Research Article

PKL electrochemical cell: physics and chemistry

K. A. Khan[1] · M. A. Mamun[2] · M. Ibrahim[3] · M. Hasan[4] · M. Ohiduzzaman[5] · A. K. M. Obaydullah[6] · M. A. Wadud[7] · M. Shajahan[2]

Abstract
The efficiency of any electric cell or battery is very important. To keep it in mind, the coulombic efficiency, voltaic efficiency and energy efficiency have been studied. It was found that the coulombic efficiency data illustrated that this efficiency was higher comparing to other efficiencies may be the absence of salt bridge or separator between the electrodes. However, the highest efficiency was obtained for 40% PKL (Pathor Kuchi Leaf) sap with 5% secondary salt in 55% aqueous solution, which implies that the concentration of PKL juice can play an important role regarding efficiency. It was also found that the average energy efficiency was 97.43%, and it was also found that the average voltaic efficiency was 57.29%. Temperature effect of the PKL electrochemical cell has also been studied. It is found that the ideal temperature for this PKL electrochemical cell is room temperature and it is from 20 to 40 °C. But, it is also usable at a lower temperature from 5 to 60 °C as like as other standard cells. Most of the results have been tabulated and graphically discussed.

Keywords Biomass energy · Renewable energy · Electrolysis · Electric power generation

1 Introduction

PKL energy is a growing renewable energy technology that is built upon the expertise of several scientific disciplines. Researchers who work in PKL power design, operation and maintenance must understand the various disciplines involved in order to meet energy production and cost reductions goals. This is equally true of professionals who are new to this new and innovative field. Energy crisis is one of the most discussed issues in today's world. Most of the countries are trying to withstand this matter by any means, but we, the people of Bangladesh, are not much aware of this issue. At present, the generation demand is nearly 10,416 MW (June, 2014), whereas only three-fourth of which is considered to be available. Only 62% of the population has access to electricity with a per capita availability of 321 kWh per annum which is significantly lesser in comparison with developing countries. Due to insufficient production of electricity, according to the demand of us, the city dwellers are suffering from load-shading in pick hours even in off-pick hours. The problem of load-shading is getting more serious because of over dependency on fossil fuel. The world reserve of natural gas is limited, and it is alarming that natural resources are about to diminish in this century. However, nuclear energy will be alternative source, but it has some major drawbacks. Burning fossil fuels cause emission of greenhouse gases (GHGs) which in turn cause global warming and pollute environment. We have to take into account that our population grows enormously and the use of energy is still significantly growing.

✉ K. A. Khan, kakhan01@yahoo.com; M. A. Mamun, zithrox@gmail.com; M. Ibrahim, mikhanjnu@gmail.com; M. Hasan, mehedi.physics@gmail.com; M. Ohiduzzaman, ohiduzzaman027@gmail.com; A. K. M. Obaydullah, obayd77@gmail.com; M. A. Wadud, wadud_shimanta03@yahoo.com; M. Shajahan, jahanms@yahoo.com | [1]Department of Physics, Jagannath University, Dhaka 1100, Bangladesh. [2]Department of Chemistry, Jagannath University, Dhaka 1100, Bangladesh. [3]Department of Chemistry, Dhaka University, Dhaka 1100, Bangladesh. [4]Department of Electrical and Electronic Engineering, City University, Dhaka, Bangladesh. [5]Department of Physics, Jessore University of Science and Technology, Jesssore 7408, Bangladesh. [6]Instructor, URC, Ministry of Primary and Mass Education, Dhaka, Bangladesh. [7]Department of Chemistry, Univercity of Rajshahi, Rajshahi, Bangladesh.

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The energy crisis will be a serious problem in future. So, we should think of suitable alternative. To fulfill the omnipresent demand of electricity, green energy would be the most suitable one. For primary cell, we can calculate the cell efficiency by the following three ways. These are the voltaic efficiency, the coulombic efficiency and the energy efficiency [1–5]. It was taken six cells for comparing the three efficiencies of the PKL (Pathor Kuchi Leaf) cell. The efficiencies were measured by using calibrated multi-meters. The data were recorded very carefully and graphically discussed.

2 Mathematical models

2.1 Theory of voltaic efficiency

The efficiency of an entity in electronics and electrical engineering is defined as useful power output divided by the total electrical power consumed (η) [6–9].

$$\therefore \text{Efficiency, } \eta = \frac{\text{Useful power output}}{\text{total power input}}.$$

When a cell produces a current, the current can be used to do work—to run a motor, for instance. Thermodynamical principle can be employed to derive a relation between electrical energy and the maximum amount of work W_{max} obtainable from the cell [10–13]. The maximum amount of work obtainable from the cell is:

$$W_{max} = -nFE_{max} \quad (1)$$

where n is the number of moles of electrons transferred and is equal to the valence of the ion participating in the cell reaction. F stands for Faraday and is equal to 96500 coulombs, and E is the emf of the cell [14–23].

$$\text{The input work, } W_{max} = -nFE_{max}$$
$$\text{The output work } W = -nFE \quad (2)$$

$$\therefore \text{Efficiency } (\eta_V\%) = \frac{\text{Useful power output}}{\text{Total power input}} \times 100\%$$
$$= \frac{-nFE}{-nFE_{max}} \times 100\% = \frac{E}{E_{max}} \times 100\% \quad (3)$$

Here, E_{max} = cell potential without load and E = load potential [24–34]

2.2 Methodology

The PKL was collected from the PKL tree and was blended by a blender machine for electricity production. The converter was taken as Zn/Cu = 1:1. After filtration, the different concentrations (g/L) of PKL extract were used in the converter for power production [35–38].

2.3 Experimental setup

The weight of the anode used was measured (W_1) first, the PKL module was then prepared, and the external connection is used with an ammeter, and simultaneously, the stopwatch was started [39, 40]. The current flow was measured with a time interval so that the fluctuation of current is not so considerable, and this flow was recorded. When the cell becomes dead, then the ammeter and the stopwatch were stopped [41–51]. The metals used as anode will be separated, cleaned with distilled water and dried. The weight of the dried metal plate was measured (W_2).

2.4 Results and discussion

Tables 1, 2, 3, 4 and 5 represent the voltaic efficiency η_V (%) and the average voltaic efficiency η_V (%) variation with time [45]. Voltaic efficiency for many cells were performed and observed at different compositions of solution fuelled in the cells. The potential is the important electrochemical parameter by which the work efficiency of an engine can be measured. So, the voltaic efficiency is very important parameter [52].

The change of voltaic efficiency with time is shown in Figs. 4, 5, 6, 7, 8 and 9 for different cell [53]. Here, the voltaic efficiency of the cell decreases with time. For most of the cells, the voltaic efficiency was almost steady for a certain time period. The voltaic efficiency was the highest at initial point and was the lowest at the end. This was probably for the highest concentration of reactive species (Cu^{2+} and H^+) and the lowest concentration of product ion Zn^{2+} [54–57]. With time, the concentration of reactive species decreases

Table 1 Difference between electrolytic and PKL electrochemical cell

Electrolytic cell	PKL quasi-galvanic cell/voltaic cell
It requires a source of external energy	It is a source of energy
It converts electrical energy into chemical energy	Converts chemical energy into bio-electrical energy
Has cathode as the negative electrode	Has cathode as positive electrode
Has anode as the positive electrode	Has anode as negative electrode
It involves oxidation at anode and reduction at cathode	It involves oxidation at anode and reduction at cathode

Table 2 Determination of the voltaic efficiency of cell-1

Time duration (min)	Load potential (V)	Open circuit voltage (V)	Maximum potential (V)	Voltaic efficiency η_V (%)	Average voltaic efficiency η_V (%)
00	5.14	6.12	6.12	83.99	50.68
20	4.70	6.02	„	76.80	
40	3.40	5.20	„	55.55	
50	3.12	4.60	„	50.98	
60	2.90	4.30	„	47.39	
100	2.70	3.68	„	44.12	
140	2.63	3.32	„	42.97	
158	2.60	3.26	„	42.48	
220	2.57	3.10	„	42.00	
365	2.57	3.10	„	42.00	
389	2.56	3.05	„	41.83	
425	2.50	3.05	„	40.85	
495	2.54	3.00	„	41.50	
560	2.54	3.00	„	41.50	
620	2.54	3.00	„	41.50	
2145	2.47	2.90	„	40.36	
2972	2.46	2.90	„	40.20	

Table 3 Determination of the voltaic efficiency of cell-3

Time duration (min)	Potential with load (V)	Open circuit voltage (V)	Maximum potential (V)	Voltaic efficiency, η_V (%)
00	2.58	4.93	4.93	52.33
10	2.54	4.61	„	51.52
20	2.50	4.21	„	50.71
32	2.49	4.00	„	50.51
45	2.48	3.90	„	50.30
58	2.47	3.80	„	50.10
115	2.47	3.75	„	50.10
165	2.47	3.75	„	50.10
187	2.47	3.75	„	50.10
245	2.47	3.75	„	50.10
305	2.47	3.70	„	50.10
365	2.47	3.70	„	50.10
445	2.47	3.70	„	50.10
515	2.46	2.90	„	49.90
2788	2.46	2.90	„	49.90

and the concentration of product ion increase as a result the potential decreases and thus the voltaic efficiency decreases [58–62]. It was observed that the potential at 0% PKL was 55.36 and that for 40, 50 and 60% of PKL was 50.68, 52.44 and 59.37, respectively. The cell-6 was constructed by the anode which was plated by zinc on iron sheet (MS) and in this case the potential efficiency for the same composition of solution of other cell was lower than this cell [32–36]. Thus, by modifying the anode by plating, the voltaic efficiency can be increased. When the plating was done on MS sheet by zinc, then the zinc on the plate may slowly corrode and thus the concentration of product ion does not drop quickly and thus the voltaic efficiency becomes steady for a time period [49].

2.5 Determination of coulombic efficiency η_Q(%)

2.5.1 Mathematical models

The coulombic efficiency is the ratio of the charge obtained to the total charge (charge obtained + charge lost by local action) supplied by the anode, i.e.,

$$\eta_Q\% = \frac{Q_{output}}{Q_{input}} \times 100\% = \frac{Q_{obtained}}{Q_{supplied}} \times 100\% \quad (4)$$

If the lifetime of the cell becomes t, with an outer circuit connection, the current measured by the ammeter is I.

Then, the output charge

$$Q_{output} = It \quad (5)$$

The source of electron is the anode where electron produced by the oxidation reaction on the metal is used as anode [50]. Thus, with reaction, the weight of the anode reduces with time. If the weight of the anode used is = $W1$, the weight after time t is = $W2$. The weight lost = $W1 - W2 = x$ g. Again, the molecular weight of the metal used as anode is M, and the oxidation number is n. Then, the reaction taking place on the anode can be represented as: $A \rightarrow An^+ + ne^-$,where A represents anode.

Table 4 Determination of the voltaic efficiency of cell-4

Time duration (min)	Load potential (V)	Open circuit voltage (V)	Maximum potential (V)	Voltaic efficiency, η_V (%)	Average voltaic efficiency, η_V (%)
00	5.60	6.25	6.25	89.60	55.36
15	5.28	6.00	„	84.48	
35	4.17	5.95	„	66.72	
65	2.60	4.10	„	41.60	
80	2.60	3.70	„	41.60	
105	2.57	3.25	„	41.12	
171	2.54	3.15	„	40.64	
245	2.49	3.15	„	39.84	
1755	2.46	3.00	„	39.36	
2615	2.45	2.90	„	39.20	
3377	2.44	2.90	„	39.04	

Table 5 Determination of the voltaic efficiency of cell-5

Time duration (min)	Potential with load (V)	Open circuit voltage (V)	Maximum potential (V)	Voltaic efficiency, η_V (%)	Average voltaic efficiency η_V (%)
00	5.40	6.34	6.34	85.17	52.44
30	4.76	5.77	„	75.08	
40	4.64	4.54	„	73.19	
55	2.88	4.45	„	45.43	
115	2.63	3.45	„	41.48	
125	2.60	3.40	„	41.00	
1125	2.54	3.00	„	40.06	
1185	2.56	2.80	„	40.38	
1250	2.54	2.80	„	40.06	
1310	2.53	2.82	„	39.90	
1405	2.50	2.71	„	39.43	
1475	2.47	2.65	„	38.96	

Thus, one mole metal will produce n mole electron. So, *M* gm metal anode (A) will supply *n* mole electron. *x* gm metal anode will supply $=\frac{n\cdot x}{M}$ mole electron $=\frac{n\cdot x\cdot N_A}{M}$ electron $=\frac{n\cdot x\cdot N_A\cdot 1.6\times10^{-19}}{M}$ coulomb charge $=\frac{nxF}{M}$ coulomb charge [where $F=1$ Faraday].That is, *x* gm anode by decaying under oxidation process supply $\frac{nxF}{M}$ coul charge. So, the input charges,

$$Q_{\text{input}} = \frac{nxF}{M}\text{coul charge} \tag{6}$$

From (4), (5) and (6), we get, $\eta_Q\ \% = \frac{Q_{\text{output}}}{Q_{\text{input}}}\times 100\% = \frac{It}{\frac{nxF}{M}}\times 100\% = \frac{ItM}{nFx}\times 100\%$

$$\text{So,}\quad \eta_Q\% = \frac{ItM}{nFx}\times 100\% \tag{7}$$

By putting the values of the quantities in Eq. (7), we can calculate the coulombic efficiency.

2.5.2 Experimental data

See Figs. 11, 12, 13, 14, 15 and 16

2.5.3 Calculations of coulombic efficiency, η_Q (%) for Cell-1

Total weight of 18 zinc plates for the construction of cell is [38] = 588.63 g, and that after dead of cell = 562.63 g. So, the weight lost by the zinc plates = 26.00 g. The reaction taking place on anode (zinc plates):

$$\begin{array}{ccccc} \text{Zn} & - & 2e^- & \rightarrow & \text{Zn}^{2+} \\ 1\text{ mol} & & 2\text{ mol} & & 1\text{ mol} \end{array} \tag{8}$$

Fig. 1 Experimental setup of PKL juice making device

Fig. 2 Different Zn/Cu-PKL modules before putting PKL extract

Fig. 3 Different Zn/Cu-PKL modules after putting PKL extract

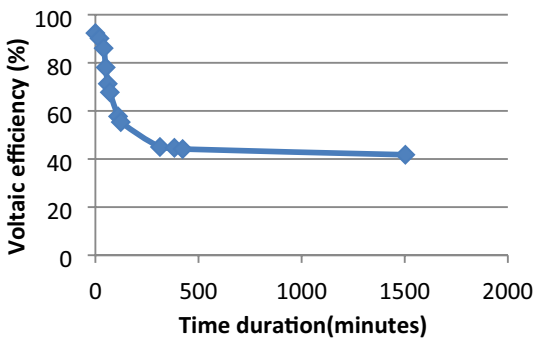


Fig. 4 Variation of voltaic efficiency with time duration for cell-1

Thus, 65.4 g zinc produces total of charge = $2F$ = 193,000C. So that, 26.00 g zinc produces total of charge = (193000 × 26.00)/65.4 = 76,727.83 Coul.

Thus, the input charge (Q_{in}) = 76,727.83C and the output charge (Q_{out}) = 4188.97C. So, the coulombic

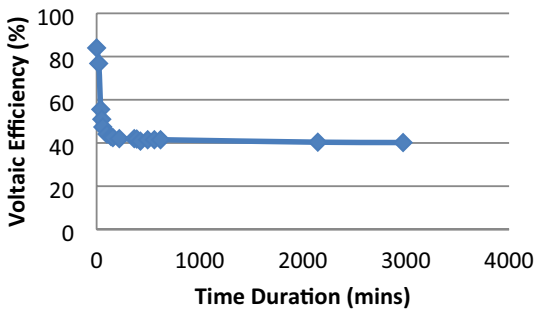


Fig. 5 Variation of voltaic efficiency with time duration for cell-2

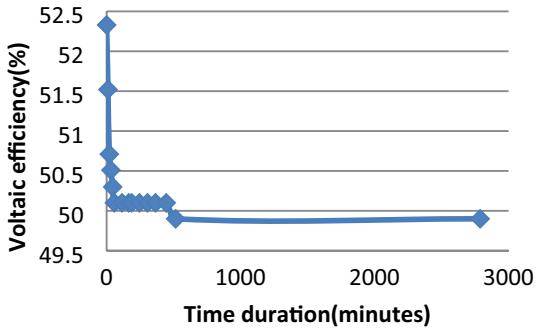


Fig. 6 Variation of voltaic efficiency with time duration for cell-3

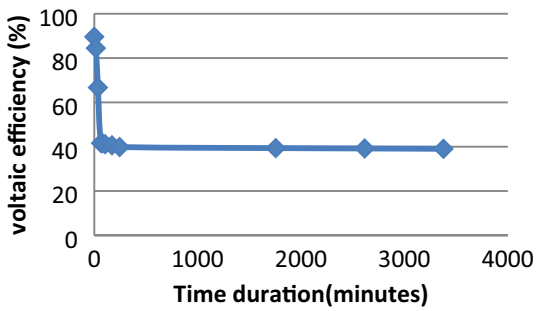


Fig. 7 Variation of voltaic efficiency with time duration for cell-4

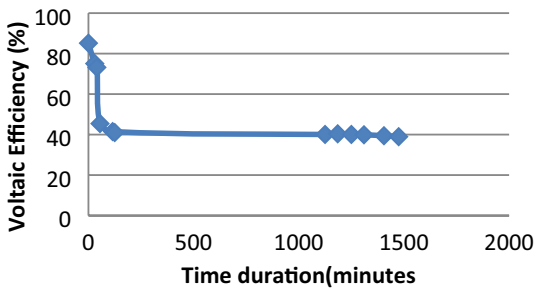


Fig. 8 Variation of voltaic efficiency with time duration for cell-5

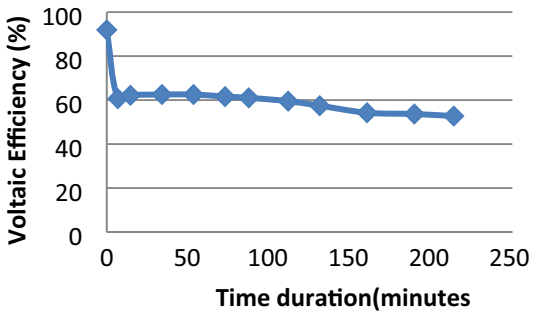


Fig. 9 Variation of voltaic efficiency with time duration for cell-6

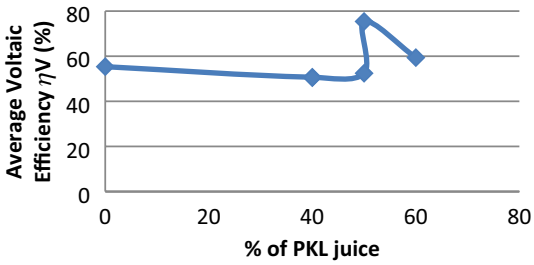


Fig. 10 Variation of voltaic efficiency with the change of % of PKL juice/extract

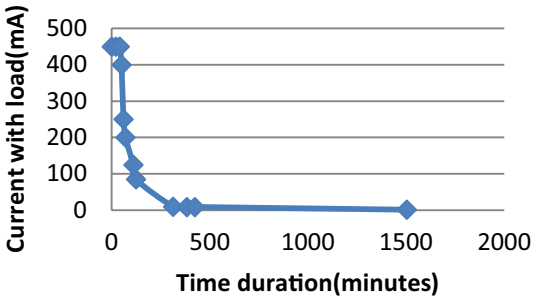


Fig. 11 Change of current with load with the time for cell-1

efficiency = Output charge/Input charge = Q_{out}/Q_{in} = 418 8.97C/76,727.83C= 5.46%. Similarly, the coulombic efficiency for the other cells can be calculated, and the results obtained are given in the following table. The change of coulombic efficiency, η_Q (%) with the change of %PKL juice, is shown in Fig. 16.

2.5.4 Difference between electrolytic and PKL quasi-galvanic/voltaic cells

There are some fundamental distinctions between electrolytic cell and PKL electrochemical cell. These are given in the following Table 1.

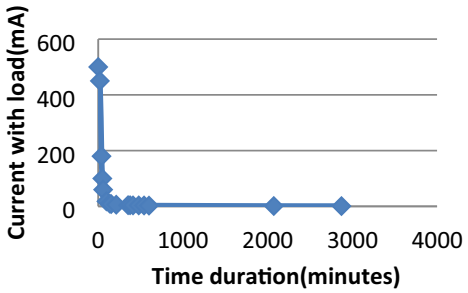


Fig. 12 Charge transfer through the circuit for cell-2

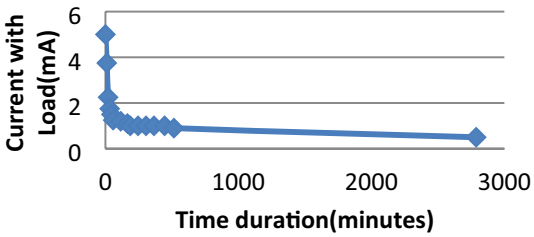


Fig. 13 Variation of current with the time for cell-3

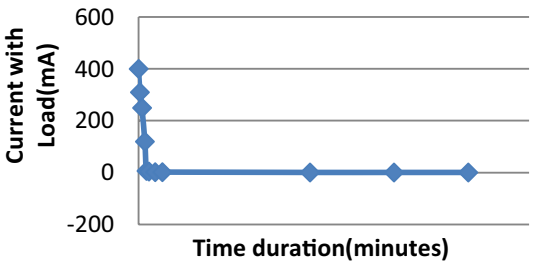


Fig. 14 Variation of current with the time for cell-4

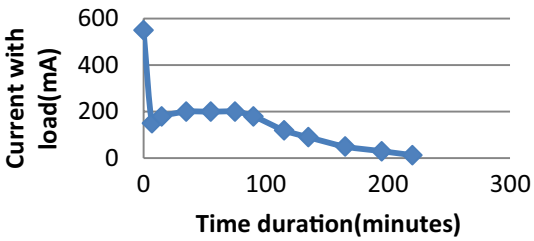


Fig. 15 Variation of current with the variation of time duration for cell-6

2.5.5 Results and discussion

Tables 2, 3 and 4 represent the current flow with time. Here, the current at first changes sharply and after a certain period this flow becomes steady having the low value of flow. To calculate the charge transferred through the circuit with a 3 W LED bulb, the average method was

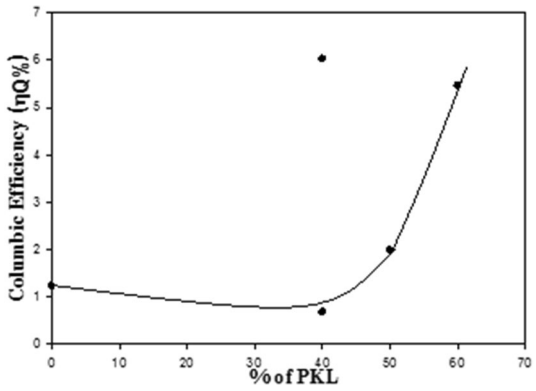
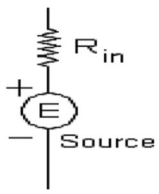


Fig. 16 Variation of coulombic efficiency (η_Q %) with the variation of %PKL

Fig. 17 Equivalent circuit of a PKL cell



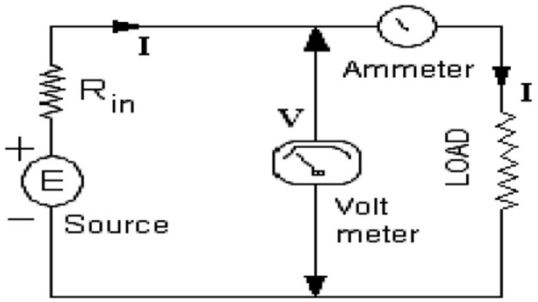


Fig. 18 Circuit arrangement for measuring power

followed. And for this, with the help of current versus time, a significant change is observed from Figs. 1, 2, 3, 4 and 5 which was marked with the sign A, B, C and D. For each portion separately, the charge transfer calculated and then added together. Table 5 and Fig. 9 both show the change of coulombic efficiency (η_Q %) with the change of PKL juice [42–48]. Here, the coulombic efficiency (η_Q %) was 5.46, 6.02, 0.68, 1.23, 1.98 at 60, 40, 40, 0, 50% of PKL juice, respectively. Here, without PKL juice, the coulombic efficiency was low again without secondary salt and the coulombic efficiency became the lowest. Again for the cell-6 where the % of PKL was 50%, yet the coulombic efficiency was only 1.98%. In this cell, the anode used was plated with zinc on MS sheet. Thus, it can be concluded that the anode should not be plated to get the high coulombic efficiency [24].The surface morphology was examined with the scanning electron microscopy (SEM) and found to be cubic grain with homogeneous distribution.

Figure 1 shows the experimental setup of PKL Juice making machine. Figure 2 shows the Zn/Cu-PKL Cell before putting extract. Figure 3 shows the Zn/Cu-PKL Cell after putting extract. Figure 4 shows the variation of voltaic efficiency with the variation of time for cell-1. Figure 5 shows the change of voltaic efficiency with time for cell-2. Figure 6 shows the change of voltaic efficiency with time for cell-3. Figure 7 shows the change of voltaic efficiency with time for cell-4. Figure 8 shows the change of voltaic efficiency with time for cell-5. Figure 9 shows the change of voltaic efficiency with time for cell-6. Figure 10 shows the change of voltaic efficiency with the change of % of PKL juice. Figure 11 shows the change of current with load with the time for cell-1. Figure 12 shows the charge transfer through the circuit for cell-2. Figure 13 shows the variation of current with the time for cell-3. Figure 14 shows the variation of current with the time for cell-4 (Figs. 15 and 16).

2.6 Determination of energy efficiency η_E (%)

Battery is subjected to charge. A battery needs to be charged before use. During charging, it uses energy and during discharging we get energy from it. The efficiency of a battery is calculated as below:

$$\text{Energy Efficiency, } \eta_E = E_D/E_C \tag{9}$$

$$\text{where, } E_D = \text{Energy during charging} = V_D I_D T_D \tag{10}$$

Here, V_D = discharging voltage (V), I_D = discharging current (A), T_D = discharging time (h). Then, we have

$$E_C = \text{Total energy during discharging} = V_C I_C T_C \tag{11}$$

Here, V_C = charging voltage (V), I_C = charging current (A), T_C = charging time (h).

Therefore, we can write,

$$\text{Energy efficiency} = \frac{V_D I_D T_D}{V_C I_C T_C}$$

or,

$$\text{Energy efficiency} = \left(\frac{V_D}{V_C}\right)\left(\frac{I_D T_D}{I_C T_C}\right)$$

or,

$$\text{Energy efficiency} = \left(\frac{\text{Discharge voltage}}{\text{Charge voltage}}\right)\left(\frac{\text{Discharge ampere hour (AH)}}{\text{Charge ampere hour (AH)}}\right)$$

Table 6 Determination of the voltaic efficiency of cell-6

Time duration (min)	Load potential (V)	Open circuit voltage (V)	Maximum potential (V)	Voltaic efficiency η_V (%)	Average voltaic efficiency η_V (%)
00	4.88	5.31	5.31	91.90	75.40
07	3.22	3.35	,,	60.64	
15	3.30	3.60	,,	62.15	
35	3.32	3.65	,,	62.52	
55	3.32	3.62	,,	62.52	
75	3.27	3.61	,,	61.58	
90	3.24	3.57	,,	61.02	
115	3.16	3.52	,,	59.51	
135	3.05	3.50	,,	57.44	
165	2.88	3.35	,,	54.24	
195	2.85	3.30	,,	53.67	
220	2.80	3.00	,,	52.73	

or,

Energy efficiency = (Voltage efficiency)(Coulomb efficiency) where Voltage efficiency $= \left(\frac{V_D}{V_C}\right)$ and Coulomb efficiency $= \left(\frac{I_D T_D}{I_C T_C}\right)$

At the beginning of charge cycle of a lead acid battery, coulomb efficiency is nearly about 100%. But, near end of charge cycle coulomb efficiency reduces.

2.6.1 Energy efficiency of PKL system

PKL system is a renewable source of electricity. This system needs not to be charged. So, the conventional method of calculating energy efficiency is not applicable for the system. But, we can easily measure the energy efficiency of a PKL system calculating the output energy and internal loss. Let us consider the equivalent circuit of a PKL cell as shown in Figs. 17 and 18.

According to these Figs. 17 and 18, circuit there is only means of loss of energy is in the internal resistance. Therefore, if we can calculate the energy loss in internal resistance R, we can calculate the energy efficiency easily (Tables 6, 7, 8, 9, 10, 11, 12 and 13).

Table 7 Observation of the average voltaic efficiency, η_V (%) with % of PKL juice

Cell no.	% of PKL juice	Average voltaic efficiency η_V (%)
1	60	59.37
2	40	50.68
3	40	50.48
4	0	55.36
5	50	52.44
6	50	75.40

If I A current flows through the output load, this current will also flow through the internal resistance R of the circuit. Now, if V is the load voltage, then the output power $= V \times I$, and power loss in internal resistance $= I^2 R$.

Therefore, we can calculate the power efficiency as

$$\text{Energy efficiency} = \frac{\text{Output}}{\text{Output} + \text{Losses}}$$

The losses may include polarization, resistance (electronic conductor and electrolytic conductor), the absence of salt bridge, the presence of impurity. Considering the loss arises only in the presence of internal resistance and neglecting other losses, we get

Or,

$$\text{Energy efficiency} = \frac{V \times I}{(V \times I) + I^2 R}$$

Energy efficiency is generally represented as percentage value.

$$\text{Energy efficiency} = \frac{V \times I}{(V \times I) + I^2 R} \times 100\%$$

2.6.2 Experimental data

The energy efficiencies for different six cells are shown in Table 14. The highest and the lowest energy efficiencies are 99.96% and 96.73%, respectively (Table 14).

2.6.3 Calculation of energy efficiency η_E(%) for cell-1

Load voltage, $V = 3.500$ V, load current, $I = 0.154$ A, internal resistance, $R = 0.6\ \Omega$. Therefore, we can find the output power = load voltage × load current = 3.50 V × 0.154 A = 0.539 W. Power loss in internal resistance of the cell = $(0.154\ \text{A})^2 \times 0.6 = 0.014$ W. Therefore, the Energy efficiency $= \frac{0.539}{0.539 + 0.014} \times 100\%$.

Table 8 Determination of the charge transfer through the circuit for cell-1

Sl no.	Sample no.	Time duration (min)	Total time *t* (s)	Load current (mA)	Average current, *I* (A)	Charge flowed ($C = It$)	Total charge transferred (C)
01	C1S2	00	12,000	450.00	0.301	3612	4188.97
02	C1S3	20		450.00			
03	–	40		450.00			
04	C1S4	50		400.00			
05	–	60		250.00			
06	C1S5	70		200.00			
07	C1S6	110		125.00			
08	–	123		85.00			
09	C1S7	313	78,180	10.00	0.00738	576.97	
10	C1S9	383		9.00			
11	–	423		9.00			
12	C1S10	1503		1.50			

Table 9 Determination of the charge transfer through the circuit for cell-2

Sl no.	Sample No.	Total time (min)	Total time *t* (s)	Load current (mA)	Average current *I* (A)	Charge flowed (C) [$Q = It$]	Total charge transferred (C)
01	C2S2	00	6000	500.00	0.22	1308	2055.87
02	C2S3	20		450.00			
03	C2S4	40		180.00			
04	–	50		100.00			
05	–	60		60.00			
06	C2S5	100		18.00			
07	C2S6	140	172,320	10.00	0.0044	747.87	
08	–	158		8.25			
09	–	220		6.00			
10	C2S7	365		4.25			
11	–	389		4.00			
12	C2S8	425		3.50			
13	–	495		3.50			
14	–	560		3.20			
15	C2S9	620		2.75			
16	C2S10	2145		1.25			
17	–	2972		1.00			

Or, energy efficiency = 97.43%. Similarly, for another cells, the calculation was done and given above table.

2.6.4 Temperature effect of a PKL cell

Cell performance of a PKL battery or PKL cell changes dramatically with temperature. At the lower extreme temperature, the electrolyte itself may freeze setting a lower limit on the operating temperature. At the upper extreme temperature, the active chemicals of PKL cell may break down destroying the battery. In between these limits, the PKL cell performance generally improves with temperature.

2.6.5 Chemical analysis

By analyzing the experimental data obtained from AAS, UV–Vis, VOM, pH metric analysis and visual inspection of the PKL cell, we can conclude the findings as—the AAS, UV–Vis and pH metric analysis show that both Cu^{2+} and

Table 10 Determination of the charge transfer through the circuit for cell-3

Sl no.	Total time (min)	Total time t (s)	Load current (mA)	Average current I (A)	Charge flowed ($C = It$)	Total charge transferred (C)
01	00	3480	5.00	0.003	8.98	167.32
02	10		3.75			
03	20		2.25			
04	32		1.75			
05	45		1.50			
06	58		1.25			
07	115	163,800	1.20	9.67×10^{-4}	158.34	
08	165		1.10			
09	187		1.00			
10	245		1.00			
11	305		1.00			
12	365		1.00			
13	445		1.00			
14	515		0.90			
15	2788		0.50			

Table 11 Determination of the charge transfer through the circuit for cell-4

Sl no.	Sample no.	Time duration (min)	Total time t (s)	Load current (mA)	Average current (A)	Charge flowed ($C = It$) C	Transferred change (C)
01	C4S2	00	4800	400.0	0.22	1043.52	1349.94
02	C4S3	15		310.0			
03	C4S4	35		250.0			
04	C4S5	65		120.0			
05	C4S6	80		7.0			
06	C4S7	105	197,820	4.0	1.55×10^{-3}	306.62	
07	–	171		2.0			
08	C4S8	245		1.8			
09	C4S9	1755		0.5			
10	–	2615		0.5			
11	C4S10	3377		0.5			

Table 12 Determination of coulombic efficiency of different PKL cells at different compositions

Cell No.	Weight of anode before using (g) [W_1]	Weight of anode after using (g) [W_2]	Weight lost by anodic process (g) [$W_1 - W_2 = x$ g	Input charge (C) ($\frac{2Fx}{65.4}$)	Output charge (C)	Coulombic efficiency, (η_Q %) $\frac{Q_{output}}{Q_{input}} 100\%$	% of PKL used in solution
1	588.63	562.63	26.00	76,727.83	4188.97	5.46	60
2	593.43	581.86	11.57	34,143.88	2055.88	6.02	40
3	589.49	581.16	8.33	24,582.4	167.32	0.68	40
4	589.29	552.13	37.16	109,661.76	1349.94	1.23	0
6	771.5	754.15	27.35	80,711.77	1601.94	1.98	50

Table 13 Determination of the charge transfer through the circuit for cell-6

Sl No	Total time (min)	Total time *t* (s)	Load current (mA)	Average current, *I* (A)	Charge flowed ($C = It$)	Charge transferred (C)
01	00	420	550	0.35	147	1601.94
02	07		150			
03	15	6480	180	0.180	1166.4	
04	35		200			
05	55		200			
06	75		200			
07	90		180			
08	115		120			
09	135	6300	90	0.0458	288.54	
10	165		50			
11	195		30			
12	220		13			

Table 14 The energy efficiency calculation for the internal resistance, R = 0.6 Ω

Cell no.	Internal resistance (Ω)	Average load potential, *V* (V)	Average load current, *I* (A)	Energy efficiency, $\eta_E = \frac{VI}{VI+I^2R} \times 100\%$
1	0.6	3.500	0.154	97.43
2	,,	3.102	0.111	98.9
3	,,	2.489	1.774×10^{-3}	99.96
4	,,	3.271	0.109	98.4
5	,,	3.358	0.166	97.12
6	,,	3.404	0.192	96.73

H^+ ions simultaneously reduce with the progress of electrochemical reaction, whereas the concentration of Zn^{2+} increases rapidly. Thus, we can infer that H^+ and Cu^{2+} ions behave as reactant species, i.e., act as oxidant, while Zn behaves as reductant species. However, the visual inspection and the reduction in weight of Zn plates also strongly support that Zn electrode is the main source of electron. On the other hand, from the VOM data, we can decide that the potential and current flow decrease with the decrease in the concentration of H^+ and Cu^{2+} ions in PKL juice solution. Therefore, we can propose the electrochemical reaction occurred in the PKL cell as follows:

$$2Zn + Cu^{2+} + 2H+ \rightarrow 2Zn^{2+} + Cu + H_2 \uparrow \quad (12)$$

$$\text{Reaction at anode: } 2Zn + 4e^- \rightarrow 2Zn^{2+} \quad (13)$$

$$\text{Reactions at cathode: } Cu^{2+} + 2e^- \rightarrow Cu \quad (14)$$

$$\text{and } 2H^+ + 2e^- \rightarrow H_2 \uparrow \quad (15)$$

Hence, the cell diagram can be symbolized as,

$$Zn \left| Zn^{2+} \right| H^+, H_2 \left| Cu^{2+} \right| Cu \quad (16)$$

From the visual observation of evolved gas as bubble, the physical test of the gas also claims that during electricity production H_2 gas is generated as a by-product. Modification of electrode by electroplating the performance of the PKL cell is enhanced may be due to the increasing of surface area of electrode and the minimizing of local action. The coulombic efficiency data illustrate that this efficiency was lower comparing to other efficiencies may be the absence of salt bridge or separator between the electrodes [39–41]. However, the highest efficiency was obtained for 40% PKL sap with 5% secondary salt in 55% aqueous solution, which implies that the concentration of PKL juice can play an important role regarding efficiency. The large value of equilibrium constant revealed that the rate of forward electrochemical reaction was higher at higher concentration of oxidants. The presence of secondary salt (5% $CuSO_4 \cdot 5H_2O$) enhances the current and the potential. This may be due to the secondary salt effect, where the secondary salt increases the rate of dissociation of weak organic acids of PKL juice.

Table 15 Observation of the energy efficiency variation with % of PKL juice

Cell no.	% of PKL juice	Energy efficiency, $\eta_E(\%) = \frac{VI}{VI+I^2R} \times 100\%$
1	60	97.43
2	40	98.9
3	40	99.96
4	0	98.4
5	50	97.12
6	50	96.73

2.6.6 Results and discussion

It is found from Tables 14 and 15 that the energy efficiency of the PKL cell is about 99.96%. It may be noted here that this value of the efficiency is for the whole lifetime. Here, average of both current and voltage is taken. Therefore, efficiency will also change. If we want to measure the efficiency for a period of time, it is better to measure the power in ampere-hour (AH). Furthermore, Figs. 6, 7, 8, 9, 10, 11 and 12 show the voltaic efficiency, charge transfer through the circuit and coulombic efficiency for different cells, respectively.

The effect of temperature on cell is basically the effect of temperature on electrolyte. In PKL cell, the electrolyte is the juice/extract of the PKL. Therefore, at lower temperature (0 °C), it becomes frozen. So, it is not possible to use this PKL cell at 0 °C. At upper temperature, the organic properties of PKL juice/extract destroyed itself. So, it is not possible to use this cell in higher temperature. It is found the ideal temperature for this PKL system is room temperature, and it is found from 20 to 40 °C. But, it is also usable at a lower temperature from 5 to 60 °C as other cells.

3 Conclusions

Finally, it can be concluded that PKL cell is:

- Less expensive.
- Highly efficient.
- Longer shelf-life.
- Environmentally friendly.

For these reasons, it introduces a sustainable platform to combat the power crisis of this world in future.

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Compliance with ethical standards

Conflict of interest On behalf of all the authors, the corresponding author declares that we do not have any conflict of interest.

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