



Alizarin Red S, Oxalic Acid and Cetylpyridinium Chloride-based Modified Photogalvanic Cell with Sustainable Conversion and Storage of Solar Energy

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In this study, an integrated photogalvanic system of Alizarin red S, oxalic acid and cetylpyridinium chloride has been fabricated and used for the conversion of solar energy into electrical energy with improved conversion efficiency and storage capacity. The photogalvanic cell is an H-shaped glass tube cell containing two electrodes dipped in a multifaceted electrolyte solution of dye-reductant-surfactant-alkali. By virtue of its photogalvanic action, it is capable of being charged by sun light. This system by way of variable concentration of chemical components were used to formulate a modified photogalvanic cell. The modified cell indicated significantly improved performance in terms of dark potential (778 mV), open-circuit potential (1189 mV), short-circuit current (420 μ A), power (147.42 μ W), charging time (17 min), half change time (16 min), conversion efficiency (2.16%) and fill factor (0.299).

Keywords: Alizarin red S, Oxalic acid, Cetylpyridinium chloride, Photogalvanic cell, Solar energy conversion, Solar energy storage.

INTRODUCTION

Photogalvanic cells are most efficient and commercially viable light sensitive electrochemical technique that can simultaneously harvest and store the clean energy at competitive cost [1-5]. This approach has directed to a cumulative interest in the sustainable resources of energy and photo-electrochemical effect [6,7]. In photogalvanic cell, the electrolyte solution consisting of dye photosensitizer, reductant, surfactant and alkali, which can convert solar energy into electrical energy *via* photo-electrochemical effect and it is known as photogalvanic effect [5].

Several reports have been found in literature with various blends of dye-reductant-surfactant and alkali. The dye-reductant-surfactant formulas such as glycerol-Azur-sodium lauryl sulphate (SLS) [8], indigo carmine-ascorbic acid [9], Brilliant green-ascorbic acid-ammonium lauryl ether sulphate (ALES) [10], oxalic acid-Brilliant cresyl [11], tropaeoline O-oxalic acid-benzalkonium chloride [12], Congo red-formaldehyde-SLS [13], Sudan I-fructose-SLS [14], Congo red-D-xylose-cetylpyridinium chloride (CPC) [15], indigo carmine-formic acid-SLS [16], toluidine blue-oxalic acid-Tween-80 [17], *etc.* have been reported to use in photogalvanic cell. There are some

mixed dye and mixed surfactant photogalvanic systems has also been reported with extraordinary results such as combination of Brilliant green + Celestine blue and SLS + CTAB, respectively [18,19]. The literature survey reveals that the photogalvanic system of Alizarin red S-oxalic acid-CPC has not been reported so far for the harvesting of solar energy and therefore, it can potentially replace the existing chemical systems for conversion of solar energy and its storage in photogalvanic cell.

This work focuses on the development of modified photogalvanic cell to improve the solar energy conversion efficiency and storage. The modification of photogalvanic cell by changing the electrode surface area, diffusion length and the replacement of electrolyte solution is not only reduced the cost of fabrication but enhance the photogalvanic effect to a striking conversion and storage of solar energy. Therefore, it is good to achieve the economic viability and ease of commercial application of photogalvanic cell. An integrated photogalvanic system of Alizarin red S (as dye), oxalic acid (as reductant) and cetylpyridinium chloride (as surfactant) has been fabricated and used for the conversion of solar energy into electrical energy with improved conversion efficiency and storage capacity. This system with variable concentration of chemical components were used to

fabricate a modified photogalvanic cell. The modified photogalvanic cell showed significantly improved performance in terms of dark potential (778 mV), open-circuit potential (1189 mV), short-circuit current (420 μ A), power (147.42 μ W), charging time (17 min), half change time (16 min), conversion efficiency (2.16%) and fill factor (0.299). An investigation was conducted to analyze the impact of different cell formulations on enhancing the performance and reducing the cost of the cell, based on the suggested methodology.

EXPERIMENTAL

In this study, chemicals, alizarin red S dye (Synonym: Mordant red 3, *m.f.* $C_{14}H_7NaO_7S$, *m.w.* 342.26 $g\ mol^{-1}$, yellow orange powder, soluble in water and alcohol) procured from Himedia Lab. Pvt. Ltd.; oxalic acid (>98%, *m.f.* $C_2H_2O_4 \cdot 2H_2O$, *m.w.* 126.07 $g\ mol^{-1}$, white crystalline, soluble in water and alcohol) and cetylpyridinium chloride (>99%, *m.f.* $C_{21}H_{38}NCl \cdot H_2O$, *m.w.* 358.01 $g\ mol^{-1}$, white powder, soluble in water and alcohol) were procured from Qualikems Laboratory Reagent. All chemicals were used as received without further purification.

The stock solutions of alizarin red S (0.002 M), oxalic acid (0.01 M), CPC (0.01 M) and NaOH (2 M) solution were prepared in double distilled water.

Characterization: The potential in millivolt (mV) were preliminarily measured by digital pH meter (pH Meter, LMPH-9, Labman Scientific Instruments Pvt. Ltd., Chennai, India; range: $\pm 1999\ mV \pm 0.1$). The current in microampere (μ A) was measured by micro-ammeter (micro-ammeter, OM Meter, Ambala Cantt, India). The artificial sunlight was getting from 200 W incandescent tungsten filament bulb and sunlight intensity were measured by light meter (HTC LX-101A Luxmeter; Accuracy: $\pm 5\%$). A carbon pot log 470 K device for changing the resistance of the circuit, a copper (Cu) wires for completing the external circuit key, a brass plug circuit key for closing the circuit, a platinum (Pt) electrode for making negative terminal of the cell and a saturated calomel electrode (SCE) as reference electrode for making positive terminal of the cell were used in this study.

Experimental methods: The experimental setup consist of a H-shaped photogalvanic cell equipped with Pt and SCE electrodes, artificial light source, digital pH meter (for measuring potential), micro-ammeter (for measuring current), carbon pot log (for changing resistance of circuit) and circuit keys, which all are connected together in photogalvanic cell set up (Fig. 1).

The H-shaped transparent and cylindrical glass tube was fabricated and filled with an identified amount of aqueous solu-

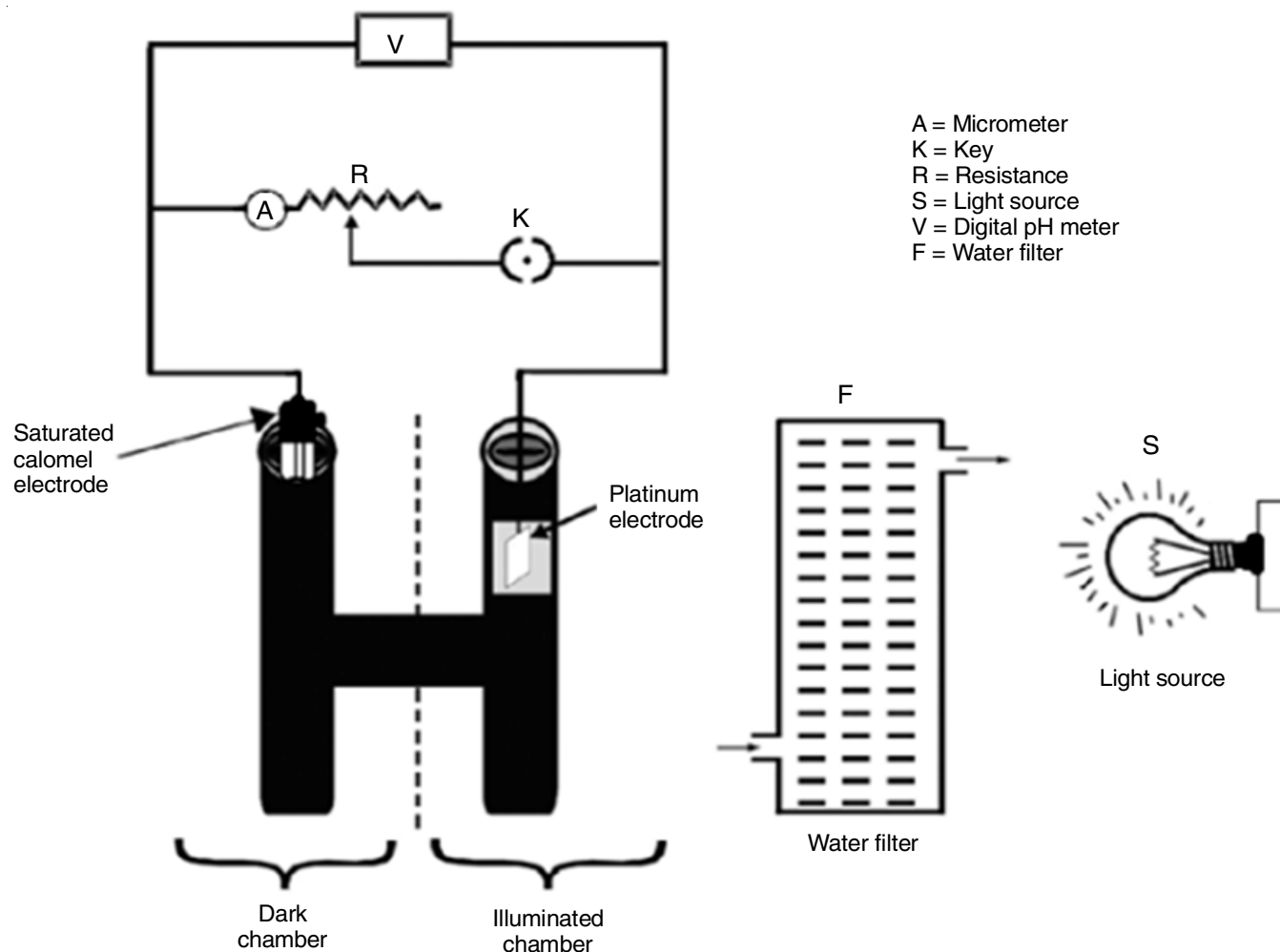


Fig. 1. Experimental setup of photogalvanic cell (A = microammeter; K = key; R = resistance; and V = digital pH meter)

tion of alizarin red S (dye), oxalic acid (reductant), CPC (surfactant) and NaOH (alkali medium). One arm of the tube is darkened and other side is un-darkened to illuminate with artificial light source (200 W incandescent tungsten filament bulb). Both SCE and Pt electrodes were submerged in the solution in darkened and un-darkened side arm of the tube, respectively. The area of Pt electrode were reduced to 12.5 times than the reported system for the purpose of reducing the cost of the galvanic cell and it was then placed in front of artificial light source. The terminals of both electrodes were connected to a digital pH meter and micro-ammeter through a key and resistance to measure the photo-potential and photo-current, respectively. According to the experimental setup, every part of the equipment is connected to one another in a circuit manner.

In order to establish a stable potential, the circuit was initially left open and put in a dark environment to obtain the dark potential (V_{dark}). The electrolyte solution was then illuminated with artificial sunlight source while the circuit was still open to charge the cell. At various time intervals, the value of photo-potential is noted down. Maximum potential (V_{max}) is the highest potential that can be measured during illumination. The cell is then said to be fully charged when it reaches a stable potential value known as open-circuit potential (V_{oc}). V_{oc} is little lower than the V_{max} . The cell's illumination is then turned off. The maximum current (i_{max}) is defined as the largest current obtained immediately after closing the circuit at resistance zero. Short-circuit current (i_{sc}) is the result of the current obtained at a quite static value over time.

The potentiometer is used to adjust the circuit's resistance. By changing the current value from i_{sc} to zero value and noting the corresponding potential value, the i - V characteristic of the cell was investigated (by altering the circuit resistance, zero current is attained at the greatest resistance). The term "power at power point" refers to the highest product of current and the matching potential value (maximum power extractable from the cell, P_{pp}). Current at power point (i_{pp}) and potential at power point (V_{pp}) are the abbreviations for the respective current and potential at power point.

The charging time (t) was calculated using the following formula:

$$t = \text{Time at which } V_{\text{oc}} \text{ is attained} - \text{Time at which illumination is started}$$

The fill factor (FF) and conversion efficiency (CE) have been calculated using the following formula:

$$\text{Fill factor} = \frac{(i_{\text{pp}} \times V_{\text{pp}})}{(i_{\text{sc}} \times V_{\text{oc}})}$$

$$\text{Conversion efficiency} = \frac{(i_{\text{pp}} \times V_{\text{pp}} \times \text{FF} \times 100\%)}{(A \times P)}$$

where A stands for Pt electrode area (cm^2) and P stands for average artificial solar intensity (mW cm^{-2}), respectively. The half change time ($t_{0.5}$), which is the amount of time it takes for the cell's power to drop to half of its highest level while being extracted from it in the dark at a particular external load, is used to measure the power storage capacity of a cell (resistance).

RESULTS AND DISCUSSION

The fabrication of modified photogalvanic cell and improved modified photogalvanic effect (solar energy conversion and storage) have been observed on the variation of working electrode surface area and concentration of dye, reductant, surfactant and alkali compounds. In this study, alizarin red S as dye, oxalic acid as reductant, CPC as surfactant, NaOH as alkali medium and platinum (Pt) electrode as working electrode have been used for the fabrication of modified photogalvanic cell and to improve the conversion and storage of solar energy with enhanced electrical output. The study of effect of different variables such as concentration of dye, reductant, surfactant and alkali and surface area of Pt electrode shows that the values of these variables affects the solar energy conversion performance of the modified photogalvanic cell. There is a characteristics value of each variable at which the modified photogalvanic cell shows the highest performance. Therefore, the optimum performance of the modified photogalvanic cell can be obtained by the careful selection of values of various variables. The optimal photogalvanic cell performance have been elucidated in terms of potential, power, photocurrent and charging time. In this modified photogalvanic cell setup, diffusion length (D_L) and artificial sunlight intensity were fixed throughout the experiments and the values were 90 mm and 10.4 mW cm^{-2} , respectively.

Effect of variation of photopotential: Effect of variation of photopotential was studied by fabricating a modified photogalvanic cell consisting of $8.0 \times 10^{-5} \text{ M}$ alizarin red S dye, $1.6 \times 10^{-3} \text{ M}$ oxalic acid reductant and $1.6 \times 10^{-3} \text{ M}$ CPC surfactant. The other conditions for modified photogalvanic cell were pH = 13.68, Pt electrode size (length \times width) = $0.5 \text{ cm} \times 0.3 \text{ cm}$, $D_L = 80 \text{ mm}$ and sunlight intensity = 10.4 mW cm^{-2} . On illumination of modified photogalvanic cell, it was found that the photopotential of cell increases fairly exponentially and reached to a highest potential value (V_{max}), which then decreases and becomes fairly constant (V_{oc}) (Fig. 2). It is due to the increasing number of excited electrons and increasing number of electrons donating dye molecules during illumination. At

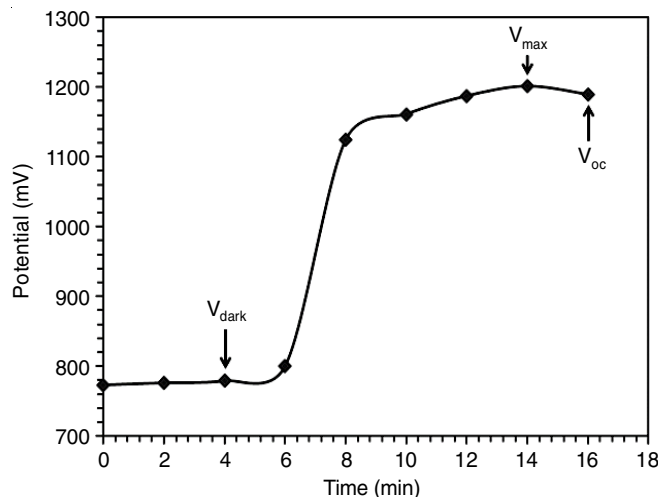


Fig. 2. Study of change in photopotential with respect to time in modified photogalvanic cell

TABLE-1
STUDY OF CHANGE IN CHEMICAL COMPOSITION OF CELL OF VARIATION OF ALIZARIN RED S PHOTOSENSITIZER DYE

Entry	Volume of chemical solution used to prepare total 25 mL mixture					Resultant concentrations			
	0.002 M Alizarin red S (mL)	0.01 M Oxalic acid (mL)	0.01 M CPC (mL)	2 M NaOH (mL)	Double distilled water (mL)	[Alizarin red S] × 10 ⁻⁵ M	[Oxalic acid] × 10 ⁻³ M	[CPC] × 10 ⁻³ M	[NaOH] pH
1	0.25	4.0	4.0	7.0	9.75	2.0	1.6	1.6	13.68
2	0.50	4.0	4.0	7.0	9.50	4.0	1.6	1.6	13.68
3	0.75	4.0	4.0	7.0	9.25	6.0	1.6	1.6	13.68
4	1.00	4.0	4.0	7.0	9.00	8.0	1.6	1.6	13.68
5	1.25	4.0	4.0	7.0	8.75	10.0	1.6	1.6	13.68

Note: #Saturated calomel electrode as reference electrode; Pt working electrode size 0.5 cm × 0.3 cm; and sunlight intensity 10.4 mW cm⁻².

V_{max} , the number of excited electrons and electron donating dye molecules were highest.

Effect of variation of alizarin red S dye photosensitizer concentration: Effect of variation of alizarin red S dye photosensitizer concentration was studied by fabricating five photogalvanic cells having different concentration of dye and rest other factors remain constant in each cell. Each photogalvanic cell contained 25 mL electrolyte solution of dye-reductant-surfactant-alkali and double distilled water (Table-1). The increasing trends in cell parameters was observed from 2.0 × 10⁻⁵ M to 8.0 × 10⁻⁵ M concentration of alizarin red S dye and afterward decreased in cell of 10.0 × 10⁻⁵ M concentration of alizarin red S dye (Table-2).

TABLE-2
EFFECT OF VARIATION OF ALIZARIN RED S DYE CONCENTRATION ON THE PERFORMANCE OF PHOTOGALVANIC CELL

Cell parameters	[Alizarin red S] × 10 ⁻⁵ M				
	2.0	4.0	6.0	8.0	10.0
V_{dark} (mV)	612	667	714	778	763
V_{max} (mV)	1173	1181	1172	1201	1208
V_{oc} (mV)	1123	1148	1136	1189	1178
i_{max} (μA)	340	380	420	520	460
i_{eq} or i_{sc} (μA)	260	320	360	420	380
V_{pp} (mV)	412	457	522	567	480
P_{pp} (μW)	57.68	82.26	114.84	147.42	86.40
i_{pp} (μA)	140	180	220	260	180
t (min)	12	19	14	17	13
CE (%)	0.728	1.176	2.061	2.160	1.069
FF	0.197	0.223	0.280	0.299	0.193

Note: [Oxalic acid] = 1.6 × 10⁻³ M; [CPC] = 1.6 × 10⁻³ M; pH = 13.68; Pt electrode size (length × width) = 0.5 cm × 0.3 cm; diffusion length (D_L) = 80 mm; sunlight intensity = 10.4 mW cm⁻².

Thus, a maxima was obtained in 8.0 × 10⁻⁵ M concentration of alizarin red S dye and found the maximum electrical output in modified photogalvanic cell. It was happened due to the optimal concentration of alizarin red S dye, which absorb appropriate amount of solar energy and donate appropriate number of electrons to Pt electrode and found maximum performance of modified photogalvanic cell. Whereas, higher concentration of alizarin red S dye (10 × 10⁻⁵ M) will not allow the absorption of appropriate amount of solar energy and therefore, a fall was obtained in the performance of modified photogalvanic cell. Fig. 3a for graphical demonstration of photocurrent and photopower of modified photogalvanic cell that was fabricated with variable concentration of alizarin red S dye and observed a peak at 8 × 10⁻⁵ M concentration of alizarin red S dye indicating maximum electrical output and improved the performance of modified photogalvanic cell.

Effect of variation of oxalic acid reductant concentration: Effect of variation of oxalic acid reductant concentration has been studied by fabricating five photogalvanic cells having different concentration of reductant and rest other factors remain constant in each cell. Each photogalvanic cell has packed with 25 mL electrolyte solution of dye-reductant-surfactant-alkali and double distilled water (Table-3). The increasing trends in cell parameters was observed from 1.2 × 10⁻³ M to 1.6 × 10⁻³ M concentration of oxalic acid reductant and afterward the decreasing trends in cell parameters was observed from 1.6 × 10⁻³ M to 2.0 × 10⁻³ M concentration of oxalic acid reductant (Table-4). Thus, a maxima was obtained in 1.6 × 10⁻³ M concentration of oxalic acid reductant and found the maximum electrical output in modified photogalvanic cell.

It was happened due to the optimal concentration of oxalic acid reductant which donate appropriate number of electrons

TABLE-3
STUDY OF CHANGE IN CHEMICAL COMPOSITION OF CELL OF VARIATION OF OXALIC ACID REDUCTANT

Entry	Volume of chemical solution used to prepare total 25 mL mixture					Resultant concentrations			
	0.002 M Alizarin red S (mL)	0.01 M Oxalic acid (mL)	0.01 M CPC (mL)	2 M NaOH (mL)	Double distilled water (mL)	[Alizarin red S] × 10 ⁻⁵ M	[Oxalic acid] × 10 ⁻³ M	[CPC] × 10 ⁻³ M	[NaOH] pH
1	1.0	3.0	4.0	7.0	10.0	8.0	1.2	1.6	13.68
2	1.0	3.5	4.0	7.0	9.5	8.0	1.4	1.6	13.68
3	1.0	4.0	4.0	7.0	9.0	8.0	1.6	1.6	13.68
4	1.0	4.5	4.0	7.0	8.5	8.0	1.8	1.6	13.68
5	1.0	5.0	4.0	7.0	8.0	8.0	2.0	1.6	13.68

Note: #Saturated calomel electrode as reference electrode; Pt working electrode size 0.5 cm × 0.3 cm; and sunlight intensity 10.4 mW cm⁻².

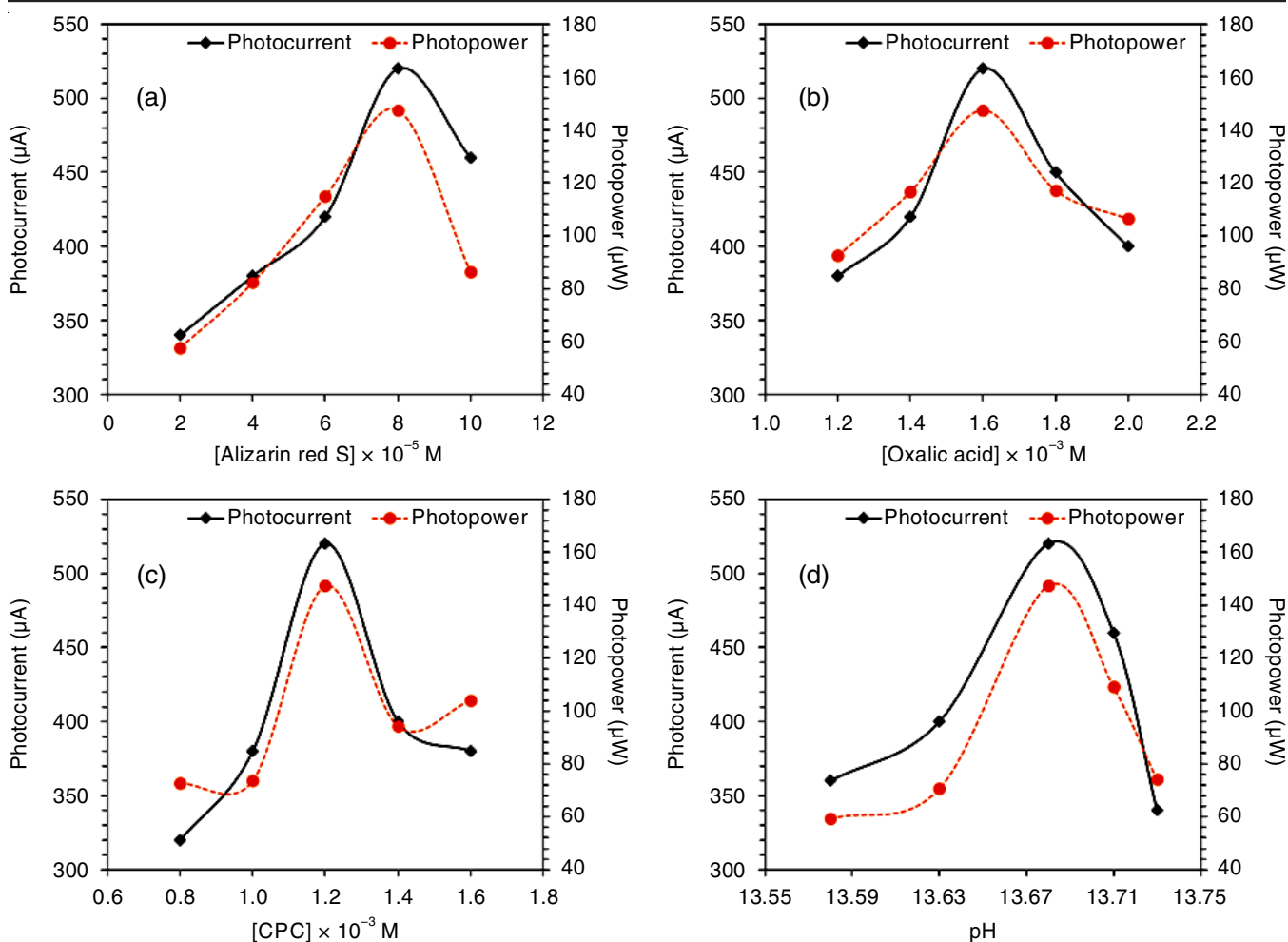


Fig. 3. Graphical demonstration of effect of variables on the photocurrent and photopower of modified photogalvanic cell, (a) Alizarin red S; (b) oxalic acid; (c) CPC; and (d) pH

TABLE-4
EFFECT OF VARIATION OF OXALIC ACID
REDUCTANT CONCENTRATION ON THE
PERFORMANCE OF PHOTO GALVANIC CELL

Cell parameters	[Oxalic acid] $\times 10^{-3}$ M				
	1.2	1.4	1.6	1.8	2.0
V_{dark} (mV)	800	805	778	799	788
V_{max} (mV)	1194	1191	1201	1196	1203
V_{oc} (mV)	1175	1150	1189	1187	1187
i_{max} (μA)	380	420	520	450	400
i_{eq} or i_{sc} (μA)	300	360	420	340	340
V_{dp} (mV)	661	648	567	586	665
P_{pp} (μW)	92.54	116.64	147.42	117.20	106.40
i_{dp} (μA)	140	180	260	200	160
t (min)	27	20	17	18	40
CE (%)	1.55	2.11	2.16	2.17	1.80
FF	0.262	0.282	0.2495	0.290	0.264

Note: [Alizarin red S] = 8.0×10^{-5} M; [CPC] = 1.6×10^{-3} M; pH = 13.68; Pt electrode size (length \times width) = $0.5 \text{ cm} \times 0.3 \text{ cm}$; diffusion length (D_l) = 80 mm; sunlight intensity = 10.4 mW cm^{-2} .

to alizarin red S dye and found maximum performance of modified photogalvanic cell. Whereas, higher concentration of oxalic acid reductant will not allow the absorption of appropriate amount of solar energy by dye molecules and hinder

the mobility of dye molecules and therefore, a fall was obtained in the performance of modified photogalvanic cell. Fig. 3b shows the photocurrent and photopower of modified photogalvanic cells with varying oxalic acid reductant concentrations. The peak at 1.6×10^{-3} M concentration indicates the optimal electrical output and improved performance.

Effect of variation of cetylpyridinium chloride (CPC) surfactant concentration: Effect of variation of CPC surfactant concentration was studied by fabricating five photogalvanic cells having different concentration of surfactant and rest other factors remain constant in each cell. Each photogalvanic cell contained 25 mL electrolyte solution of dye-reductant-surfactant-alkali and double distilled water (Table-5). The increasing trends in cell parameters was observed from 1.2×10^{-3} M to 1.6×10^{-3} M concentration of CPC surfactant and afterward the decreasing trends in cell parameters was observed from 1.8×10^{-3} M to 2.0×10^{-3} M concentration of CPC surfactant (Table-6). Thus, a maxima was obtained in 1.6×10^{-3} M concentration of CPC surfactant and found the maximum electrical output in modified photogalvanic cell. It was happened due to the critical micelle concentration (CMC) of CPC surfactant, which formed dye-micelle system. This system allow dye molecule to discard electrons from dye-micelle system to aqueous system.

TABLE-5
STUDY OF CHANGE IN CHEMICAL COMPOSITION OF CELL OF VARIATION OF
CETYLPIRIDINIUM CHLORIDE (CPC) SURFACTANT

Entry	Volume of chemical solution used to prepare total 25 mL mixture					Resultant concentrations			
	0.002 M Alizarin red S (mL)	0.01 M Oxalic acid (mL)	0.01 M CPC (mL)	2 M NaOH (mL)	Double distilled water (mL)	[Alizarin red S] × 10 ⁻⁵ M	[Oxalic acid] × 10 ⁻³ M	[CPC] × 10 ⁻³ M	[NaOH] pH
1	1.0	4.0	3.0	7.0	10.0	8.0	1.6	1.2	13.68
2	1.0	4.0	3.5	7.0	9.5	8.0	1.6	1.4	13.68
3	1.0	4.0	4.0	7.0	9.0	8.0	1.6	1.6	13.68
4	1.0	4.0	4.5	7.0	8.5	8.0	1.6	1.8	13.68
5	1.0	4.0	5.0	7.0	8.0	8.0	1.6	2.0	13.68

Note: #Saturated calomel electrode as reference electrode; Pt working electrode size 0.5 cm × 0.3 cm; and sunlight intensity 10.4 mW cm⁻².

TABLE-6
EFFECT OF VARIATION OF CETYLPIRIDINIUM
CHLORIDE (CPC) SURFACTANT CONCENTRATION
ON THE PERFORMANCE OF PHOTO GALVANIC CELL

Cell parameters	[CPC] × 10 ⁻³ M				
	1.2	1.4	1.6	1.8	2.0
V _{dark} (mV)	750	772	778	780	783
V _{max} (mV)	1102	1119	1201	1132	1130
V _{oc} (mV)	1067	1062	1189	1118	1098
i _{max} (μA)	320	380	520	400	380
i _{eq} or i _{sc} (μA)	260	260	420	340	320
V _{pp} (mV)	605	460	567	589	577
P _{pp} (μW)	72.60	73.60	147.42	94.24	103.86
i _{pp} (μA)	120	160	260	160	180
t (min)	22	20	17	18	20
CE (%)	1.219	1.259	2.160	1.498	1.964
FF	0.262	0.267	0.229	0.248	0.295

Note: [Alizarin red S] = 8.0 × 10⁻⁵ M; [oxalic acid] = 1.6 × 10⁻³ M; pH = 13.68; Pt electrode size (length × width) = 0.5 cm × 0.3 cm; diffusion length (D_L) = 80 mm; sunlight intensity = 10.4 mW cm⁻².

The eliminated electrons are subsequently drawn by the Pt electrode, resulting in the best performance of the modified photogalvanic cell. Fig. 3c shows the photocurrent and photopower of modified photogalvanic cells with varying CPC surfactant concentrations. The peak at 1.6 × 10⁻³ M concentration indicates optimal electrical output and improved performance.

Effect of variation of pH: Effect of variation of pH was studied by fabricating four types of photogalvanic cells having different concentration of NaOH and rest other factors remain constant in each cell. Each photogalvanic cell contained 25 mL electrolyte solution of dye-reductant-surfactant-alkali and double distilled water (Table-7). The increasing trends in cell parameters was observed from pH 13.58 to 13.68 and afterward the decreasing trends in cell parameters was observed from pH

13.71 to 13.73 (Table-8). Thus, a maxima was obtained at pH 13.68 and found the maximum electrical output in modified photogalvanic cell.

TABLE-8
EFFECT OF VARIATION OF pH ON THE
PERFORMANCE OF PHOTO GALVANIC CELL

Cell parameters	pH of solution				
	13.58	13.63	13.68	13.71	13.73
V _{dark} (mV)	557	668	778	712	691
V _{max} (mV)	1152	1189	1201	1191	1167
V _{oc} (mV)	1098	1119	1189	1143	1102
i _{max} (μA)	360	400	520	460	340
i _{eq} or i _{sc} (μA)	220	280	420	320	260
V _{pp} (mV)	424	442	567	496	463
P _{pp} (μW)	59.36	70.72	147.42	109.12	74.08
i _{pp} (μA)	140	160	260	220	160
t (min)	8	12	17	16	14
CE (%)	0.932	1.020	2.160	2.080	1.220
FF	0.245	0.225	0.229	0.298	0.258

Note: [Alizarin red S] = 8.0 × 10⁻⁵ M; [oxalic acid] = 1.6 × 10⁻³ M; [CPC] = 1.6 × 10⁻³ M; Pt electrode size (length × width) = 0.5 cm × 0.3 cm; diffusion length (D_L) = 80 mm; sunlight intensity = 10.4 mW cm⁻².

It happened because of the interaction between alkali and reductant, and the optimal pH value enhances the availability of reductant in its anionic form, putting it in a better position to donate electrons. Thus, the performance of modified photogalvanic cell was improved at a particular pH. Fig. 3d shows photocurrent and photopower of redesigned photogalvanic cell produced with variable pH range. A peak at pH 13.68 indicates maximum electrical output and increased performance.

Effect of variation of platinum electrode size and area: The effect of variation of Pt electrode's size and area was also

TABLE-7
STUDY OF CHANGE IN CHEMICAL COMPOSITION OF CELL OF VARIATION OF SODIUM HYDROXIDE (NaOH) AND pH AT 60 °C

Entry	Volume of chemical solution used to prepare total 25 mL mixture					Resultant concentrations			
	0.002 M Alizarin red S (mL)	0.01 M Oxalic acid (mL)	0.01 M CPC (mL)	2 M NaOH (mL)	Double distilled water (mL)	[Alizarin red S] × 10 ⁻⁵ M	[Oxalic acid] × 10 ⁻³ M	[CPC] × 10 ⁻³ M	[NaOH] pH
1	1.0	4.0	4.0	6.0	10.0	8.0	1.6	1.6	13.58
2	1.0	4.0	4.0	6.5	9.5	8.0	1.6	1.6	13.63
3	1.0	4.0	4.0	7.0	9.0	8.0	1.6	1.6	13.68
4	1.0	4.0	4.0	7.5	8.5	8.0	1.6	1.6	13.71
5	1.0	4.0	4.0	8.0	8.0	8.0	1.6	1.6	13.73

Note: #Saturated calomel electrode as reference electrode; Pt working electrode size 0.5 cm × 0.3 cm; and sunlight intensity 10.4 mW cm⁻².

studied by fabricating five types of photogalvanic cells with variable sizes of Pt electrode and rest other factors remain constant in each cell which was optimized previously. The size (length \times width in cm) of Pt electrode in all five cells were 0.3×0.2 , 0.4×0.2 , 0.4×0.3 , 0.5×0.3 and 1.0×1.0 and the resultant area (cm^2) of Pt electrode in each cell was 0.06, 0.08, 0.12, 0.15 and 1.00, respectively. A photogalvanic cell with a $0.5 \text{ cm} \times 0.3 \text{ cm}$ Pt electrode and 0.15 cm^2 area produced the best electrical output (Table-9). It was happened due to the optimal optimum number of electrons striking to the smaller sized Pt electrode and faster mobility of electrons. In terms of electrical output, the smaller electrode that contained the modified photogalvanic cell performed the best.

TABLE-9

EFFECT OF VARIATION OF PLATINUM ELECTRODE SIZE ON THE PERFORMANCE OF PHOTOGALVANIC CELL

Cell parameters	Platinum electrode size (length \times width) in cm and area				
	0.3 \times 0.2 (0.06 cm^2)	0.4 \times 0.2 (0.08 cm^2)	0.4 \times 0.3 (0.12 cm^2)	0.5 \times 0.3 (0.15 cm^2)	1.0 \times 1.0 (1.00 cm^2)
V_{dark} (mV)	743	749	734	778	781
V_{max} (mV)	1187	1184	1198	1201	1204
V_{oc} (mV)	1148	1154	1168	1189	1175
i_{max} (μA)	260	380	440	520	460
i_{eq} or i_{sc} (μA)	220	340	380	420	400
V_{pp} (mV)	467	412	457	567	456
P_{pp} (μW)	74.72	107.12	109.68	147.42	118.56
i_{pp} (μA)	160	260	240	260	260
t (min)	13	9	12	17	18
CE (%)	1.41	1.87	1.73	2.16	1.91
FF	0.295	0.273	0.247	0.229	0.252

Note: [Alizarin red S] = 8.0×10^{-5} M; [oxalic acid] = 1.6×10^{-3} M; [CPC] = 1.6×10^{-3} M; pH of solution = 13.68; diffusion length (D_L) = 80 mm; sunlight intensity = 10.4 mW cm^{-2} .

Effect of variation of illumination light intensity: Effect of variation of illumination light intensity was studied by fabricating previously optimized photogalvanic cells and perform the experiment with variable light intensity. The illumination light intensities were 3.1, 5.2, 10.4, 15.6 and 26.0 mW/cm^2 . The highest electrical output was observed in the modified photogalvanic cell that was illuminated with 10.4 mW/cm^2 light intensity (Table-10).

Effect of variation of diffusion length: Effect of variation of diffusion length was studied by fabricating the optimized photogalvanic cells and perform the experiment with variable diffusion length. The diffusion lengths were 60, 70, 80, 90 and 100 mm. The highest electrical output was observed in modified photogalvanic cell that has 80 mm diffusion length (Table-11).

Photocurrent, photopotential and power characteristics of modified photogalvanic cell: The optimal concentrations of dye, reductant, surfactant and alkali in a modified photogalvanic cell contained 1.0 mL of 0.002 M alizarin red S dye, 4.0 mL of 0.01 M oxalic acid reductant, 4.0 mL of 0.01 M CPC surfactant, 7.0 mL of 2 M NaOH and 9.0 mL distilled water to make up to 25 mL total volume has been studied for other characteristic parameters. The other specification for this cell were $D_L = 90 \text{ mm}$, sunlight intensity = 10.4 mW cm^{-2} ,

TABLE-10

EFFECT OF VARIATION OF ILLUMINATION LIGHT INTENSITY ON THE PERFORMANCE OF PHOTOGALVANIC CELL

Cell parameters	Illumination light intensity (mW/cm^2)				
	3.1	5.2	10.4	15.6	26.0
V_{dark} (mV)	750	739	778	693	712
V_{max} (mV)	1174	1208	1201	1195	1189
V_{oc} (mV)	1123	1174	1189	1148	1157
i_{max} (μA)	380	460	520	420	360
i_{eq} or i_{sc} (μA)	320	400	420	360	320
V_{pp} (mV)	488	555	567	521	441
P_{pp} (μW)	87.84	122.10	147.42	104.20	79.38
i_{pp} (μA)	180	220	260	200	180
t (min)	9	16	17	13	14
CE (%)	1.37	2.03	2.16	1.68	1.08
FF	0.244	0.260	0.229	0.252	0.214

Note: [Alizarin red S] = 8.0×10^{-5} M; [oxalic acid] = 1.6×10^{-3} M; [CPC] = 1.6×10^{-3} M; Pt working electrode size (length \times width) = $0.5 \text{ cm} \times 0.3 \text{ cm}$; pH of solution = 13.68; diffusion length (D_L) = 80 mm.

TABLE-11

EFFECT OF VARIATION OF DIFFUSION LENGTH ON THE PERFORMANCE OF PHOTOGALVANIC CELL

Cell parameters	Diffusion length (mm)				
	60	70	80	90	100
V_{dark} (mV)	754	776	778	779	763
V_{max} (mV)	1195	1189	1201	1204	1194
V_{oc} (mV)	1142	1154	1189	1178	1124
i_{max} (μA)	380	460	520	380	400
i_{eq} or i_{sc} (μA)	320	420	420	340	320
V_{pp} (mV)	478	452	567	480	451
P_{pp} (μW)	86.04	126.56	147.42	105.60	72.16
i_{pp} (μA)	180	280	260	220	160
t (min)	12	9	17	14	15
CE (%)	1.29	2.11	2.16	1.78	0.93
FF	0.235	0.261	0.229	0.263	0.200

Note: [Alizarin red S] = 8.0×10^{-5} M; [oxalic acid] = 1.6×10^{-3} M; [CPC] = 1.6×10^{-3} M; Pt working electrode size (length \times width) = $0.5 \text{ cm} \times 0.3 \text{ cm}$; pH of solution = 13.68; sunlight intensity = 10.4 mW cm^{-2} .

optimized Pt electrode area = 0.15 cm^2 , pH = 13.68 and temperature = 310 K.

The photocurrent-photopotential (i - V) characteristics of the modified photogalvanic cell shows that the highest power ($147.42 \mu\text{W}$) is extractable from cell at 567 mV photopotential and the photocurrent is $260 \mu\text{A}$ at this point (Fig. 4a). This point is then nominated as power point. The power point power (P_{pp}) and photocurrent (i_{pp}) were $147.42 \mu\text{W}$ and $260 \mu\text{A}$, respectively. Therefore, the cell performance of modified photogalvanic cell has been studied at this stage.

The cell performance of the modified photogalvanic cell shows that the power of cell decreases with time as a result of deactivation of dye molecules in dark (Fig. 4b). The power at power point reduces to its half value in 16 min that is called as half change time ($t_{0.5}$). Even after $t_{0.5}$, the improved photogalvanic cell continues to supply power until it has completely discharged. The cell parameters of this modified photogalvanic cell at specification given above were summarized as $V_{\text{dark}} = 778 \text{ mV}$; $V_{\text{max}} = 1201 \text{ mV}$; $V_{\text{oc}} = 1189 \text{ mV}$; $i_{\text{max}} = 520 \mu\text{A}$, $i_{\text{sc}} = 420 \mu\text{A}$; $V_{\text{pp}} = 567 \text{ mV}$; $P_{\text{pp}} = 147.42 \mu\text{W}$; $i_{\text{pp}} = 260 \mu\text{A}$; charging

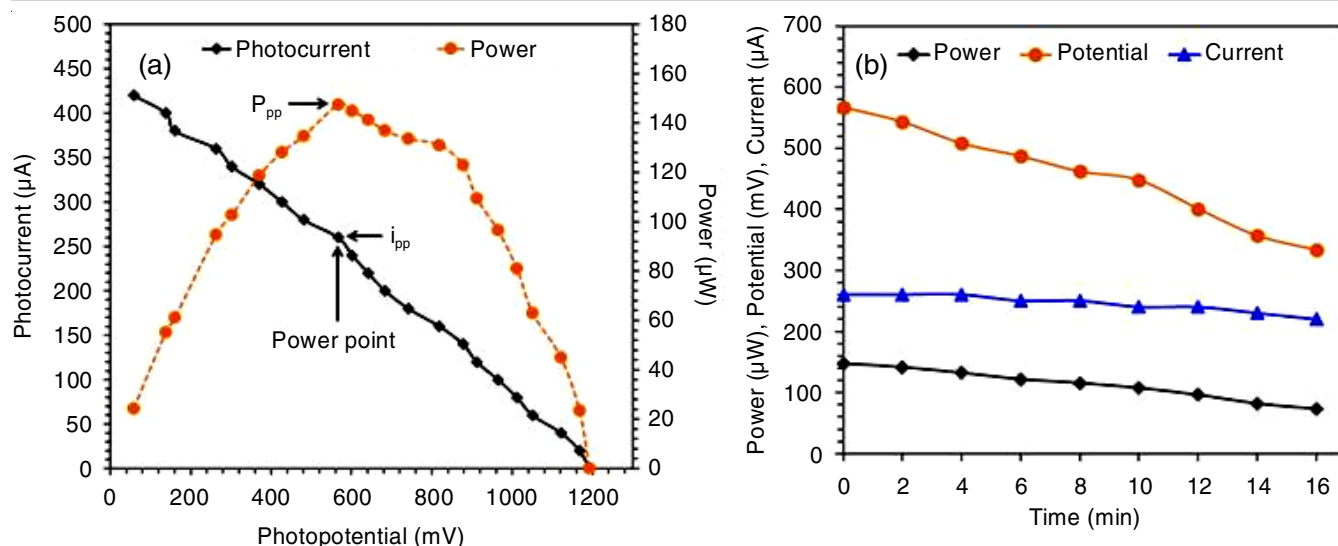


Fig. 4. Study of modified photogalvanic cell, (a) photocurrent-power characteristics; (b) cell performance with respect to time (time vs. power; time vs. potential; and time vs. current)

time (t) = 17 min; half change time ($t_{0.5}$) = 16 min; potential at $t_{0.5}$ = 334 mV; current at $t_{0.5}$ = 220 µA; power at $t_{0.5}$ = 73.48 µW; CE = 2.16%; and FF = 0.299.

Conclusion

This study on improved photogalvanic cells for solar energy conversion and storage addresses issues such as conversion efficiency, storage capacity and electrical output. An integrated photogalvanic system of alizarin red S (as dye), oxalic acid (as reductant) and cetylpyridinium chloride (as surfactant) has been fabricated and used for the conversion of solar energy in to electrical energy with improved the conversion efficiency and storage capacity. The modified photogalvanic cell with optimized concentration of dye-reductant-surfactant showed significantly improved performance. It can be expressed in terms of dark potential (778 mV), open-circuit potential (1189 mV), short-circuit current (420 µA), power (147.42 µW), charging time (17 min), half change time (16 min) and conversion efficiency (2.16%). The improved performance has been obtained with the optimum size of platinum electrode and diffusion length. It is concluded that the modified photogalvanic cell with optimum concentration of dye-reductant-surfactant showed improved performance. Therefore, it is good to achieve the economic viability and ease of commercial application of photogalvanic cell.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

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