, oxidations of zinc atoms occur when an external load is connected between the two electrodes. For 72 hours of harvesting process, the zinc electrode experienced a mass loss of 3.2mg compared to electrochemistry prediction which is 0.0853mg when 1MΩ load was used. However, using a lower load resistor (1kΩ), the measured mass loss of the zinc increased to 6.7mg compared to the prediction which is 4.0452mg. This means that there is an increase of efficiency when a lower load resistance is used, which is 60.4% for 1kΩ, compared to 2.67% when using 1MΩ. This shows that the electrochemistry process is influenced by the load connected to the system. This finding improvises a better understanding on the energy production mechanism of the system.

Keywords: Weak energy source, living plants, green electricity, living-plant fuel cell

Abstrak

Elektrik boleh dituai daripada tumbuhan hidup dengan menghasilkan tindakbalas di antara tumbuhan dengan pasangan logam yang berbeza. Kaedah ini berpotensi tinggi dalam penghasilan tenaga mampan kerana penjanaan tenaga elektrik melalui pendekatan ini adalah berasaskan teknologi hijau dari punca yang berterusan. Penyelidikan terdahulu mendapati bahawa proses elektrokimia bertanggungjawab atas mekanisma penjanaan tenaga yang terhasil. Dalam kertas kerja ini, sifat pengaliran ion dalam sistem elektrod-tumbuhan dimodel dan digambarkan. Untuk tujuan ini, sistem penuaian tenaga terdiri daripada elektrod Zn-Cu dan aloe Vera telah digunakan di mana elektrod dibenam dalam daun aloe Vera. Ia dihipotesis bahawa sepanjang proses penuaian tenaga, pengoksidaan berlaku pada atom zink apabila beban disambungkan di antara dua elektrod berkenaan. Dalam proses penuaian selama 72 jam, elektrod zink mengalami pengurangan jisim sebanyak 3.2mg berbanding ramalan elektrokimia iaitu 0.0853mg apabila beban 1MΩ digunakan. Bagi perintang yang lebih rendah (1kΩ), pengurangan jisim diukur untuk zink meningkat kepada 6.7mg berbanding ramalan iaitu sebanyak 4.0452mg. Ini bermakna kecekapan sistem meningkat apabila rintangan yang lebih rendah digunakan, iaitu 60.4% untuk 1kΩ berbanding hanya 2.67% untuk 1MΩ. Ini menunjukkan bahawa proses elektrokimia dipengaruhi oleh beban perintang yang disambung dalam sistem. Keseluruhan penemuan menambahbaik pemahaman mengenai mekanisma penghasilan tenaga dalam sistem.

Kata kunci: Sumber tenaga lemah, tumbuhan hidup, elektrik hijau, sel bahanapi tumbuhan hidup

1.0 INTRODUCTION

Renewable energy sources have been extensively investigated as part of an effort to safeguard our future and the Earth [1]. From the environmental point of view, switching to renewable energy sources for electricity generation provides beneficiary management strategies [2]. Renewable energy sources include wind energy [3], solar energy [4-5], ocean energy [6-8] and ambient power harvesting such as piezoelectric [9-13] are among the popular selection.

Plant-based energy generation is a method that harvests electrical energy from living plants. The use of living plants to harvest energy is environmentally friendly, cost effective and most importantly its source is locally abundant. This inexhaustible source of energy that literally around us can be converted into usable electric power. Many of the safety concerns surrounding fossil fuels do not exists with the plant-based energy source.

Previous studies have found that living plants can generate bioelectricity by transforming sunlight into electricity based on photosynthesis process [13-14]. This development has the potential to provide an unlimited supply of constant, clean energy without relying on fossil fuels [15-16]. More recently, Choo & Dayou [17] presented some fundamental procedures to harvest weak electricity from living plants which consist of harvester selection, type of plants and with potential application. The origin of energy production was further investigated by using Flame Atomic Absorption Spectroscopy (FAAS) and it was found that electrochemistry process is responsible for the mechanisms [18-19]. This source of energy is termed as Living-plant Fuel Cell (LFC) in this paper. It converts chemical energy to electrical energy by embedding pair of electrodes into the plant. The principal idea is that organic matter of the living-plants will be utilized as the electrolyte with the combination of electrodes to generate electricity. The attention in LFC is increasing mainly because they offer the possibility of directly harvesting electricity from living plants.

In this paper, the mechanism of energy production of LFC is modelled. To verify the proposed model, the reduced mass of zinc electrode is measured and compared with the predicted equivalent mass. Details of the experimental works are explained in section II. The findings suggest that the origin of the energy production in LFC can be modelled according to the principle of electrochemistry with necessary consideration on the efficiency effect.

2.0 MATERIALS AND METHODS

It is hypothesized that, based on the previous investigations, electrochemistry has been the origin of the mechanisms of the generation of the weak electricity in living-plant fuel cell, or LFC [13-14]. This paper is intended to model the electricity generation in LFC based on the electrochemistry mechanisms. In the experiment presented in this paper, a pair of clean copper and zinc electrodes is embedded into aloe Vera leaf to make the LFC system. The cell is connected to load of 1MΩ resistor as illustrated in Figure 1. There are free end wires at both ends of the load made available to a digital multi-meter for voltage measurement whenever needed. The LFC (with the load of 1MΩ) was left running for three days. After that, both copper and zinc electrodes were rinsed with distilled water and allow them to dry completely. The weight before and after the experiment were taken to the nearest milligram using Sartorius TE214S to assess the mass reduction which later is compared with the theory. The reduced mass of zinc by subtracting the initial weight of electrode from its final weight, which termed as measured mass loss (ML). On the other hand, the predicted equivalent mass (EM) is calculated based on the Faraday's principle which is further discussed in the later part of the comparison.

a) Photo for the set-up   b) Schematic diagram
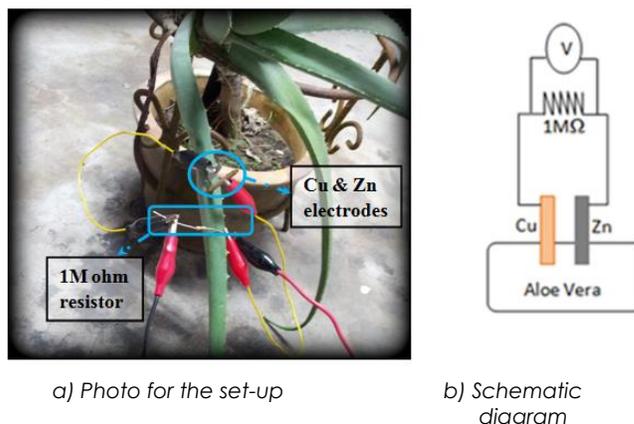
Figure 1 Photo (a) and schematic diagram (b) for the experimental set-up

3.0 RESULTS AND DISCUSSION

Table 1 shows the measured ML of the zinc electrode before and after the experiment. It can be seen that the mass loss of zinc electrode that left running up to 3 days is 3.2mg. The value is then compared to the predicted equivalent mass (EM) which is determined as follows.

Table 1 Measured ML in, gram of the zinc electrode before and after experiment

Condition	Mass of Zinc electrode, g			
	1	2	3	Mean
Initial	0.3722	0.3726	0.3725	0.3724
Final	0.3690	0.3694	0.3692	0.3692
Mass loss	0.0032	0.0032	0.0033	0.0032

According to the Faraday's law, the weight of substances discharged into a solution or media during the electrochemistry process is directly proportional to the amount of the current passing through the electrochemical cell which is normally known as gram equivalent mass. For a given amount of electrical current flowing in the LFC system, the mass m of the zinc released into the media should be given as [20]

$$m = \frac{(\frac{Q}{2e})M}{N_A} \qquad (1)$$

where e is the electronic charge which is 1.6 x 10-19 Coulombs, M is the molar mass of zinc, which is 65.39g/Mol, NA is the Avogadro's number given by 6.023 x 1023 mol-1 and Q is the total electrical charge flowing in the circuit given by the multiplication between current and the time $Q = It$ or in unit coulombs.

To get Q, the voltage, V across the load of 1MΩ was first measured consistently throughout the experiment which is given in Table 2. The average value which is 0.970V was then taken to get Q using the Q=(v/R)t relationship. This is the total charge coming from zinc dissolution reaction: $Zn \rightarrow Zn^{2+} + 2e^-$ which mean atoms of Zn released into the media. Using this information, the predicted EM is determined using (1) and was found to be 0.08mg. Therefore, in comparison, the measured value ML is greater than EM by 3.12mg.

Table 2 Measurement of voltages, V in three days time for 1MΩ used

Day	Voltages, V			
	0900	1200	1500	Daily Average
Day 1	0.959	0.968	0.959	0.962
Day 2	0.962	0.964	0.980	0.969
Day 3	0.980	0.979	0.980	0.980
	Total Average			0.970

The difference between predicted EM and measured ML is likely caused by the efficiency effect. This effect refers to how efficient the electrons move in the circuit through the load (1MΩ) and is measured by the ratio between the output electrons to the input electrons. Figure 2(a) represents the illustrative diagram of the electrons through the load and the total electrons released in the media (aloe Vera). To explain the efficiency effect, the living-plant fuel cell is modelled in an equivalent circuit as illustrated in Figure 2(b). In the system, the total electrons released by the zinc in the media gives the electron input. On the other hand, the total electrons flow through the load serves as output electrons.

In this experiment, the total electron charge QO that flow through the load can be used to represent the electrons output. Using the relationship

$$Q_O = It = \frac{V}{R}t \qquad (2)$$

(All the symbols are as given before), the output electron charge is found to be QO= 0.2514C. On the other hand, the total electron charge (or input charge, QI) released by the zinc electrode in the media can be calculated by rearranging (1) which is

$$Q_I = \frac{mN_A 2e}{M} \qquad (3)$$

It was found that the input charge is given by QI = 9.4319C. Using this information, the efficiency is found to be

$$Q_{Eff} = \frac{Q_O}{Q_I} = \frac{0.2514C}{9.4319C} = 0.0267 \qquad (4)$$

or 2.67%. It can be seen that the efficiency of the system is very low and the reason for this can be explained as follow.

The electrons releases by zinc atom in the media (aloe Vera) are classified into two groups, conducting and non-conducting. Conducting electrons are electrons that flow through the load (refer to Figure 1). However, there are electrons that are not flowing through the load which are the non-conducting that instead move to copper through the media (aloe Vera). The total charge in (2) measures only the conducting electrons that exclude the non-conducting electrons. On the contrary, the measured ML is the total dissipation of the zinc atom into the media (aloe Vera) that make both the conductive and non-conductive electrons.
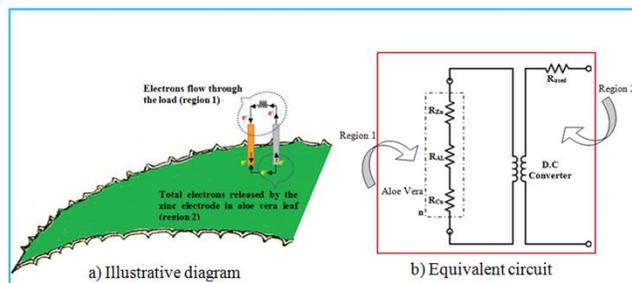
Figure 2 The representation of the living-plant fuel cell in a) illustrative diagram; b) equivalent circuit where electrons in red represent conductive electrons in predicted region and electrons in yellow represent non-conductive electrons in measured region

The efficiency of the LFC is governed by the resistance in the system. The resistance is categorized into internal (Rint) and external resistance (Rext) where the former and latter represents the resistance of the aloe vera itself and resistor used, respectively and is illustrated in Figure 2. The close distance (0.5cm) between copper and zinc electrode results in low resistance in the media (aloe Vera). In this way, the internal resistance is notably lower than the external resistance, this explains measured ML is much greater than the predicted EM as more non-

conductive electrons flow through the measured region.

It is hypothesized that the efficiency of the system will increase if a lower load resistance is used. To prove this, similar experiment is performed, but replaced with 1kΩ resistor. The voltage profile across the resistor over three days is shown in Table 3 and the corresponding measured ML is depicted in Table 4. By using equation 1-4, the predicted EM for 1kΩ load is 4.05mg which is 50 times greater than the predicted EM for 1MΩ (which is 0.0852mg). For the 1kΩ load, the ML is higher 2.65mg compared to EM (refer to Table 4). This is corresponding to 60.4%, which is much higher compared to when 1MΩ load was used (2.67%). This shows that higher number of electrons flow through the load when lower load resistance is used in LFC.

Table 3 Measurement of voltages, V in three days time for 1kΩ used

Day	Voltages, V			
	0900	1200	1500	Daily Average
Day 1	0.067	0.070	0.059	0.065
Day 2	0.031	0.040	0.042	0.038
Day 3	0.037	0.028	0.037	0.034
	Total Average			0.046

Table 4 Measured ML in, gram of the zinc electrode before and after experiment for 1kΩ load

Condition	Mass of Zinc electrode, g			
	1	2	3	Mean
Initial	0.3817	0.3816	0.3817	0.3817
Final	0.3751	0.3752	0.3748	0.3750
Mass loss	0.0066	0.0064	0.0069	0.0067

Table 5 Results summary at 1MΩ and 1kΩ

Resistor	Measured ML	Predicted EM	Input Charges, Q_I	Output Charges, Q_O	Efficiency
1MΩ	3.2mg	0.0853mg	0.2514C	11.9232C	2.67%
1kΩ	6.7mg	4.0452mg	9.4319C	19.7481C	60.4%

Table 5 is the conclusive summary for measured ML, predicted EM, input charges (Q_I), output charges (Q_O) and efficiency at the two resistances tested. From the Table 5, the measured ML at 1MΩ is about 2 times lesser than 1kΩ. The resistance is the opposition to the electrons flow, therefore the higher the resistance, the lower the electrons flow. Eventually less conductive electrons are induced along the wire when loaded with 1MΩ resistor. This creates a group of stranded electrons saturated at the Zn electrode, yielding a lower rate of successive oxidation (Figure 3). On the other hand, when 1kΩ was used, the LFC is

in its non-saturated condition so the successive rate of oxidation is higher and therefore higher ML is observed and so the efficiency.
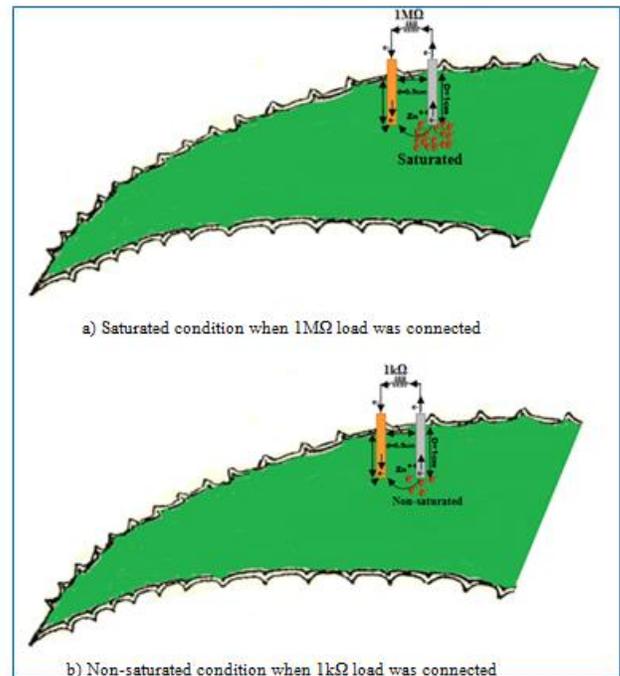
Figure 3 Illustrative diagram of stranded electrons in a) saturated condition and b) non-saturated condition
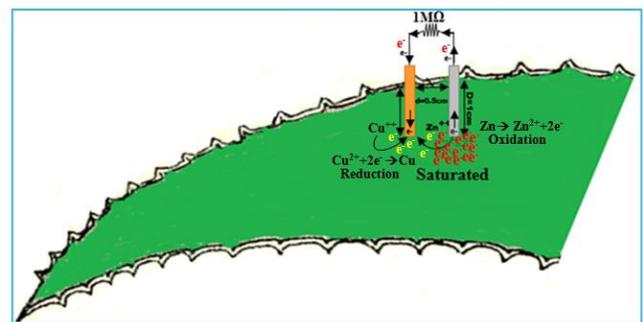
Figure 4 Modelling of the behaviour of ions flow in LFC according to the principle of electrochemistry with considerisation on the efficiency effect

Figure 4 presents the general model of the LFC based on the electrochemistry process. In the electrochemistry process, the direction of electron flow in a cell is determined partly by the relative ease of oxidation of the electrode materials. Zinc gives up electrons more readily than copper as zinc is more reactive; therefore, it causes electrons to flow through an external wire which leads from zinc to the copper. Within the system, a group of stranded electrons are accumulated at the zinc electrode due to the higher of the oxidation rate compared to the electron flow. Electrons that flow through along the wire are conductive electrons (red) while electrons

that flow through the aloe Vera gel are non-conductive electrons (yellow). The efficiency effect is governed by the successive rate of oxidation in the system.

4.0 CONCLUSION

In this paper, the mechanism of energy production of LFC is modelled based on the principle of electrochemistry process. The measured mass loss and the predicted equivalent mass were compared to verify the proposed model. Based on the obtained results, the measured ML is not in accord with predicted EM. The efficiency effect is believed to be the factor that contributes to this difference. When lower external resistor was used, more conductive electrons are induced to flow through the load, resulting in a non-saturated condition. In this way, the successive rate of oxidation is increased accordingly.

References

[1]   Hinrichs, R. A. and M. H. Kleinbach. 2006. *Energy – Its Use and the Environment*. 4th Edition. Thomson/Brooks Cole.

[2]   Varun, R. P. and I. K. Bhat. 2009. Energy, Economics And Environmental Impacts Of Renewable Energy Systems. *Renewable and Sustainable Energy Reviews*. 13 (9): 2716-2721.

[3]   Elgammal, A. and A. M. Sharaf. 2012 Dynamic Self Adjusting FACTS-Switched Filter Compensation Schemes for Wind-Smart Grid interface Systems. *International Journal of Renewable Energy Research*. 2(1): 103-111.

[4]   Toong, W. Y. and K. Sulaiman. 2011. Fabrication and Morphological Characterization of Hybrid Polymeric Solar Cells Based on P3HT and Inorganic Nanocrystal Blends. *Sains Malaysiana*. 40(1): 43-47.

[5]   Afrouzia, H. N., S. V. Mashaka, Z. A. Maleka, K. Mehranzamira, and B. Salimia. 2013. Solar Array and Battery Sizing for a Photovoltaic Building in Malaysia. *Jurnal Teknologi*. 64(4): 79-84.

[6]   Chee, F. P., S. K. Lee, J. Dayou, E. Saleh, and H. L. H. Chong. 2014. Improving Power Output Prediction from Ocean Salinity and Temperature Energy Converter using Viscosity Model. *Advances in Environmental Biology*. 8(14): 70-77.

[7]   Lee, S. K., J. Dayou, Ag. S. A. Hamid, E. Saleh, and B. Ismail. 2012. A Theoretical Investigation on the Potential Application of Ocean Salinity and Temperature Energy Conversion (OSTEC). *International Journal of Renewable Energy Research*. 2(2).

[8]   Tzen, E. and M. Papapetrou. 2012. Promotion Of Renewable Energy Sources For Water Production Through Desalination. *Desalination and Water Treatment*. 39(1-3): 302-307.

[9]   Dayou, J. and M. S. Chow. 2011. Performance Study Of Piezoelectric Energy Harvesting To Flash A LED. *International Journal of Renewable Energy Research*. 1(4): 323-332.

[10] Chow, M. S., J. Dayou, and W. Liew. 2012. Increasing The Bandwidth Of The Width-Split Piezoelectric Energy Harvester. *Microelectronics Journal*. 43(7): 484-491.

[11] Chow M. S., J. Dayou, and W. Y. H. Liew. 2013. Increasing The Output From Piezoelectric Energy Harvester Using Width-Split Method With Verification. *International Journal of Precision Engineering and Manufacturing*. 14(12): 2149-2155.

[12] Jedol D., J. Kim, J. Im, L. Zhai, A. C. H. Ting, and W. Y. H. Liew. 2015. The Effects Of Width Reduction On The Damping Of A Cantilever Beam And Its Application In Increasing The Harvesting Power Of Piezoelectric Energy Harvester. *Smart Materials and Structures*. 24(4): 045006 (6pp).

[13] Johari, J., J. Yunas, A. A. Hamzah, and B. Y. Majlis. 2011. Piezoelectric Micropump with Nanoliter Per Minute Flow for Drug Delivery Systems. *Sains Malaysiana*. 40(3): 275-281.

[14] Ryu, W. H., S. J. Bai, J. S. Park, Z. Huang, J. Moseley, T. Fabian, R. J. Fasching, A. R. Grossman, and F. B. Prinz. 2010. Direct Extraction of Photosynthetic Electrons from Single Algal Cells by Nanoprobing System. *Nano Letters*. 10: 1137-1143.

[15] Flexer, V. and N. Mano. 2010. From Dynamic Measurements Of Photosynthesis In A Living Plant To Sunlight Transformation Into Electricity. *Analytical Chemistry*. 82(4): 1444-1449.

[16] Wacker, T. 2006. *Canton Firm's Alternative To Oil: Plug In To A Tree*. The Boston Globe.

[17] Choo, Y. Y. and J. Dayou. 2013. A Method to Harvest Electrical Energy from Living Plants. *Journal of Science and Technology*. 5(1): 79-90.

[18] Choo, Y. Y. and J. Dayou, and N. Surugau. 2014. Origin of Weak Electrical Energy Production from Living-Plants. *International Journal of Renewable Energy Research*. 4(1): 198-203.

[19] Choo Y. Y., and J. Dayou. 2014. Increasing the Energy Output from Living-plants Fuel Cells with Natural Photosynthesis. *Advances in Environmental Biology*. 8(14): 20 - 23

[20] Lower, S. 2004. Electrochemistry. Chemical Reactions At An Electrode, Galvanic And Electrolytic Cells. URL http://www.chem1.com/acad/webtext/elchem/.