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Article *in* Research Journal of Applied Sciences, Engineering and Technology · July 2014

DOI: 10.19026/rjaset.8.934

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Research Journal of Applied Sciences, Engineering and Technology 8(1): 9-19, 2014
DOI:10.19026/rjaset.8.934
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: October 19, 2013 Accepted: October 25, 2013 Published: July 05, 2014

Research Article

Comparative Energy Generation of Irish-potato, Tomato and Pineapple ZN/CU Vegetative Batteries

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Abstract: Environmental pollution associated with petroleum sources of energy has reinvigorated interest in the need to find "greener" electrical energy alternatives without a net carbon emission into the ecosystem to solve these problems. This research study analyzed electricity generation through bioelectrolytic reaction from an *irish-potato, pineapple* and *tomato* as electrolyte for the vegetative batteries with Zn/Cu as electrode. Treatments were performed on samples. In the first treatment, vegetative samples were heated at varied temperatures (19.5-80°C) and at varied holding times (20-60 min). In the second type, sample tissues were sandwiched between two aluminium plates through which pulses of *ac* current were passed at varied frequencies (2.63-100,000 Hz) maintained at 312 mV. With 108 cm^3 of sample, the battery capacities in untreated state were: *irish-potato* 53.7 mAh, *pineapple* 84.2 mAh and *tomato* 80.4 mAh; heat treated state: *irish-potato* 66.86 mAh, *pineapple* 116.4 mAh and *tomato* 108.8 mAh; while in electro orated state: *irish-potato* 68.9 mAh, *pineapple* 96.0 mAh and *tomato* 105.67 mAh. All these capacities were found experimentally to power a LED of forward current 1.44 mA, resistance of 270 Ω and supply voltage of 3V. Primary cost analyses showed that electro orated Zn/Cu vegetative battery samples generates portable energy of 5.74-50.54 cts/Wh, which is *14-124* times more than the currently available dry cell (D-type) cells retailed at 7.14 Ksh/Wh. Given that irish-potato is ranked fourth (after maize, wheat and rice) in the world and the second most important food crop after maize in Kenya in terms of abundance, it was recommended as an alternative vegetative battery.

Keywords: Electroporation, heating, treatment

INTRODUCTION

The absence of commercially supplied energy in a society, especially electricity, tends to accentuate the existence of social asymmetry in conditions of living. This can take the form of increased poverty, lack of opportunity for development, migratory flow to large cities and a society's disbelief regarding its own future. There is a general belief that, with the arrival of electricity, such societies might acquire a higher degree of economic sustainability and a better quality of life (Pereira *et al*., 2010).

The availability of modern energy in South Asia and Sub-Saharan Africa continues to lag far behind the rest of the world, in spite being vegetative crop farmers (Skipper, 2010).

The grid electricity defficiency in rural areas give rise to the use of alternative electrical power sources. Sources of power like dry cells for powering small electronics and lighting are relatively expensive and can not be aforded by some people in rural areas. The option left is the use of vegetative batteries, which when implemeted well, will suplement to the available sources of energy in driving the rural economy into self sustainability.

Currently there has been an increase in the volumes of irish-potatoes processed as chips and crisps, with an annual production of 2,192,280 metric tons (HDA, 2008). Otipa *et al*. (2003) found that irish-potato (*Solanumtuberosum*) is ranked fourth most important food crop in the world after wheat, maize and rice with annual production approaching 300 million tons. It is the second most important staple food crop in Kenya after maize. Tomatoes are consumed in both fresh and processed state. They are grown under both rain fed and irrigation conditions. Lately farmers have extensively adopted high yielding varieties and modern technologies. This has resulted to an annual production of 567,780 metric tons (HDA, 2008). Pineapples are grown for both local and export markets as fresh and

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processed products. Smooth Cayenne is the commonly grown variety and has high brix content. Central Province is the main producer with the bulk coming from Delmonte K Ltd and Kakuzi Ltd with an annual production of 429,065 metric tons (HDA, 2008).

In this research, expeimetal electrical energy analysis were carried on Irish-potato Tomato and Pineapple vegetative crops with an aim to provide electric power to the rural dwellers who are vegetative crop farmers.

MATERIALS AND METHODS

Materials: Samples for experiments (irish-potatoes, tomatoes and pineapples were collected from the farmers in Uasin Gishu County, Kenya.

Equipments: Function generator, Oscilloscope, multimeters and water bath were all obtained from the laboratories of school of engineering of Moi University, Kenya. Copper and Zinc plates were purchased from school chemicals and equipment shop at Eldoret town, Kenya.

Methods: Electrode strips were cleaned with extra fine steel wool to remove any corrosion on the surface, thus, improve the conductivity. Fresh samples were used in each experiment. The amount of each sample used in the experiment at a time was obtained by considering the cubic space of the biogalvanic cell model (6.9 lengths, 4.9 height and 3.2 cm distance between electrodes) which was found to be 108 cm^3.

For the untreated (raw) experiments, samples were carefully inserted between a flat parallel copper and zinc rectangular electrode to make a model of biogalvanic cell. For heat treated sample, the samples were placed in a fabricated container for heating in the water bath. Heating was done at 40°C, 60°C and 80°C for each holding time duration of 20, 40 and 60 min at a time. Samples were used after cooling to room temperature of 19.5°C. The maximum observed OCVs were obtained and record on the data sheet, from which the optimum heat treatment conditions were obtained.

For electro orated experiment, samples were carefully placed in the battery casing sandwiched between two aluminium electrode plates. Using the function generator (FG601), the frequency of the alternating current was varied from 2.63 to 100,000 Hz at a fixed voltage of 3.12 mV as suggested by Zimmermann *et al*. (1976). This was to enable the determination of the optimum treating frequency of the electrooration. Once the desired frequency was set, the oscilloscope probes were disconnected from the function generator output terminals while the function generator power set off. The probes of the terminal were then connected to the battery terminals; the function generator alternating current was then passed through the samples at approximately 1s by setting the power ON/OFF to electro orate the cells.

Sketch of the circuit connection

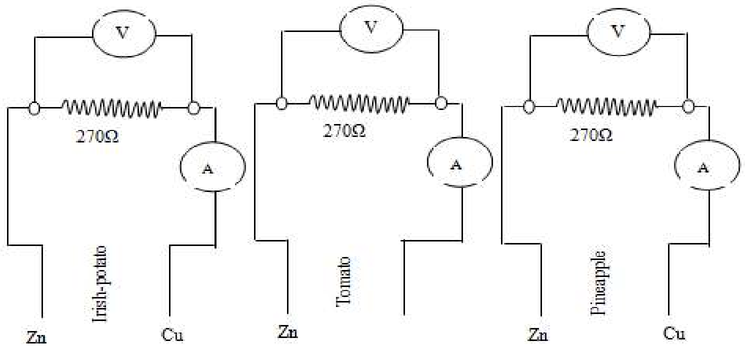

Fig. 1: Circuit connection with fixed external resistor

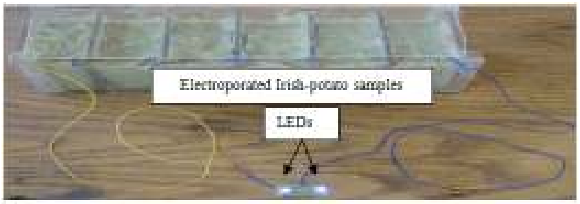

Fig. 2: Lighting application

Observed maximum OCV was first obtained and recorded before the application of the external resistor. The readings for the voltage and current were recorded on a data sheet, as the external resistance was simultaneously varied from 3 to 95,000 Ω using a variable resistor. For the determination of sample cell capacity and energy generation, a fixed external resistor of 270 Ω was applied to the cell for a continuous period of 20 h (Fig. 1).

During this research, the potential of this vegetative sample cell to respond to low power electrical energy needs were demonstrated in the laboratory through experimentation with electro orated irish-potato sample (Fig. 2 and 3). Two white Light-Emitting Diodes (LEDs) extracted from dry cells torch, requiring a minimum forward current of 1.44 mA and a voltage of 3 V were connected in series to six electroorated irish-potato sample cells. In this case, the LEDs emitted a continuous light for 1h until voluntarily disconnected. On the other hand, eleven cells were connected in series and with the help of a *dc* cellular phone charger; used to carry out charging. The charging proceeded for approximately 2 min. This implies that if more cells are involved, then the cellular phone can be charged fully.

RESULTS AND DISCUSSION

Determination of optimum heat treatment temperature and holding time: The effect of physical disruption treatment of the samples by heating at various holding time at various temperatures as well, were presented graphically as shown in Fig. 4 to 6.

At each holding time during the heat treatment of the samples at varied temperatures, an increase in OCV was observed at the beginning which eventually dropped after holding temperature above 60°C. The drop in the OCV was attributed to the thermal effect of the intercellular membrane that results to hardening of the cell membrane, hence, increase in resistance that

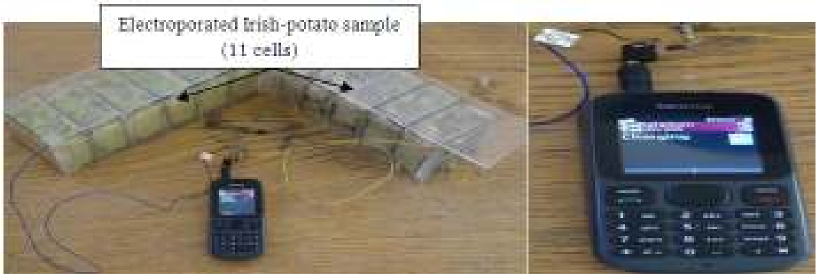

Fig. 3: Cellular phone charging application

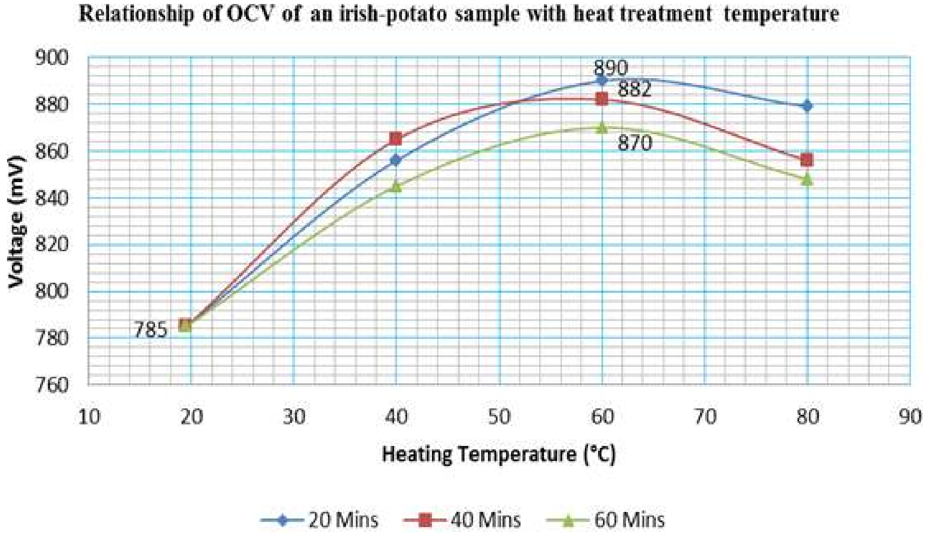

Fig. 4: Effect of heat treatment of irish-potatoe sample on OCV

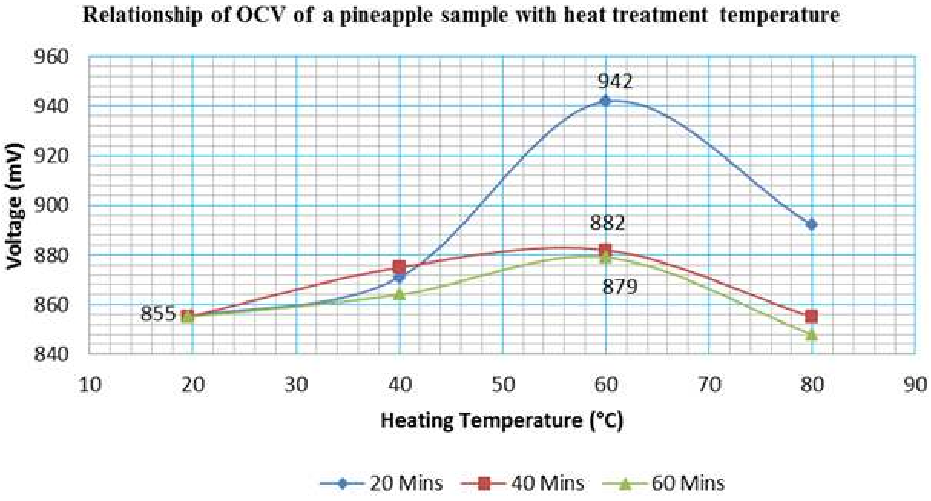

Fig. 5: Effect of heat treatment of a pineapple sample on OCV

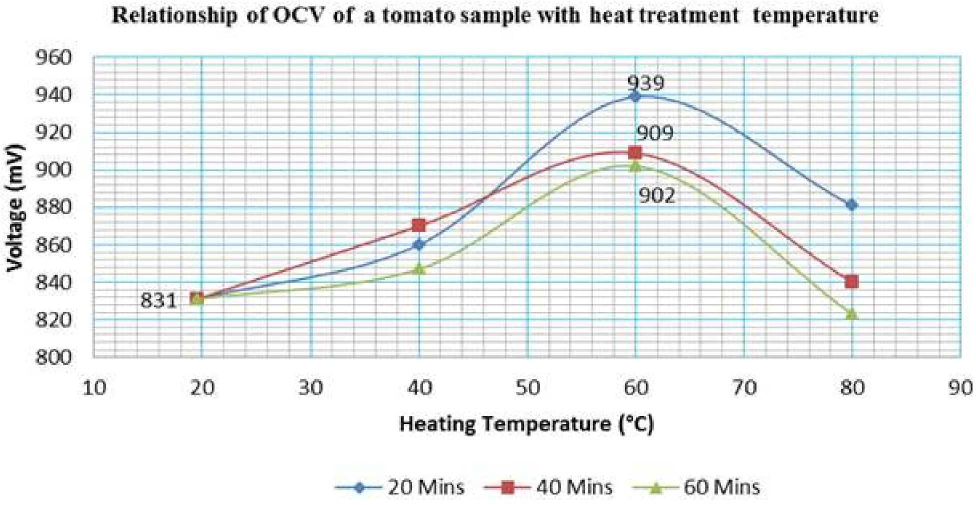

Fig. 6: Effect of heat treatment of a tomato sample on OCV

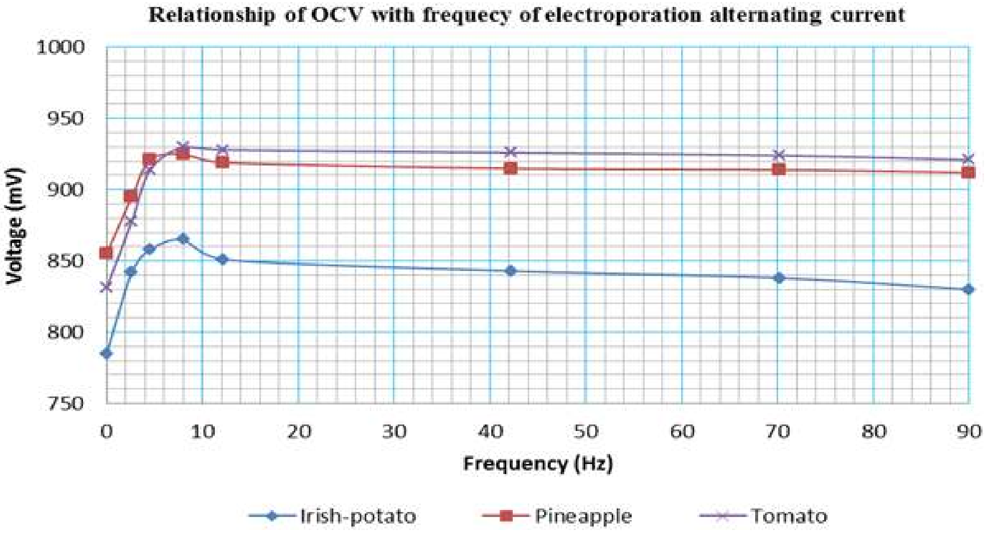

Fig. 7: Effect of electroporation treatment of the battery samples on OCV

Table 1: Maximum observed current at optimal electrooration current frequency

Biogalvanic cell	Irish-potato	Pineapple	Tomato
Max. observed current	0.006 mA	0.008 mA	0.008 mA

Table 2: Maximum open circuit voltage

	mV		
Samples	Irish-potato	Pineapple	Tomato
Untreated	785	855	831
Heated	890	942	939
Electro orated	865	925	930

leads to reduction of the OCV at higher holding temperature above 60°C. It was evident that heat treatment at temperature of 60°C for holding time of 20 min yields maximum OCV (Irish-potato: 890 m V, Pineapple: 942 mV and Tomato: 939 mV), neglecting the environmental effects.

Determination of the optimum electrooration current frequency: For the electroporation treatment, results were presented graphically as shown in Fig. 7. The data were only up to a frequency of 90 Hz because of the subject of interest for maximum OCV. This was because there was a drop in OCV with the subsequent onward frequencies. It was noted that, OCV increases with current frequency from 2.63 Hz which eventually dropped. The fall in OCV was attributed to thermal effect on the intercellular cell membrane that caused hardening. From the graphical trend; it was observed that maximum OCV occurs at 8 Hz of alternating current frequency, thus, regarded as optimal electrooration treatment condition.

The maximum observed current at corresponding optimal alternating current frequency was as shown in Table 1.

Open circuit voltage: Under the subjected conditions there was no external electric current due to absentia of the external load between the terminals, even though there could be current internally (e.g., self-discharge currents in samples). For the sample batteries, the maximum open circuit voltage measured was tabulated as shown in Table 2.

It was seen that untreated samples of the cell possessed the lowest OCV. The order of OCV from the lowest was irish-potato, tomato and pineapple with the highest. With heat treatment, OCV measured from lowest was irish-potato (13.4% increases), tomato (13.8% increase) and finally pineapple (11.1% increase) with the highest; while after electrooration treatment, OCV measured in order from the lowest was irish-potato (10.2% increase), pineapple (8.2% increase) and finally tomato (11.9% increase) with the highest.

Polarization curves for the vegetative battery samples: It was seen that polarization increases with treatment (Fig. 8 to 10). Treatment opens the cell membrane, hence, increase in saturation of the ionic conductivity. It was clear that untreated sample possessed a larger activation barrier which must be overcome in order to initiate the electrochemical reaction, smaller ohmic polarization and mass transfer zones. Heat treated samples were observed to possess smaller activation and mass transfer zones while larger ohmic zone. It was seen that generally, treatment increase ohmic zone. Treatment improves the ohmic zone greatly, hence, higher ions for electrical conductivity. This may be attributed to the creation of micro-porous layer in vegetative samples that results to opening of the cell membrane.

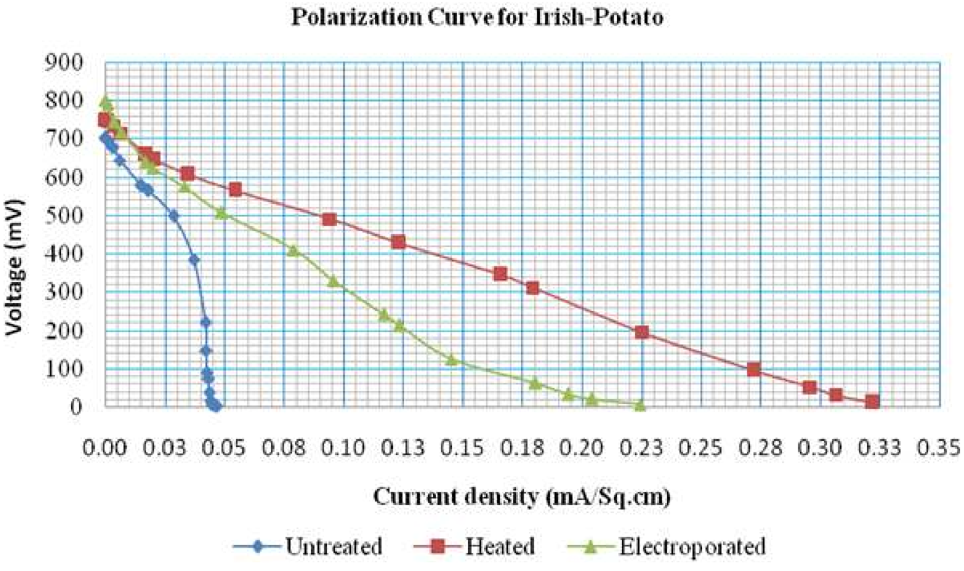

Fig. 8: Effect of sample treatment on polarization curve of the Irish-potato sample cell

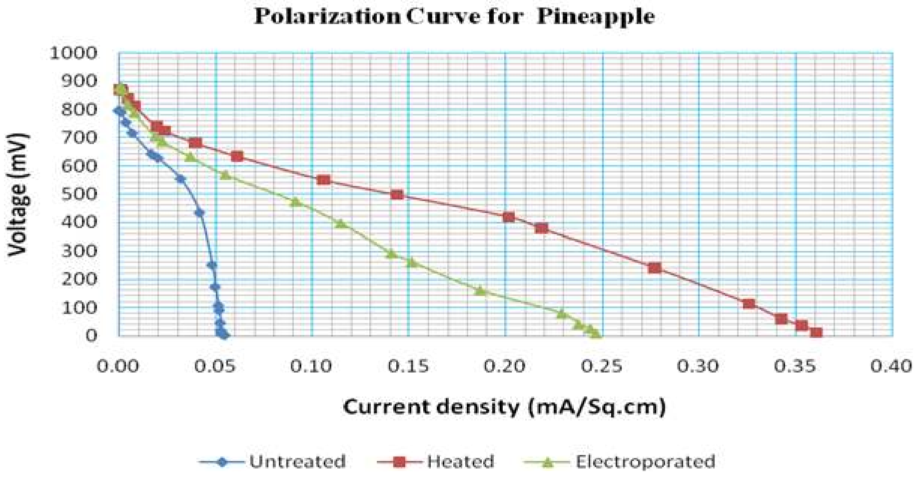
Polarization Curve for Pineapple

Fig. 9: Effect of sample treatment on polarization curve of the pineapple sample cell

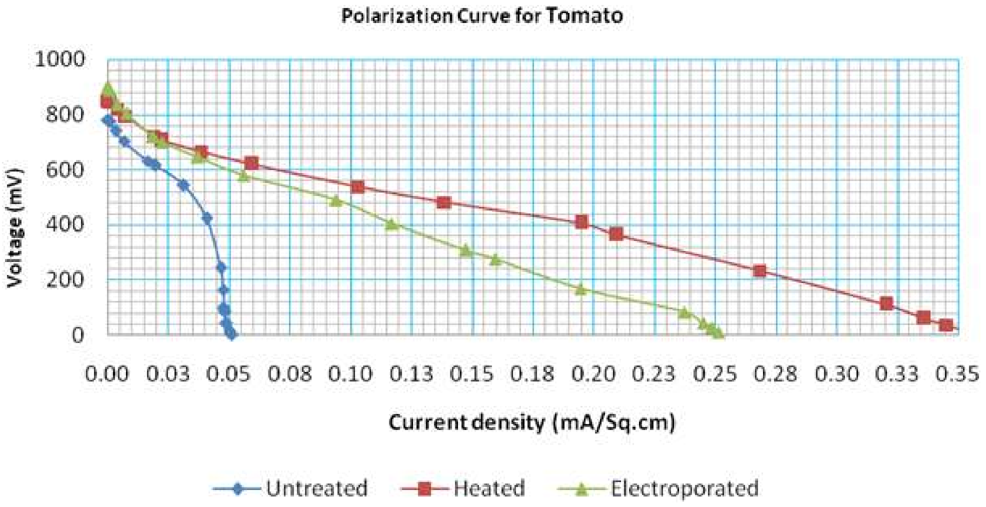
Polarization Curve for Tomato

Fig. 10: Effect of sample treatment on polarization curve of the sample tomato cell

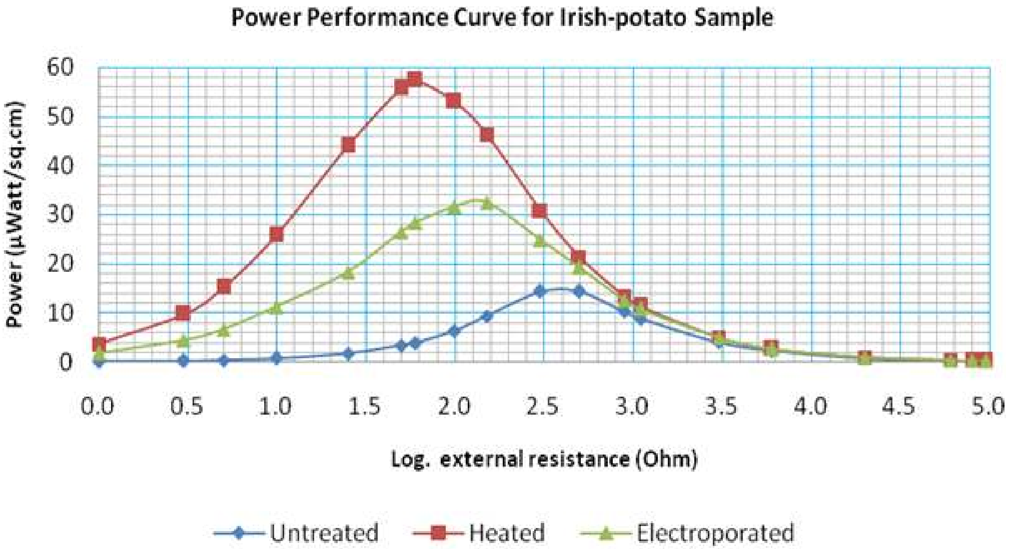
Power Performance Curve for Irish-potato Sample

Fig. 11: Effect of application of external load on Irish-potato sample power generation

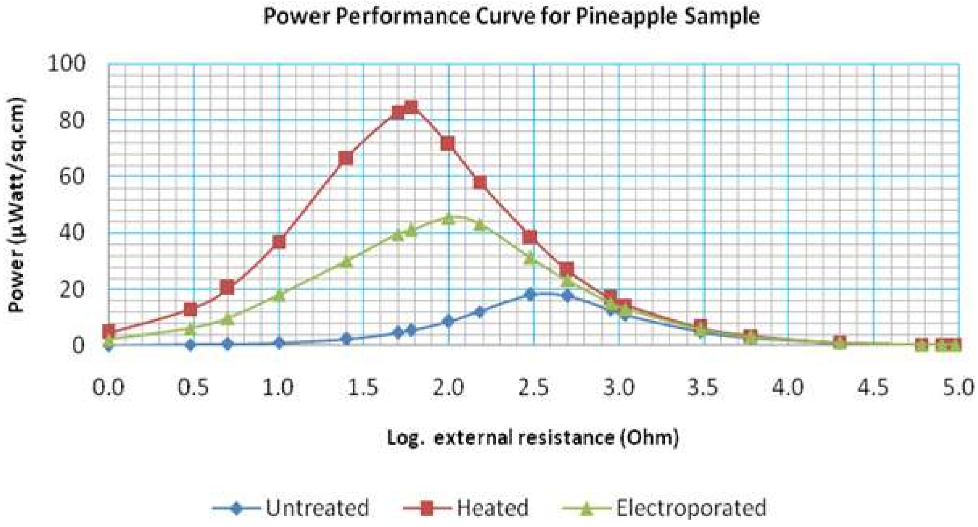

Fig. 12: Effect of application of external load on pineapple sample power generation

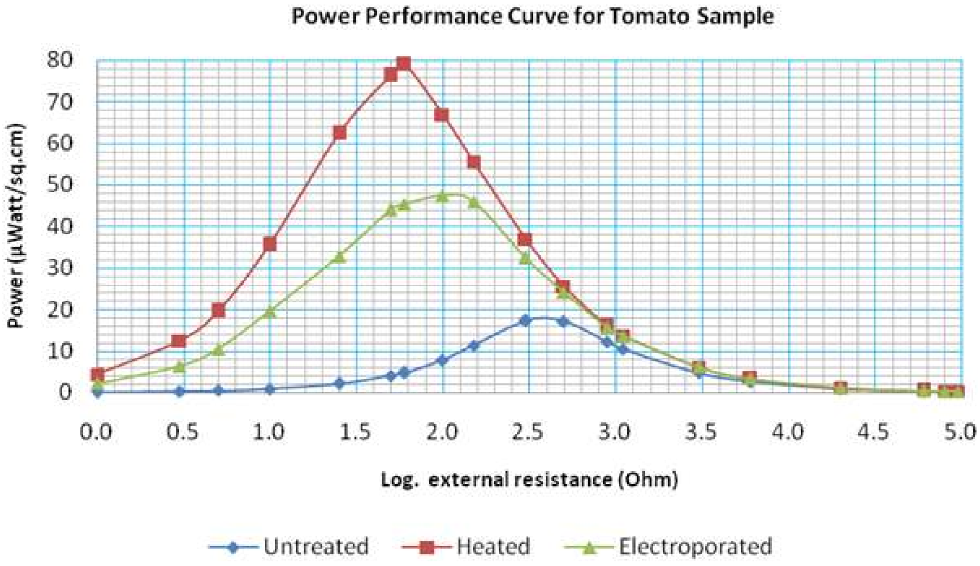

Fig. 13: Effect of application of external load on tomato sample power generation

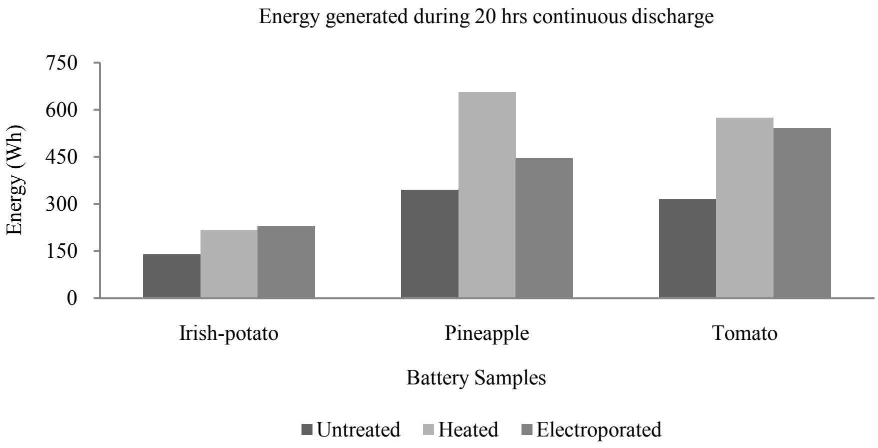

Fig. 14: Energy produced by samples during the 20h discharge over constant external load (270 Ω)

Effect of physical disruption of a sample cells on application of external loads: Power density analyses were graphically presented in Fig. 11 to 13.

The power delivered is maximized when the external load matches the internal resistance of the cell i.e., max power occurs when $R_L = R_m$. From the graphs, it can be seen that value for the external load shifts to the left for the maximum power delivery. Hence, it was deduced that treatment reduces the internal impedance of the sample cell leading to higher power generation.

Electrical energy of the battery sample: From the computations, the energy generated by the battery samples was presented as in Fig. 14.

It was found that energy generating capabilities of samples made of physically disrupted tissues were significantly higher than those delivered by untreated (fresh) ones.

Galvanic apparent internal impedance: Plotting $\frac{1}{I_d}$ against R_{ext} (Fig. 15) showed a highly linear performance, thus, supporting the evidence that the vegetative samples react as ohmic resistance over a wide range of external loads. This linear response allows a good estimate of GAII (Galvanic Apparent Internal Impedance), which reflects the conductance of the salt bridge between the electrodes during the electrolytic process.

Comparison of power discharge of each sample (untreated and treated samples): The power performance of the battery samples were studied by

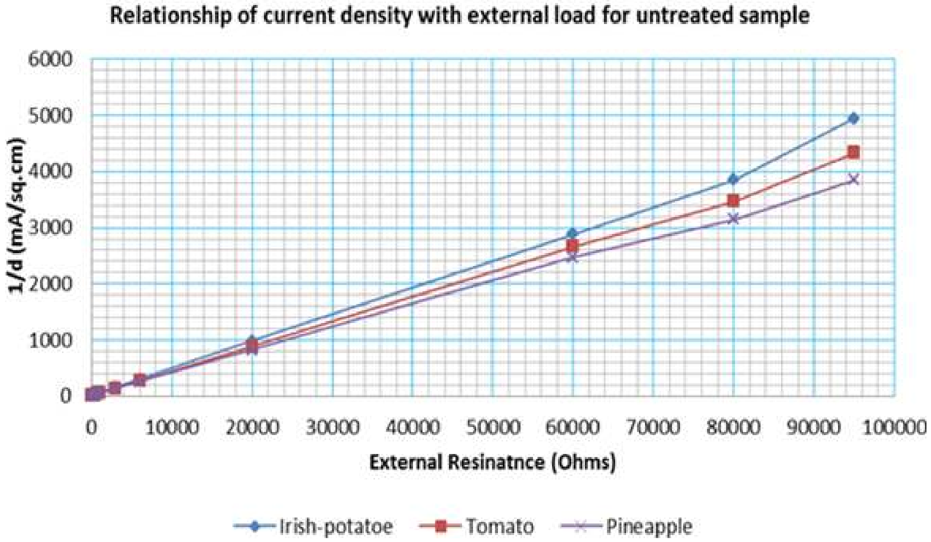

Fig. 15: Relationship of current density of untreated samples with external load

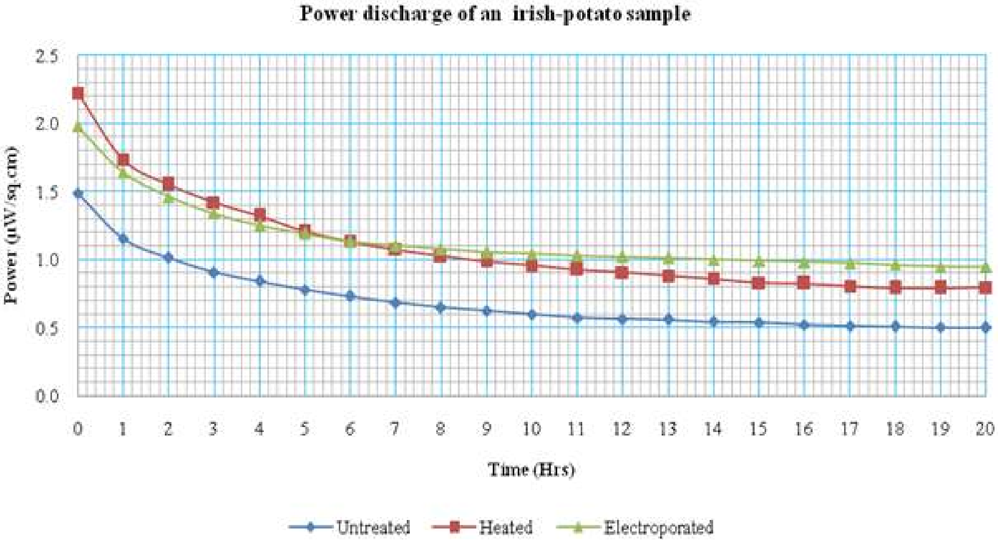

Fig. 16: Power discharge characteristic of an Irish-potato battery sample

discharging the batteries through fixed external load of 270 Ω. The analysis was presented graphically (Fig. 16 to 18).

In all the samples, it was observed that power possessed by untreated samples was significantly lower compared to that of treated. Treating creates micro-pores in the cell membrane, hence, reducing the internal impedance leading to higher power generation. In all the states, there was a decrease in the energy generation with time as discharging proceeds.

Energy balance: Electrical energy generation for the direct current produced is given by Eq. (1):

$$E_e = I^2{}_{r.m.s} \times R \times T \qquad (1)$$

E_e = Electrical energy generated by heat treated sample
$I^2{}_{r.m.s}$ = Equivalent direct current (Root mean square current)
R = External load (270 Ω)
T = Total discharge time (72000s)

Thermal energy of heat treatment by the water bath is by Eq. (2):

$$E_{ht} = mc\Delta\theta \qquad (2)$$

where:
E_{ht} = Thermal energy of heat treatment by water bat
m = Mass of water bath (1.2 kg)

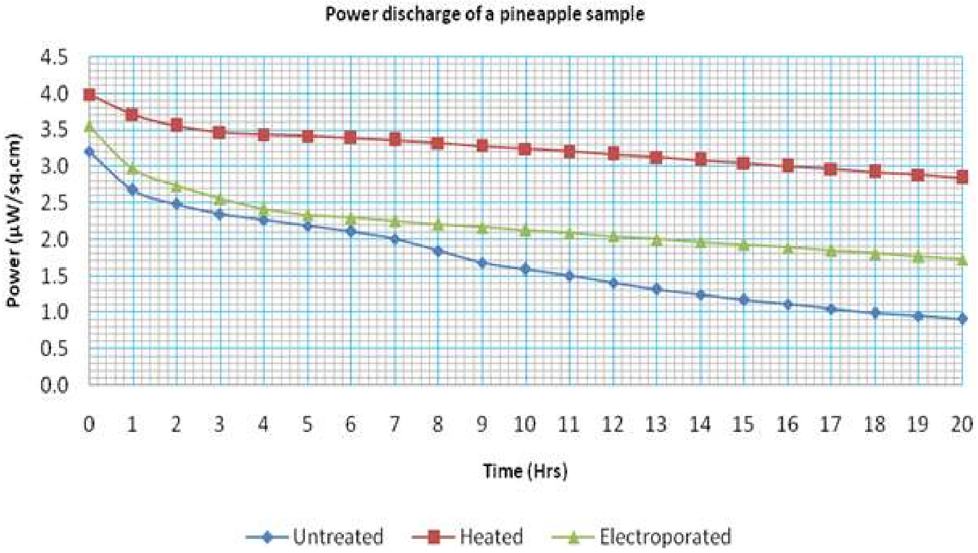

Fig.17: Power discharge characteristic of pineapple battery sample

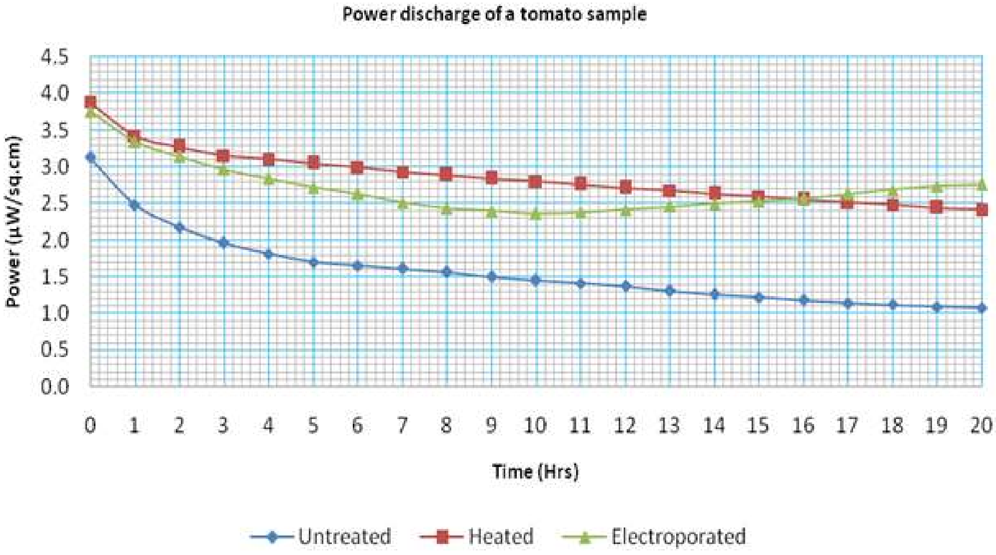

Fig.18: Power discharge characteristic of tomato battery sample

c = Specific heat capacity of water (4200 J/kg K)
$\Delta\theta$ = Temperature change (K)

Electrical energy generation for the alternating current is given by Eq. (3):

$$E_{et} = \frac{V_m \times I_m}{2} \times t \tag{3}$$

where:

E_{et} = Electrooration energy absorbed during treatment
V_m = Max. applied voltage
I_m = Max. Current
t = Electrooration time (s)

Using Eq. (1), energy generated by the untreated samples during discharge was: Irish-potato - 67.82 kJ; Pineapple, - 67.38 kJ and Tomato, - 67.46 kJ.

Using Eq. (1) and (2), energy balance of heat treated samples was: Irish-potato, -54.14J; Pineapple, - 53.56J and Tomato, -53.66J.

Since maximum applied voltage was 312 mV, electrooration pulse time of approximately 1 second and given the maximum circuit current (Table 1); using equation (1) and (3), energy balance of samples treated by electrooration was: Irish-potato, +230.05J; Pineapple, -+446.03J and Tomato +541.96J. Percentage increase in energy generated through electrooration treatment was: Irish-potato, 64.76%; Pineapple, 29.45% and Tomato 72.51%.

From the energy balance calculation, it was noticed that:

- Energy balance values of samples treated by heating (Table 3) were both negative. This was attributed to a high specific heat index of water-water absorbs a lot of heat before it begins to get hot. Thus, to attain the specific heat value, a substantial amount of heat energy must be supplied. The negative energy value implied that a lot of energy was consumed during treatment than that generated. Considering from this point of view of sample treatments, it means that economically heat treatment did not add value to the energy generation of the battery samples.
- Energy balance from samples treated through electrooration showed a positive value throughout (Table 4). This implied that, there was an increase in energy generation after treatment, thus, recommended treatment method.

Table 3: Energy balance for heat treated battery samples

Battery sample (Heat treated)	Energy generated by heat treated sample $E_e = I^2_{r.ms} \times R \times T$	Energy of heat treatment $E_{ht} = \frac{mc\Delta\theta}{3}$	Energy, Ebh(kJ)
Irish-potato	$\frac{3.35^2 \times 270 \times 72000}{1{,}000{,}000}$	$\frac{1.2 \times 4200 \times (60 - 19.5)}{3}$	- 67.8218
Pineapple	$\frac{5.81^2 \times 270 \times 72000}{1{,}000{,}000}$	$\frac{1.2 \times 4200 \times (60 - 19.5)}{3}$	-67.3
Tomato	$\frac{5.44^2 \times 270 \times 72000}{1{,}000{,}000}$	$\frac{1.2 \times 4200 \times (60 - 19.5)}{3}$	- 67.4647

Table 4: Energy balance for samples treated by electroporation

Battery sample (Heat treated)	Energy generated by heat treated sample $E_e = I^2_{r.ms} \times R \times T$	Energy of heat treatment $E_{et} = \frac{V_m \times I_m}{2} \times t$	Energy, Ebh(kJ)
Irish-potato	$\frac{3.44^2 \times 270 \times 72000}{1{,}000{,}000}$	$\frac{312 \times 0.006}{2 \times 1{,}000{,}000} \times 1$	$+230.05$
Pineapple	$\frac{4.79^2 \times 270 \times 72000}{1{,}000{,}000}$	$\frac{312 \times 0.008}{2 \times 1{,}000{,}000} \times 1$	$+446.03$
Tomato	$\frac{5.28^2 \times 270 \times 72000}{1{,}000{,}000}$	$\frac{312 \times 0.008}{2 \times 1{,}000{,}000} \times 1$	$+541.96$

ENERGY ECONOMIC ANALYSIS

Eveready manufacturer's data sheet specifies the dry cell's maximum capacity as 2.8 Ah. Thus, its total energy contents amounts to (2.8 *Ah x* 1.5 *V*) 4.2 Wh. The retail price of this specific battery equals to 30 Ksh/ 4.2 Wh i.e., 7.14 Ksh/Wh.

From the computations, it was found that the total cost of energy for samples treated by electrooration (in 20 h) i.e., cost of the vegetative sample plus cost of Zn metal consumed for irish-potato was 43.60 cts/Wh, tomato sample was 18.51 cts/Wh and pineapple was 22.57 18.51 cts/Wh.

Hence, it is clear that the power generated by Zn/Cu- vegetative samples was much cheaper (excluding the marginal costs of electricity consumed during electrooration treatment and Cu electrode that was not consumed) than any conventional portable battery, hence, produces with LED's substantially cheaper lighting than dry cell. The proposed technology may be implemented in the developing countries for improving the life quality on numerous people who do not have access to grid electricity.

APPLICATION

Vegetative crops are widely available in the word i.e., irish-potato is fourth in the world (FAO, 2007). Since there was significant increase in both energy balance and capacity after treatment through electroporation, it was ranked as the best vegetative sample to serve as an alternative source of electrical energy.

Mills *et al*. (2009) reported that in developing countries, LEDs consuming 8.3-53.1 lm/W are available for off grid lighting. Due to the depletion of fossils fuels including environmental hazards associated with it, it is obvious that using the former for lighting can increase power availability to people in undeveloped areas and reduce the said pollution.

Simple electrooration can be carried out using a *dc* cell with a help of *dc* to *ac* inverter while boiling is affordable all over; hence, the said technology may be implemented for lighting and also for other applications such powering portable radios requiring low electrical energy consumption and charging of cellular phones. Both the latter will go a long way to having informed population through enhanced communication (Mills *et al*., 2009).

CONCLUSION

Investigation on the performance of irish-potato, pineapple and tomato vegetative as an alternative source of renewable energy for small electric current generation allowed the following conclusions to be made:

- An irreversible change in the cellular and tissue structures either through irreversible electrooration or heating significantly affects the electrical characterization values, with the consequence of increasing the magnitude of the electrical power generation.
- Tomato was found to be the best vegetative battery sample in terms of electrical performance. However, its major shortcoming is its lack of popularity among the farmers. Irish-potato was found to be the least in the performance but its major advantage is its abundance in availability, being the second most important staple food crop in Kenya after maize and ranked fourth most important food crop in the world after wheat.
- Power generated by Zn/Cu vegetative samples was much cheaper than any conventional portable battery.

The overall conclusion is that, treatment leads to formation of micro-pores in cell membrane, leading to reduction in the internal impedance of the salt bridge.

ACKNOWLEDGMENT

The authors acknowledge the financial support provided by Moi University, Kenya.

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