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Potential of Root Crops as Source of Electrical Energy

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ABSTRACT

Energy from edible and inedible root crop roots and tubers using galvanic cell and processing wastewaters through microbial fuel cell (MFC) technology was harnessed. Electrolyte in the roots and tubers was tapped for galvanic cell and the microorganisms from waste waters act as catalyst in MFC. In galvanic cell, the optimized responses of *Badiang,* cassava and sweetpotato were greatly affected by the surface area and distance between anode and cathode electrodes. An increase of *nata-de-coco* membrane size in MFC increased the voltage and current by 4.94 and 11.71 times, respectively. Increasing the width of anode also enhanced the responses. Different types of microorganisms were isolated from the biofilm anode of MFC. Their growth and proliferation which corresponded to the generation of electricity were also demonstrated in this study. A total of 54 bacterial isolates were collected from the biofilm at the anode of single-chamber MFC (SCMFC). The generated electricity observed using light emitting diodes (LED) showed potential both for galvanic and microbial fuel cell. The generated regression models are reliable tools in predicting desired outputs for future applications. These promising results demonstrated basic information on the electrical energy recovery from root crop waste waters and roots/tubers.

Key words: energy, galvanic cell, root crop, microbial fuel cell, biofilm, *nata-de-coco* membrane

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INTRODUCTION

Root crops when processed into starch, dried grates and other food products produce processing waste by-products such as wastewater. Treatment facility should be installed in any processing plant so as not to pollute the environment. During the treatment process, the processing wastes are degraded by microorganisms until safe to be discharged to bodies of water. It is not generally known is that during the treatment process, wastewaters have microorganisms that can potentially produce electricity through microbial fuel cell technology (Rabaey *et al*., 2005). With this information, it is therefore necessary to explore the potential of the root crops processing wastewater as source of electricity because of its high energy content which is a good source of food for the microorganisms. While utilizing cassava wastewater as medium to the microbial fuel cell (MFC), other alternatives of membranes used in MFC which are cost-effective and would bring about the advancement of MFC technology, need also to be explored.

Another potential of root crops as source of electrical energy is their high water content which may be a good source of an electrolyte. It has been studied that potato can produce electricity by placing the copper and zinc electrodes deep within the potato root itself (Abdalla and Al-Ghamdi, 2011).

This study evaluated the potential of edible and inedible root crops as source of electrical energy, developed microbial fuel cells from root crop wastes, and isolated the microorganisms found in the cassava wastewater that generated electricity.

MATERIALS AND METHODS

Variable Screening for MFC and Galvanic Cells

Figure 1 shows the different MFCs used in the study. A preliminary experiment used the H-type double chamber MFC equipped with salt-bridges concentrated with salt solution in the agar medium. During the screening proper, vertical configuration of double-chamber MFC shown in Figure 1b was constructed mainly with two containers faced upside-down. Due to pressure build up at the anode chamber, the agar salt-bridge was changed to a treated *nata-de-coco* film as alternative. The feed on the anode chamber was cassava wastewater (*Lakan* variety).

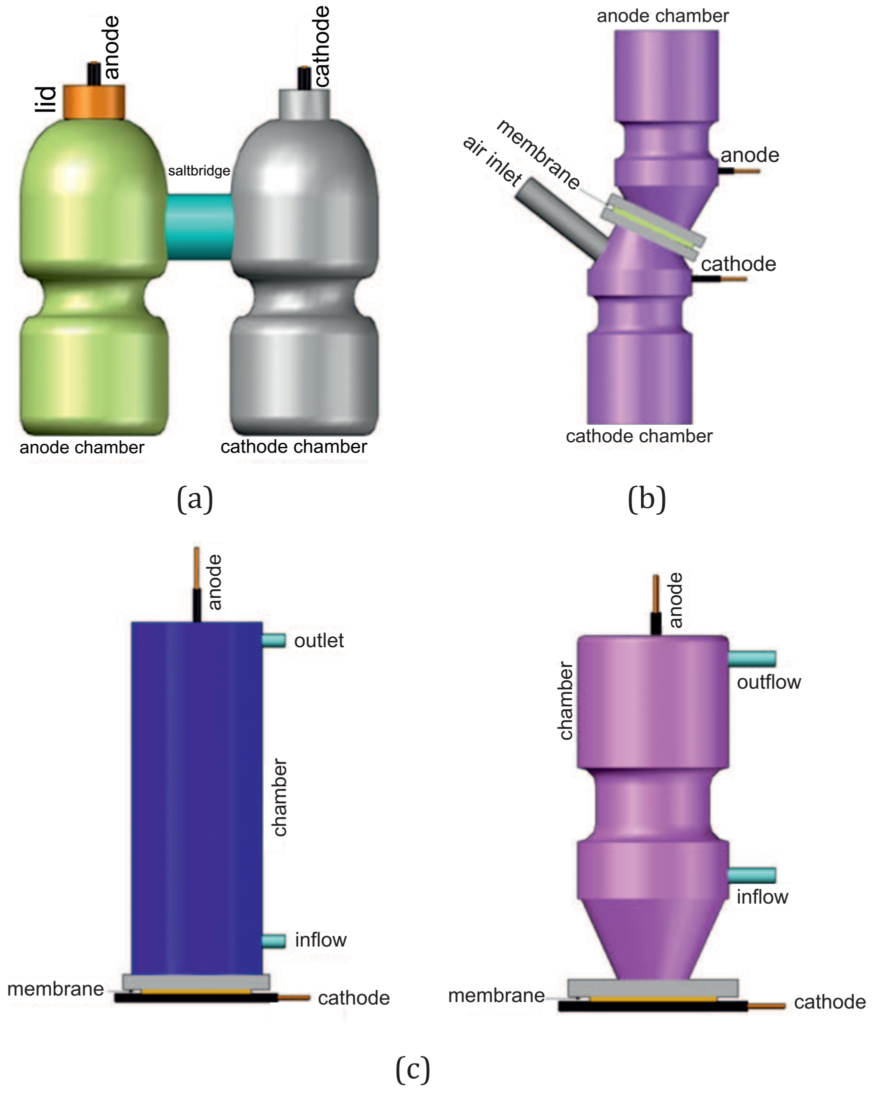

Figure 1. Various types of microbial fuel cell and its components used in the study: (a) double-chamber MFC equipped with salt bridge, (b) upside-down MFC equipped with nata-membrane and (c) batch/continuous single-chamber MFCs.

Badiang roots were used in the screening of variables for galvanic cells. Electrodes used were Copper (Cu) tubes or wires and Zinc (Zn) wires or tubes as cathode and anode, respectively. Zinc electrodes were plates made into tubes. These electrodes were then inserted to the roots.

Construction and Optimization of Microbial Fuel Cells

Single–chamber microbial fuel cells (SCMFC) using the blue PVC pipes (Figure 1c) were constructed for the optimization experiment and only two variables (size of *nata-de-coco* membrane and size of anode) were run due to insufficient carbon electrodes available. The fabricated MFC was equipped with an air-cathode carbon block directly exposed to the air. Connected to these electrodes were solid wires as terminals. The ion-exchange membrane sandwiched by the cathode and anode was a treated *nata-de-coco* film. Wastewater fed to the chamber was from cassava processing grates.

Especially fabricated MFCs were designed and constructed for easy collection of biofilms present on the anode electrodes. For preliminary monitoring, a double-chamber MFC was used in the microbial isolation and after sometime, SCMFC (Figure 1c) were assembled for the enrichment of fresh cassava waste as fuel to the cell. The MFCs were fed with 20 ml fresh cassava wastewater every 5th day.

Microbial Analysis

Screening and evaluation of microorganisms from waste waters from cassava grates and taro wine processing for the production of electricity

Two types of substrates were utilized and evaluated by measuring the voltage generated in fuel cells. These are the wastewaters from cassava grates and taro wine processing. When cassava grates were used, pure culture of lactic acid bacteria which was isolated from sweet potato pickles was inoculated into the substrate while the taro wine wastewater was directly fed to the anode chamber of the H-type MFC (Figure 1a). Continuous single chamber MFC utilizing blue PVC pipes was used during fermentation.

Isolation and characterization of microorganisms that produce electricity

Microorganisms were isolated from a continuous single-chamber MFC. All isolates were purified and partially characterized based on their cultural characteristics specifically on their growth behavior in media such as Nutrient agar slant/stab and Nutrient broth. Isolation was done every week for 6 weeks through destructive sampling.

Galvanic Cell Optimization

Galvanic cell set-up was separately conducted on three different roots or tubers (*Badiang*, sweetpotato-*SP17variety*, and cassava-*Lakanvariety*); each ran with 3 variables (distance between electrode, diameter of electrodes, and depth of penetration to the roots). Materials included: Copper tubes and wires (3 sizes), Zinc tubes and wires, soldering iron and leads, and alligator clips. The sizes of copper tubes were readily available while Zinc plates were made into tubes due to unavailability of prefabricated ones. Verification was conducted to validate and confirm the predicted values in the regression analysis. An endurance test was done in each root using light emitting diodes (LED) lamps.

Experimental Designs, Data and Statistical Analysis

An 8-run Plackett-Burman (PB) design was used in the screening of variables both for the MFC and galvanic cell. During the optimization, MFC experiment was laid on 3x3-full factorial while galvanic cell experiments were on 3x3x3-full factorial design. The voltage (mV) and current (mA) were monitored daily using digital multimeter and were statistically analyzed using SAS (for PB) and evaluation software of the DX7 (Design Expert Version 7.1). Comparison between means was achieved using Fisher's least significant difference (multiple-paired T-test) at the Dx7.

RESULTS AND DISCUSSION

Optimal Electrical Generation of Single-chamber MFC

Regression models resulted an optimum voltage and current of 447.74 mV and 5.43 mA (Table 1) respectively. On the average, peak actual voltage (398 mV) and current (2.03 mA) were between the first and second day

(Figure 2). This trend was also revealed in the study of Rosenbaum *et al.* (2005) and Kim *et al.* (2005) on domestic wastewaters. The abundance of carbohydrates present at this period increased the microorganisms.

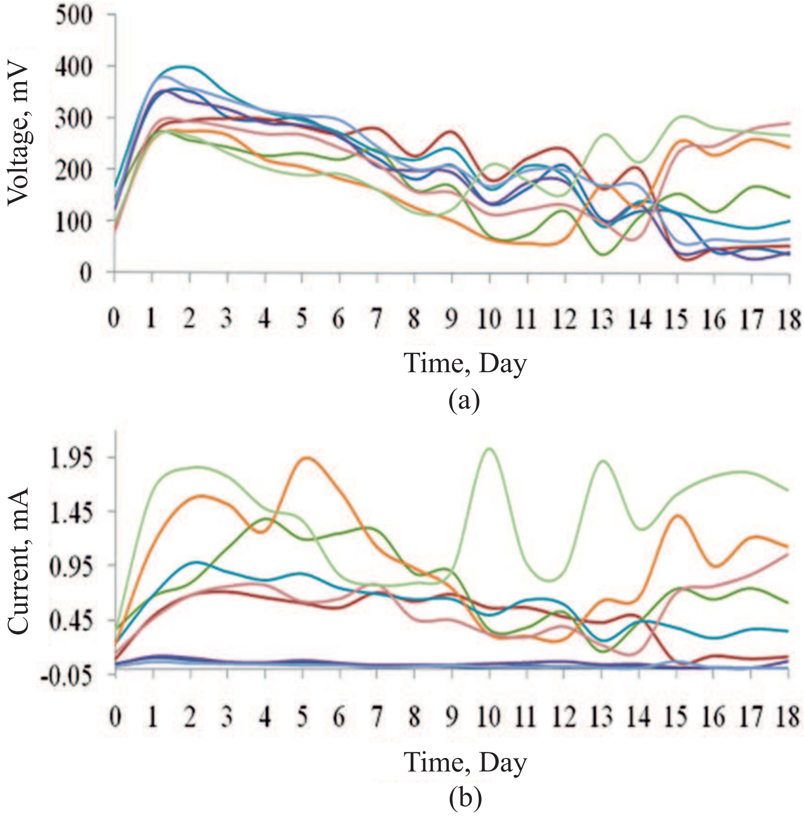

Figure 2. Actual generated voltage (a) and current (b) of single-chamber MFC during the optimization experiment.

Variables Affecting the Voltage and Current of Microbial Fuel Cell

Effect of Nata-de Coco Membrane to the voltage and current of the SCMFC

The actual maximum voltage and higher responses were reached at *nata-de-coco* membrane size greater than 5 mm. At 50 mm anode width, voltage increased by 4.94 times in an increase of *nata-de-coco* membrane from 5 to 21 mm while current increased by 11.71 times. Oh and Logan (2006) reported that proton exchange membranes need to be larger in surface area in order to boost the power generation.

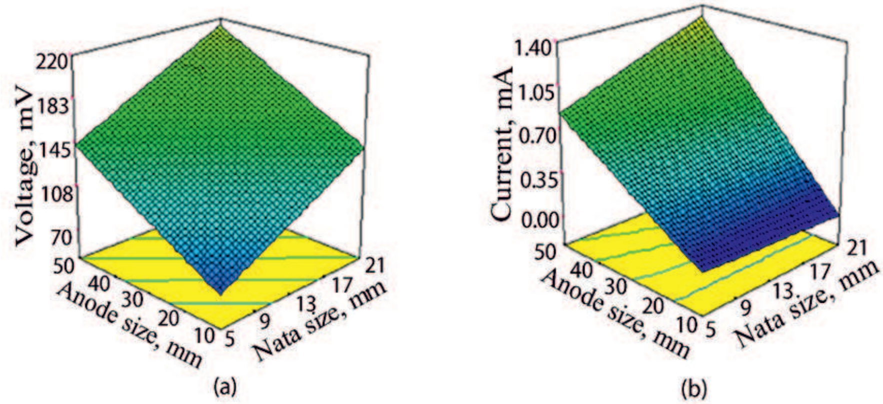

Figure 3. Contour plots: a) voltage and b) current resulted from the optimization of single-chamber microbial fuel cell.

Table 1. Optimum predicted responses and variables from single-chamber MFC.

	Source		F Value	p-value
Model	mV = 31.82662+4.37708*A+1.81028*B		8.50[b]	0.0016
	mA = -0.034106-0.013523*A+0.014484* B+0.000858925*A*B		86.44[a]	0.0001
Optimum	Voltage (mV)	Current (mA)	Values of Factors	
			A (mm)	B (mm)
	447.74	5.43	51.81	104.48

Note: A- nata-membrane size, B-anode width, mV-millivolt, mA-milliamps; a-significant at P<0.001; b-significant at P<0.05

Table 2. ANOVA for the voltage and current of MFC at the two main variables.

Source	Average Voltage		Average Current	
	F Value	p-value Prob > F	F Value	p-value Prob > F
A	8.22[b]	0.0085	8.72[b]	0.0071
B	8.79[b]	0.0068	239.15[a]	0.0001

Note: A- *nata-de-coco* membrane size, B-anode width; a- significant at P<0.001, b-significant at P<0.05

Effect of Anode Size

Size of anode electrode greatly influenced the voltage (P<0.as05) and current generation (P<0.001) of SCMFC (Table 2). Increasing the width of anode from 10 mm to 50 mm increased the voltage 2.5 times while current increased by 21.32 times (Figure 2). Microorganisms might be concentrated at larger areas of anode electrodes. Similar result was reported by Di Lorenzo *et al*. (2010) that an increase in anode surface area with decreased distance of electrodes reduced the internal resistance, thus, would lead to higher generation of power.

Microbial Analysis

Screening and evaluation of microorganisms from waste waters from cassava grates and taro wine processing for the production of electricity

The voltage readings from MFC with continuous single chamber utilizing blue PVC pipes fed with wastewaters from cassava grate and taro wine processing were determined and compared with one another (Figure 4). Wastewater from taro wine processing when used as substrate in MFC produced a consistent voltage readings during the entire duration of fermentation. When wastewater from cassava grate processing was utilized, an abrupt increase of voltage was observed on the third and fourth days (Figure 4). It has to be noted that waste water from taro wine processing contained various types of microorganisms such as molds, yeasts and bacteria (Sujaya *et al.,* 2004). In the case of waste waters from cassava grates processing, only one type of bacteria belonging to lactic acid bacteria group was utilized. MFC that operate using mixed cultures achieve substantially greater power densities than those with pure cultures (Rabaey *et al.,* 2004 *and* Rabaey *et al.,* 2005). However, Ringeisen *et al*. (2006) showed that with pure culture, high power generation was attained. The device however, was not tested in acclimatized mixed cultures and the cells were grown to the device externally.

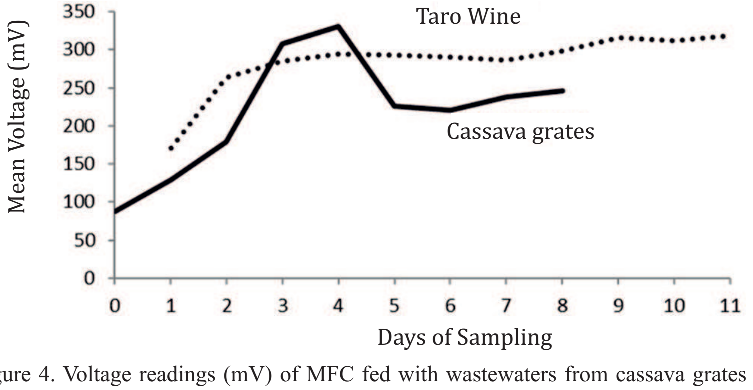

Figure 4. Voltage readings (mV) of MFC fed with wastewaters from cassava grates and taro wine processing.

Isolation and characterization of microorganisms that produce electricity

A total of 54 isolates were collected and purified from the biofilm anodes (Table 3). Aerobic microorganisms predominated in the biofilm anode. From these isolates, 31 were aerobes, 11 were anaerobes and 12 were facultative aerobes/anaerobes. The number of aerobes increased from 7 to 14 days but decreased after 42 days of fermentation. Anaerobes were consistently low in number throughout the fermentation time. Facultative aerobes/anaerobes however increased in number towards the end of fermentation time. In the study of Rabaey *et al*. (2004) on biofuel cell, facultative anaerobic bacteria such as *Alcaligenes faecalis* and *Enterococcus gallinarum*, along with *Pseudomonas aeruginosa* and other *Pseudomonas* species were also isolated. These microorganisms were able to grow considering composition of biofilm anode that would favor the growth and proliferation of different types of microorganisms. The biofilm matrix is sticky which is composed of complex of extracellular proteins, sugars and bacterial cells and tiny conductive nanowires that may help facilitate electron conduction (http://www.dailygalaxy.com/my_weblog /2008/08/the-biofilm-mat.html).

The growth of microorganisms in the anode which corresponded to the generation of electric current was demonstrated in this study. The increase in microbial counts resulted in the increase in voltage and current readings. However, the relationship of the growth and proliferation of aerobes, anaerobes and facultative aerobes and anaerobes was not clearly demonstrated. There is a need to study the activity of specific type of microorganisms and their combinations in the generation of electricity in a defined medium and MFC design.

The production of electric current is based on biofilm formation on the anode. Kato Marcus et al. (2007) reported that before passing through an external circuit to generate electricity, the electrons that are produced by bacterial respiration in a microbial fuel cell must be transferred first to the anode. Because of the environment that is favorable for respiration of bacteria, biofilm is produced at the anode. The thickness of the biofilm must be seriously considered in order to maximize the production of current. Thin biofilm cannot generate substantial current but too thick biofilm reduces current since electrons cannot reach the anode (Kato Marcus et al., 2007).

Table 3. Cultural characteristics of potential MFC Isolates.

Days of Sampling	Mean Voltage (mV)	Mean Current (mA)	Total Plate Count	*Type of Isolates*	Number of Isolates	Cultural Characteristics			
						Nutrient Agar Slant/Stab		Nutrient Broth	
						Color	Form	Surface	Subsurface
0	57	0.12	$<10^2$	-	-	-	-	-	-
				-	-	-	-	-	-
				-	-	-	-	-	-
7	298	0.48	*10^6*	*Aerobic*	2	White, Yellow	Echinulate, Filiform	Ring	Turbid
				Anaerobic	2			Ring	Turbid
				Facultative An/Aerobic	2	White, Light Brown	Echinulate, Beaded	Ring	Turbid
14	430	0.51	*10^7*	*Aerobic*	8	White, Light Brown	Beaded, Echinulate, Filiform	Membranous, Ring, Floculent, Pellicle	Turbid, Slightly Turbid, Granular
				Anaerobic	2	-	-	Ring, Membranous	Turbid, Slightly Turbid
				Facultative An/Aerobic	0				
21	386	0.42	*10^7*	*Aerobic*	6	White, Light Brown	Filiform, Echinulate, Beaded	Floculent, Membranous, Ring	Turbid
				Anaerobic	2			Ring	Turbid
				Facultative An/Aerobic	0				
28	412	0.56	*10^7*	*Aerobic*	6	White, Light Brown, Yellow	Filiform, Echinulate, Beaded	Floculent, Membranous, Ring	Turbid, Slightly Turbid, Floculent
				Anaerobic	1			Floculent	Floculent
				Facultative An/Aerobic	1	Light Brown	Echinulate	Ring	Slightly Turbid
35	408	0.76	*10^6*	*Aerobic*	7	White, Light Brown, Yellow	Filiform, Echinulate, Beaded	Floculent, Ring	Turbid, Slightly Turbid, Floculent
				Anaerobic	2			Membranous, Pellicle	Floculent
				Facultative An/Aerobic	2	White	Echinulate, Filiform	Ring	Slightly Turbid, Floculent
42	211	0.34	*10^7*	*Aerobic*	2	Light Brown	Filiform	Membranous, Floculent	Turbid
				Anaerobic	2			Floculent, Pellicle	Floculent
				Facultative An/Aerobic	7	White, Light Brown	Echinulate, Filiform	Membranous, Floculent, Pellicle	Turbid, Floculent

Note: Total Number of isolates - 54; Total Number of Aerobes – 31; Total Number of Anaerobes – 11; Total Number of Facultative Aerobes/anaerobes – 12; Voltage and current readings at 0 day were taken right after the set up was installed

Electrical Generation of Galvanic Cells from Various Root Crops

Badiang Roots

The average voltage generated by the galvanic cell using *Badiang* ranged from 656 mV to 949 millivolts (mV) and the current averaged 3.69 milliamps (mA) as shown in Figure 5. Optimum predicted responses were 969.11 mV and 3.85 mA (Table 4). These responses, including the diameter of electrode (45.88 mm) and penetration of electrode (65.48 mm), were found to be outside the design space. Only the optimum level of distance (4.46 mm) was inside the design space.

Cassava Roots

Cassava roots generated voltage range of 559-860 mV (Figure 6a) was relatively lower compared to *Badiang* which generated voltage range of 656-949 mV (Figure 5a). Generated current, however, increased through time as shown in Figure 6b., different composition of electrolytes could significantly change cell potentials. Similar to the result of *Badiang*, the optimum levels of variables were also outside the design space except the distance between electrodes.

Sweet Potato

Similar results were observed for sweet potato with the other crops on the analysis for the effect of variables to generated voltage and current (Table 4). However, the monitoring period shown in Figure 7 was longer (31 days) due to its ability to sprout under ambient conditions. Predicted optimum responses (668.2 mV and 0.127 mA) and levels of variables shown in Table 4 were inside the design space.

Verification of Regression Models

All regression equations corresponding to voltage and current of the selected root crops were all significant (Table 4). Furthermore, the predicted responses of the models were statistically insignificant compared to the observed responses (Table 5) which suggests the reliability of the models on designing practices and other future applications.

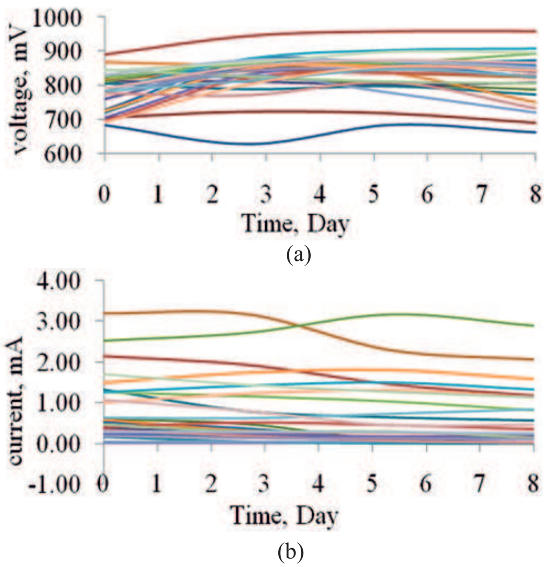

Figure 5. Actual generated voltage (a) and current (b) of galvanic cell using *Badiang.*

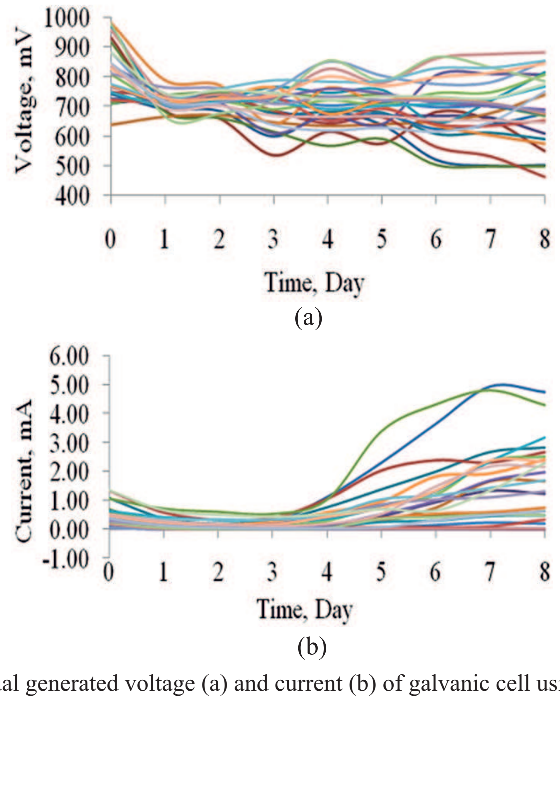

Figure 6. Actual generated voltage (a) and current (b) of galvanic cell using cassava roots.

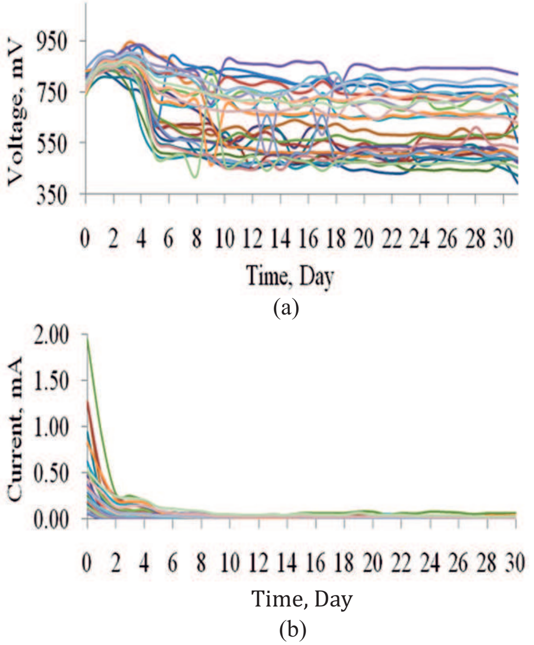

Figure 7. Actual generated voltage (a) and current (b) of galvanic cell using Sweet potato.

Variables Affecting the Outputs of Galvanic Cells

All variables screened statistically affected the current while the voltage was not affected by the distance between electrodes. The significance of the shape of electrodes was influenced by disproportionate surface area (Hu *et al.*, 2010) of the flat and rounded electrodes. Ntengwe *et al.* (2010) revealed that an increase in temperature increased a current density of galvanic cells, thus, time of harvest significantly affected the responses—3 P.M. generated higher voltage and current over 6 A.M. reading. Difference in temperature for standing and harvested roots and tubers must also be the reason why there were significant differences in voltage and current readings at different times of harvest. The diffusion of ions might be slower at the basal part (usually harder because there weredifficulty of insertion of electrodes) probably contributing to the significant differences of the responses. More electrolytes on larger roots would mean more ions between electrodes and more electron-transfer activities. Furthermore, Shah (2007) stated that cell current is dependent on cell size. Other significant variables of the optimization process were the 3 main variables (distance between electrodes, diameter, and penetration of electrodes).

Table 4. Regression models and predicted optimum responses (voltage and current) of different root crop galvanic cells as affected by the three main variables.

Root Crop		Source			F Value	Prob > F
Badiang	Model	mV= 635.2899+13.6144*A+10.761*B+4.1799*C-0.2844*A*B-0.17422*A*C- 0.141*B*C-0.316*A^2-0.034*B^2+0.004*C^2			8.42^a	0.0001
		mA = -0.59545+0.010464*A+0.06133*B +0.020847*C-0.00337*A*B-0.00298*A*C +0.004374*B*C+0.002572*A^2-0.00286*B^2+0.000679*C^2			56.89^a	0.0001
	Optimum	Voltage (mV)	Current (mA)	Values of Factors		
				A (mm)	B (mm)	C (mm)
		969.11	3.85	2.9	47.24	34.08
Cassava		Source			F Value	Prob > F
	Model	mV = 600.77+11.55*A+4.76*B-0.54*A*B			8.42^a	0.0001
		mA = -0.43+0.014*A+0.103*B+0.017*C-0.0044*A*B			56.89^a	0.0001
	Optimum	Voltage (mV)	Current (mA)	Values of Factors		
				A (mm)	B (mm)	C (mm)
		819.08	5.42	1	49	56.76
Sweet Potato		Source			F Value	Prob > F
	Model	mV = 402.97+22.02*A+39.02*B+1.29*C-0.41*A*C-0.84*A^2-1.15*B^2			8.42^a	0.0001
		mA = -0.59545+0.010464*A+0.06133*B+0.020847*C-0.00337*A*B-0.00298*A*C+0.004374*B*C+0.002572*A^2-0.00286*B^2+0.000679*C^2			56.89^a	0.0001
	Optimum	Voltage (mV)	Current (mA)	Values of Factors		
				A (mm)	B (mm)	C (mm)
		668.2	0.127	9.48	15.92	37.62

Note: A-distance; B-diameter; C-penetration; mV-millivolt; mA-milliamps; a- significant at $P<0.001$, b- significant at $P<0.05$

Effect of Distance between Electrodes

Distance between electrodes highly affected ($P<0.001$) the voltage and current in galvanic cells for the three root crops used (Table 6). Decreased distance from 18 mm to 2 mm while simultaneously increasing the diameter (from 1 mm 17 mm) and penetration of electrodes (from 10 mm to 30 mm) increased the current and voltage by 13.48 times and 9.90% respectively (*Badiang*). In sweet potato, a 5.30% voltage increase was produced when distance between electrodes was reduced (from 18 mm to 2 mm) while there was a simultaneous increase in penetration and diameter of electrodes.

Table 5. Analysis of the verification of the regression models.

Root Crops	Responses	Predicted Response	Observed Response	Mean Difference	t for H0 Coeff=0	Prob > |t|
badiang	E	969.11	930	39.11	0.67431[a]	0.5696
	I	3.85	4.94	-1.145	-2.51648[a]	0.1282
cassava	E	819.08	890	-120.5	-3.05063[a]	0.0927
	I	5.42	10.08	-6.78	-3.39[a]	0.0771
Sweet-potato	E	668.2	726.5	-58.3	3.76129[a]	0.064
	I	0.127	0.215	-0.143	2.383333[a]	0.14

Note: a-not significant, E-voltage, I-current

Table 6. ANOVA for the average voltage and current generated by the galvanic cell of selected root crops at different combinations of the three main variables.

	Source	Badiang		Cassava		Sweet Potato	
		F Value	Prob > F	F Value	Prob > F	F Value	Prob > F
Voltage	A	3.62[c]	0.0611	49.49[a]	0.0001	20.76[a]	0.0001
	B	45.83[a]	0.0001	0.52[c]	0.4728	78.65[a]	0.0001
	C	6.27[b]	0.0146	0.83[c]	0.3644	6.98[b]	0.0101
	Source	Badiang		Cassava		Sweet Potato	
		F Value	Prob > F	F Value	Prob > F	F Value	Prob > F
Current	A	31.46[a]	0.0001	8.96[b]	0.0038	16.82[a]	0.0001
	B	163.30[a]	0.0001	47.54[a]	0.0001	200.85[a]	0.0001
	C	208.88[a]	0.0001	6.46[b]	0.0132	51.67[a]	0.0001

Note: A-Distance, B-Diameter, C-Penetration, a-significant at P<0.001; b-significant at P<0.05; c-not significant

Effect of Surface Area of Electrodes

Increasing the penetration of electrodes to *Badiang* from 10 mm to 30 mm increased the current and voltage by 13.48 times and 9.90%, respectively. Most likely, these increases were due to improved surface area of the electrodes creating higher current densities (Hu *et al.*, 2010). For cassava roots, an increase of penetration and diameter of electrodes while decreasing the distance from 18 mm to 2 mm increased the current to 86.5 times. Given the same conditions, voltage decreased by 17.09%. The same is true in the case of sweet potato wherein a 30 mm penetration was 3.05 times higher than penetrating the electrodes to 10 mm using 17 mm diameter.

Endurance of Prototypes

In the galvanic cell, durations of 2 white light emitting diode (LED) connected in series lasted 13 and 17 days for sweet potato and cassava, respectively and 42 days for *Badiang* with 1 LED. Single-chamber MFC lasted only up to 4 days on a LED.

CONCLUSION

The following conclusions can be drawn from this study: energy could be generated from MFCs fed with cassava wastewater employing the nata-de-coco as ion exchange membrane; root crop roots/tubers and wastewaters are potential for generation of electricity; the generated regression models are reliable tools in predicting desired outputs for future applications; the generated amounts of energy can be one defining properties of Badiang, cassava and sweet potato. The different types of microorganisms which were isolated from the biofilm anodes were partially characterized.

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