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Photogalvanics of the platinum working electrode in the Allura Red D-Galactose-didecyl dimethyl ammonium chloride-NaOH electrolyte

Pooran Koli^{1*} and Jyoti Saren¹

Abstract

Photo-galvanic cell is a photochemical cell device whose performance depends on the combination of several factors like dye and reductant concentrations, dye stability, pH, light intensity, electrodes used, Pt electrode area, diffusion length, etc. An entirely new and unexplored combination of platinum with Allura Red photosensitizer, D-Galactose reductant, and didecyl dimethyl ammonium chloride (DDAC) surfactant has been explored in present research to upgrade the electrical performance of these cells. Allura Red is a water-soluble azo dye which shows good absorbance in region 501–507 nm. The Allura Red and DDAC is an anionic and cationic species, respectively, and therefore, the opposite charges of dye and surfactant molecules are expected to form a stable dye-surfactant complex enhancing the dye solubility and stability. D-Galactose has been used for its good reducing properties. This unexplored combination of Pt-Allura Red-D-Galactose-DDAC with these characteristics has encouraged further enhancement of the electrical output of the photogalvanic cells. The electrical output, stability, and spectral property of the photogalvanic cells have been studied in the present work. The observed power, current, potential, efficiency, and storage capacity (as half time) are of the order of 443.8 μ W, 2400 μ A, 721 mV, 11.61%, and 28 min, respectively. These observed results are higher than some reported data. In the spectral study, nearly the same band intensity of the pre-illuminated and post-illuminated electrolyte solution shows quite good photo-stability of the Allura Red dye in electrolyte form. This new combination of platinum-electrolyte still has the scope to achieve the enhanced cell performance of photogalvanic cells for future development.

Keywords Photogalvanics, Platinum working electrode, Allura Red, D-Galactose, Didecyl dimethyl ammonium chloride, Electrolyte

Introduction

The solar energy is the most versatile source of the energy. There are various solar power techniques to harness the solar energy. Some of the examples of these solar techniques are as-photovoltaic cells (Al-Ezzi & Ansari, 2022), perovskite solar cells (Ogomi et al., 2014), polymer solar cells (Cai et al., 2010), dye-sensitized solar cells

(Mahmoud & Fouad, 2015; Wang et al., 2011), photogalvanic cells (Mahmoud & Mohamed, 2015), etc. The photogalvanic cells are diffusion-controlled and dye sensitized solar cell devices capable of simultaneous solar power generation and storage. The basic principle of photogalvanic cell is to convert solar energy chemically into electricity which works on the phenomena of photogalvanic effect in which the photochemical reaction occurs within the electrolyte's body instead of electrode's surface (Rabinowitch, 1940a, 1940b). The pair of electrodes immersed in the electrolyte is naturally inert, and their work is only to exchange electrons from sensitizer to the outer circuit without undergoing any chemical

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reactions. The electrolyte consists of dilute concentration of photo-sensitizer (photon absorbing species), reductant (electron donating species) and surfactant (efficiency enhancer agent) in alkaline medium. When certain dyes are dissolved in a solution containing a suitable reducing agent, the solution becomes photo-chemically active. Thus, reductant and photo-sensitizer are required for the extraction of solar energy, while surfactant improves the photogalvanic cell's solar energy conversion efficiency.

From the detail review of literature, it has been observed that many photogalvanicists have worked on different photo-galvanic system of photosensitizer-reductant-surfactant in alkaline medium like-Rose Bengal-D-Xylose-sodium lauryl sulfate (SLS) (Gangotri & Bhimwal, 2010a), Brilliant Cresyl Blue-D-Xylose-SLS (Gangotri & Bhimwal, 2010b), Toluidine blue-D-Xylose-SLS (Gangotri & Bhimwal, 2010c), Methyl Orange-D-Xylose-SLS (Gangotri & Bhimwal, 2011), Safranine-Arabinose-SLS (Solanki & Gangotri, 2011a), Thymol Blue-Mannose-SLS (Solanki & Gangotri, 2012), Safranine-D-Xylose-SLS (Solanki & Gangotri, 2011b), Naphthol Green B-Fructose-SLS (Koli, 2014), Sudan-I-Fructose-SLS (Koli, 2021), Formic Acid-Sodium Lauryl Sulphate Surfactant-Indigo Carmine dye (Koli et al. 2021), Congo Red-formaldehyde-SLS (Koli, 2020), Bromo Cresol Green-formaldehyde-SLS (Koli et al., 2022a), Metanil yellow-formic acid-SLS (Koli et al., 2019), Tropaeoline O-oxalic acid-Benzalkonium (Koli et al., 2022b), etc., to get better electrical output and storage capacity. Recently, the photogalvanic cells based on the Tris (2,2'-Bipyridyl) ruthenium (II) chloride hexahydrate-diethyl ammonium tetrachloroferrate-oxalic acid electrolyte (Bendary et al., 2022), Rose Bengal-D-Xylose-Dioctyl Sodium Sulphosuccinate electrolyte (Bhimwal et al., 2022), D-Xylose-Methylene Blue-Brij-35-sodium lauryl sulphate electrolyte (Lal & Gangotri, 2023), and quinoline yellow-cellobiose-dioctyl sulfosuccinate sodium electrolyte (Jonwal et al., 2024) have been reported. The published work reveals that no attention has been paid to the Allura Red (photo-sensitizer), D-Galactose (reductant) and didecyl dimethyl ammonium chloride (surfactant).

Further, it is also revealed from the published literature that the photogalvanics of Platinum electrode has been extensively studied using variety of dye sensitizers in the presence of diversities of reductant-surfactant systems in alkali medium. The study of photogalvanic effect of platinum electrode in the Allura Red-D-Galactose-DDAC photogalvanic system has been explored with hope of further enhancing the cell performance.

The Allura Red is an azo dye containing the azo group ($-N=N-$) as chromophore, linked to benzene or/and naphthalene rings with lateral $-OH$ and $-SO_3H$ groups to increase their water solubility (Bellakhal, 2016).

Azo dyes have been researched extensively due to their absorbance in visible region and light harvesting efficiency. These dyes have also been reported with a large open-circuit potential (1.037–1.128 eV) (Mahmood et al., 2015). Allura Red has good stability to pH changes from pH 3 to 8, showing no appreciable change. It has an excellent solubility in water with a solubility of 22 g/100 ml at 25 °C. It has very good stability to light, fair to poor stability to oxidation and good stability to heat.

There are few reports on the application of azo dyes as photo-sensitizers on dye-sensitized solar cells (DSSCs) (Hosseinnezhad & Rouhani, 2016). Azo dyes are employed in DSSCs because they combine their optical and electrical characteristics with strong chemical stability and solution process (Mahmood et al., 2015). Also, there are some reports on the use of some azo dyes like Congo red (Koli, 2020), Methyl orange (Gangotri & Bhimwal, 2011), and Sunset yellow (Koli et al., 2023) in the photogalvanic cells, but there are no studies or reports on use of the Allura Red dye as a photo-sensitizer in photogalvanic cell.

The surfactant used in photo-galvanic cell enhances the stability and solubility of dye. Various surfactants like sodium lauryl sulphate (SLS) (Koli, 2020), Triton-X 100 (Ameta et al., 1990), Brij-35 (Lal & Gangotri, 2022), Tergitol-7 (Gangotri et al., 2013), CPC (1-cetylpyridinium chloride) (Ameta et al., 1990), cetyltrimethyl ammonium bromide (CTAB) (Tiwari, 2020), etc., have been extensively used in the photogalvanic cell. But, the use of DDAC surfactant in photogalvanics has not been reported and studied in the photogalvanic cell. The DDAC is a non-volatile, photolytically stable salt, and it is also highly soluble in the water solvent. The DDAC has been used as a surfactant in the present work due to its cationic nature also.

Further, it has also been reported in the literature that dye and surfactant having opposite charges form stable dye-surfactant complex in which dye molecule is surrounded by surfactant micelles in some regular geometry which retards the intermolecular twisting results in an enhancement of fluorescence (Genwa & Sagar, 2011).

Further, there are no reports on exploitation of the D-Galactose as a reductant in the photogalvanic cell. The D-Galactose is a reducing sugar that is capable of acting as a good reducing agent. In an alkaline solution, a reducing sugar forms some aldehyde or ketone, which allows it to act as a good reducing agent. The role of some reducing sugars like glucose (Gangotri et al., 1999), fructose (Koli, 2021), etc., is reported in the photogalvanic cells. Other reducing agents like oxalic acid (Koli et al., 2022b), formic acid (Koli, 2019), formaldehyde (Koli et al., 2022a), etc., has also been reported in the photogalvanic cells, but the use of the D-Galactose has not been reported yet.

Therefore, in the present work, the photogalvanics of the platinum-working electrode in an entirely new and novel electrolyte consisting of the Allura Red (Dye sensitizer), D-Galactose (reductant), and didecyl dimethyl ammonium chloride (DDAC, as surfactant) in an alkaline medium has been studied. The present research has been studied in terms of the charging, i-v characteristics, power storage capacity, optimization through variation of concentrations/dimensions/etc., and stability of the photogalvanic cell. The spectral property of the pre-illuminated electrolyte and post-illuminated electrolyte has also been studied in the present work.

The observed power, short circuit current, open circuit potential, conversion efficiency, and storage capacity (as half time) are of the order of 443.8 μ W, 2400 μ A, 721 mV, 11.61%, and 28 min, respectively. These observed results are higher than some reported data and lower than some reported data. The higher results of the photogalvanics of Pt in the present system from reported Pt photogalvanics may be attributed to the use of small sized Pt electrode, use of cationic surfactant with anionic dye sensitizer and use of graphite counter electrode instead of saturated calomel electrode (SCE) in the present work. In the spectral study, nearly same band intensity of the pre-illuminated and post-illuminated electrolyte solution shows quite good photo-stability of the Allura Red dye in electrolyte form. This new combination of Platinum-electrolyte still has the scope to achieve the enhanced cell performance of photogalvanic cell for future development.

Materials and methods

Chemicals used

Allura Red has been used as a photosensitizer. D-Galactose, Didecyl dimethylammonium chloride and NaOH have been used as reductant, surfactant, and alkaline medium, respectively. The stock solutions of Allura Red dye (M/500), D-Galactose (M/100), Didecyl Dimethyl ammonium Chloride (M/10) and NaOH (1N) have been prepared in the de-ionized distilled water. To keep the colored stock solution safe from light, it is stored in a dark container.

Allura Red dye: Allura Red has been used as photo-sensitizer in the present research (Fig. 1). It has been purchased from the Loba Chemie, Mumbai, India. Some of its characteristics are as follows- purity of sample 80%; IUPAC name: disodium 6-hydroxy-5-[(2-methoxy-5-methyl-4-sulphophenyl) azo]-2-naphthalenesulfonate; a red azo dye; M.F.C₁₈H₁₄N₂Na₂O₈S₂; M.W. 496.42; absorption maxima 501–507 nm; appearance dark red powder or granules; soluble in water (solubility in water 22 g/100 ml at 25 °C) and insoluble in ethanol. It is a naphthalenesulfonic acid and a food dye.

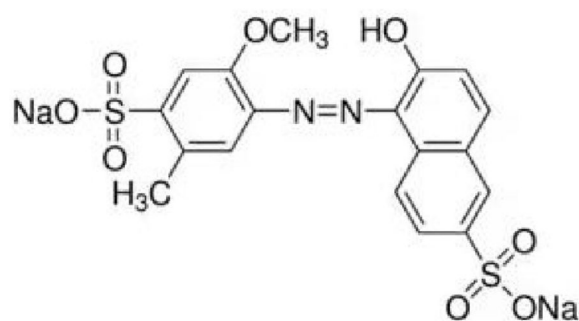


Fig. 1 Allura Red Dye structure

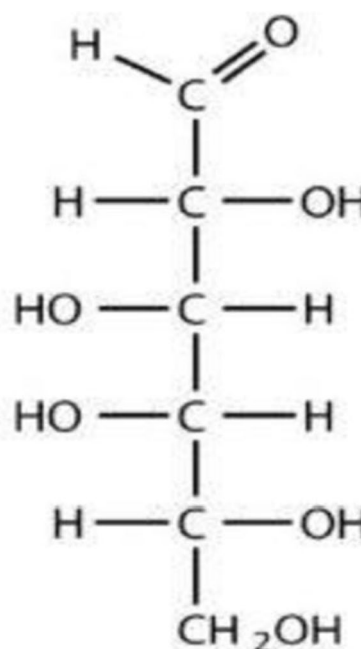


Fig. 2 D-galactose structure

D-Galactose: D-Galactose has been used as reductant in the present research. Its molecular formula, MW and IUPAC name is C₆H₁₂O₆, 180.16 gmol⁻¹, and D-galactohexopyranose, respectively (Fig. 2). Some of the characteristics of the D-Galactose are as-appearance white powder; forms colorless and clear solution when dissolved in 10% water. Room Temperature should be used for storage. D-Galactose is a monosaccharide sugar that serves as an energy source and glycosylation component. Galactose is a component of the disaccharide lactose and released upon hydrolysis by β -galactosidase enzymes. Therefore, the galactose used as reductant in present is obtainable from natural resources lactose.

Didecyl Dimethyl Ammonium Chloride (DDAC): The DDAC has been used as surfactant (Fig. 3). IUPAC name

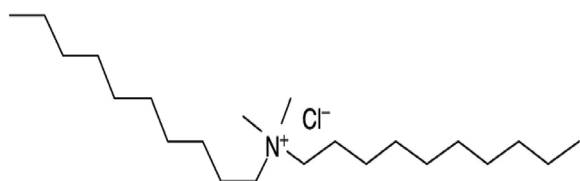


Fig. 3 Didecyl dimethyl ammonium chloride structure

of DDAC is *N*-Decyl-*N,N*-dimethyldecan-1-aminium chloride. Its characteristics are as- a cationic surfactant, M.F. $C_{22}H_{48}ClN$, M.W.362.08 g/mol, liquid, density 0.87 g/ml, and solubility in water 500 g/l at 20 °C. It is a quaternary ammonium compound used as antiseptic/disinfectant.

Electrodes used

Platinum electrode: platinum is the most inert electrode suitable for facilitating an efficient exchange of electrons between the electrode and the electrolyte solution.

Graphite electrode: graphite has a wide range of possible uses, including energy storage and conversion. It is good for environment because graphite electrode doesn't need to be changed regularly, it has a long operating life and easily available in the batteries.

Apparatus/instrument/equipment used

Present research has used following apparatus/instrument/equipment: two digital multimeters (model-DT830D UNITY), one for measuring potential in millivolts and another for measuring current in micro-amperes, copper connecting wires (for making circuit wires), Rheostat/Potentiometer Elcon B 1M 1706 (1Meg-awatt capacity) (for changing the circuit's resistance), a brass plug circuit key (for closing the circuit), a 200 W Philips bulb (as an illuminating source), a HTC LX-101A Luxmeter ($\pm 5\%$ of the reading) (for measuring the illumination intensity), a digital pH meter (Nexqua company) (for measuring the pH of electrolyte solution), and a water quality test meter C-100 (for measuring TDS/EC/SALT/S.G/TEMP).

Micro spectrophotometer (Model-MT 129: purchased from the Manti Lab Solution, Haryana, India; wavelength accuracy ± 2 nm) has been used to determine the absorption property in range 320–900 nm.

A HTC LX-101A Luxmeter ($\pm 5\%$ of the reading) has been used for measuring the illumination intensity of the lamp. While measuring the intensity of illumination of the cell, the luxmeter is placed at same place in same orientation (with respect to illuminating source) in which the cell is placed. The same position and orientation of the cell and luxmeter ensures that the luxmeter measures

the same illumination intensity which actually strike at the cell.

Experimental setup, experimental method and calculation formula

A very simple experimental set-up has been used in the present research. The experimental set-up consist of a light source (200-W Philips bulb), two digital multimeters (DT830D UNITY) for measuring current and potential, a rheostat/potentiometer Elcon B 1M for adjusting the resistance of the circuit, a circuit key, and an externally blackened H-shaped glass tube with a diffusion length of 4.5 cm. One arm of the H-shaped glass tube has a transparent window for illumination which acts as an illuminated chamber and other arm without window act as dark chamber. A Platinum electrode immersed in illuminated chamber against window have been used as a working electrode (as negative terminal, anodic) while a graphite electrode (cylindrical shape, length 4.1 cm \times diameter 0.3 cm) immersed in the dark chamber have been used as counter electrode (as positive terminal, cathodic) (Fig. 4). During the experiment, a complete electrolyte solution consisting of Allura Red (photosensitizer), D-Galactose (reductant), DDAC (surfactant) and Sodium hydroxide is put into the H-cell and then a stable potential (called dark potential, V_{dark}) is observed in the dark while the circuit is open. The bulb is then turned on, and the Pt electrode which is employed in this experiment as a working electrode gets illuminated. A rise in potential is then noticed at a regular interval of time. There is a sudden jump in the potential (called maximum potential, V_{max}), and after that the potential gradually goes down to a relatively stable potential (called open-circuit potential, V_{oc}). To observe the maximum current (I_{max}) at zero external resistance (load), the circuit is then closed using the circuit key. After sometime, the current gradually decreases to equilibrium current (I_{eq}), (called short-circuit current, I_{sc}). The potential at I_{sc} is nearly zero. To study the I - V characteristics of the cell, the resistance of the circuit is adjusted using a potentiometer/rheostat from minimum to maximum. The power corresponding to the highest value of product of 'I' and 'V' is called power at PowerPoint (P_{pp})/maximum power. Potential corresponding to this P_{pp} is potential at power point (V_{pp}) and the current corresponding to this P_{pp} is current at power point (I_{pp}). Cell performance is determined by calculating the conversion efficiency (CE), fill factor (FF), and storage capacity (in terms of the half change time, $t_{0.5}$). The FF and CE is calculated as follows:

$$FF = \frac{P_{\text{output}}}{V_{\alpha} \times I_{\text{sc}}}$$

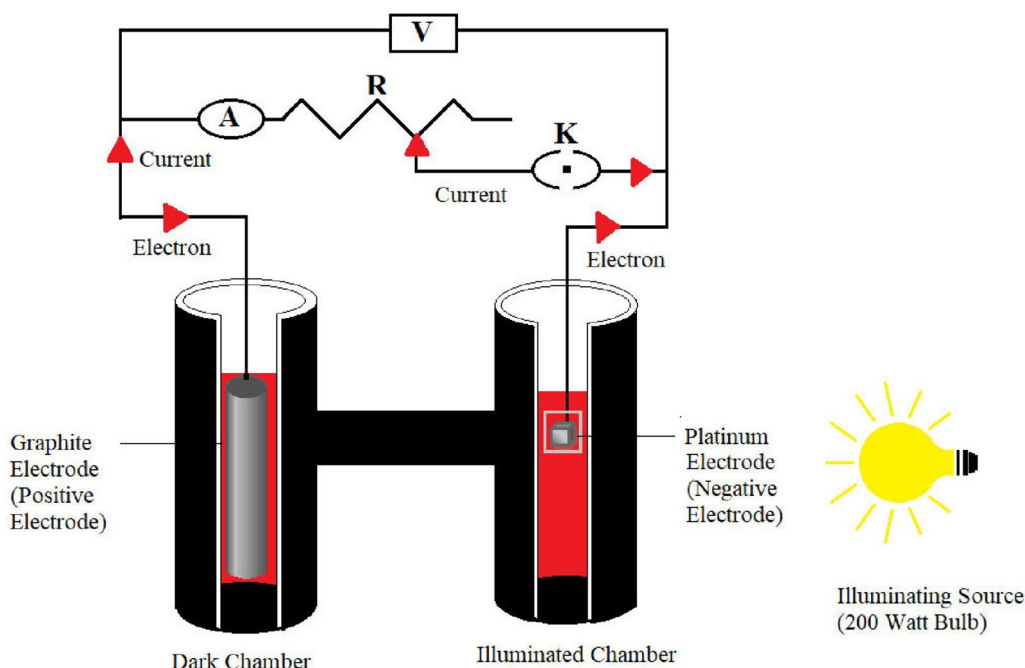


Fig. 4 Experimental set up of a photo-galvanic cell (here; 'A', a digital multi-meter as ammeter; 'V', another digital multi-meter as voltmeter; 'R', a potentiometer/rheostat; K, key)

$$CE = \frac{P_{\text{output}}}{P_i \times A} \times 100\%.$$

where P_i and A is the illumination intensity in mW/cm^2 , and the total surface area of all the six faces of the Pt electrode in cm^2 , respectively. The $t_{0.5}$ value is the time duration in which the extracted cell power value becomes half of the maximum power.

Authors have used the Haoyue digital multi-meters (model-DT830D UNITY) for the measurement of the current and potential in this research. Before using the Haoyue digital multi-meters (model-DT830D UNITY), these multi-meters were calibrated for potential and current measurements with the help of the Systronic digital pH meter-Model: 335 (for measuring potential in millivolt-mV) manufactured by Systronics India Ltd., Ahmedabad, India; and micro-ammeter (for measuring current in microampere- μA) manufactured by OSAW, Haryana, India.

The value of current measurement from the Haoyue digital multi-meters (model-DT830D UNITY) matches with the value measured from the micro-ammeter (for measuring current in microampere- μA) manufactured by OSAW, Haryana, India. Similarly, the value of potential measurement from the Haoyue digital multi-meters (model-DT830D UNITY) also matches with the value measured from the Systronic digital pH meter-Model: 335 (for measuring potential in millivolt-mV)

manufactured by Systronics India Ltd., Ahmedabad, India.

Therefore, the authors can claim that they have used proper electrochemical equipment (i.e., the Haoyue digital multi-meters-model-DT830D UNITY) to measure the output voltage and current.

Authors have been prompted to use the Haoyue digital multi-meters (model-DT830D UNITY) for measuring the current and potential in present research for following scientific, economic, and reported reasons:

First, the measurement value of the current and potential from the Haoyue digital multi-meters-model-DT830D UNITY is scientifically same as from the other scientific instruments like the Systronic digital pH meter-Model: 335 (for measuring potential in millivolt-mV) manufactured by Systronics India Ltd., Ahmedabad, India, and the micro-ammeter (for measuring current in microampere- μA) manufactured by OSAW, Haryana, India.

Second, the cost of the Systronic digital pH meter-Model: 335 and the OSAW Micro-ammeter (for measuring current in microampere- μA) in Indian market is high, i.e., approximately 166 USD, and 11 USD, respectively. Whereas, the cost of the Haoyue digital multi-meters-model-DT830D UNITY is only ~2.6 USD in Indian market.

Third, the measurement of the potential and current from the Haoyue digital multi-meters-model-DT830D

UNITY has already been accepted as scientifically valid by the experts (Koli & Saren, 2024), and;

Finally, the error analysis for each cell has been correlated with the accuracy of the current and potential measurement by the Digital multi-meter. In this experiment, the Haoyue digital multi-meters (model-DT830D UNITY) have been used. The accuracy of measurement of DC current and DC potentials from this multi-meter is $\pm 2.0\%$, and $\pm 1.0\%$, respectively. Therefore, in the observation data in the manuscript, the error $\pm 2.0\%$, $\pm 1.0\%$, and $\pm 3.0\%$, is estimated in the measurement of the current, potential, and power of the cell, respectively.

Results and discussions

The photogalvanics of the platinum electrode in the Allura Red-D-Galactose-DDAC-Platinum photogalvanic system has been studied by constructing 48 cells. The photogalvanics of the Platinum electrode material has been enhanced by optimization of cell fabrication variable. The study has been done in two successive stages— optimization of photogalvanics of the Platinum electrode in the Allura Red-D-Galactose-DDAC-Platinum photogalvanic system followed by comparison of the present data with the published work. The results of the optimization of photogalvanics of the Platinum electrode in the Allura Red-D-Galactose-DDAC-Platinum photogalvanic system are described as follows.

Effect of variation of the Allura Red dye concentration on the Allura Red-D-Galactose-DDAC-platinum photogalvanic system

The effect of variation of dye photosensitizer (Allura Red) on the photogalvanics of Platinum electrode in the Allura Red-D-Galactose-DDAC-Platinum photogalvanic system

has been studied by constructing eight photogalvanic cells having all the factors (like chemical concentrations of reductant, surfactant and alkali; electrode dimensions; light intensity; diffusion length; etc.) common for all the eight cells except the dye concentration (Table 1). The electrical parameters of the Allura Red-D-Galactose-DDAC-Platinum photogalvanic system are observed by taking 35 ml of the total solution in each eight cells. Each cell has 0.5 ml of M/100 D-Galactose (reductant) with resultant concentration 1.42×10^{-4} M, 0.5 ml of M/10 Didecyl Dimethyl Ammonium Chloride (surfactant) with resultant concentration 1.42×10^{-3} M, and 16 ml of 1N NaOH having resultant pH 13.66. The volume of M/500 Dye for eight cells is 0.1 ml, 0.3 ml, 0.5 ml, 0.7 ml, 0.9 ml, 1.1 ml, 1.3 ml. and 1.5 ml, respectively, with resultant concentration 0.57×10^{-5} M, 1.71×10^{-5} M, 2.85×10^{-5} M, 4.0×10^{-5} M, 5.14×10^{-5} M, 6.28×10^{-5} M, 7.42×10^{-5} M, and 8.57×10^{-5} M, respectively. It has been observed in the study that various electrical parameters [like dark potential— V_{dark} (mV); maximum potential— V_{max} (mV); open-circuit potential— V_{oc} (mV); charging time (t); maximum current— i_{max} (μA); short-circuit current— i_{sc} (μA); maximum power— P_{pp} (μW); potential at power point— V_{pp} (mV); current at power point— i_{pp} (μA); solar conversion efficiency—CE (%); and fill factor—FF] was found different for each of the eight cells on changing the dye concentration. This shows that the dye concentration affects the cell performance. It means the cell performance is dye concentration dependent, and the cell shows highest performance at some optimal dye concentration. The study of effect of variation of concentration of Allura Red dye for Allura Red-D-Galactose-DDAC-platinum photogalvanic system shows optimum cell performance at 2.85×10^{-5} M dye concentration. It is found

Table 1 Effect of variation of the Allura Red dye concentration on the Allura Red-D-Galactose-DDAC-Platinum photogalvanic system

Cell parameters	[Allura Red] $\times 10^{-5}$ M ^a							
	0.57	1.71	2.85	4.0	5.14	6.28	7.42	8.57
V_{dark} (mV)	466	441	435	419	445	407	443	464
V_{max} (mV)	733	749	726	749	770	723	761	763
V_{oc} (mV)	729	720	721	725	728	720	722	729
t (min.)	20	20	20	15	15	20	21	25
i_{max} (μA)	6050	5330	5510	5030	5520	4210	6470	6220
i_{sc} (μA)	2500	2260	2400	2120	2000	1780	1790	2450
P_{pp} (μW)	384.0	359.7	443.8	365.7	355.0	346.3	370.0	343.2
V_{pp} (mV)	251	218	269	254	263	296	257	260
i_{pp} (μA)	1530	1650	1650	1440	1350	1170	1440	1320
CE (%)	8.33	8.21	11.61	8.66	8.92	9.66	10.94	6.81
FF	0.21	0.22	0.25	0.22	0.24	0.27	0.28	0.19

^a At [D-Galactose] = 1.42×10^{-4} M, [DDAC] = 1.42×10^{-3} M, Platinum electrode size = 0.3 cm \times 0.2 cm, Platinum electrode area = 0.1325 cm², Graphite electrode area = 4.1 cm \times 0.3 cm, Light intensity = 7.299 mWcm⁻², Diffusion length (D_L) = 4.5 cm, pH = 13.66

in the observations that at both the lower and higher side of the optimal dye concentration (2.85×10^{-5} M), the electrical power output is low. This trend of results can be explained considering particle nature of both the matter and sunlight. It is to be noted that both the electromagnetic radiations (sunlight) and matter have the wave particle duality. The sunlight consists of the tiny particles called photons, and the matter also consists of the tiny particles called the ions/atoms/molecules. The lower power output (at dye concentrations below and above of 2.85×10^{-5} M) is due to the fact that at lower concentration, a smaller number of molecules are available for the absorption of the photons. At very high concentrations of the dye sensitizer, the electrical power output of the cell is low. This downfall trend in the power output of the cell may be attributed to some reasons like J/H aggregate formation of the Allura Red dye, deprivation of the dye molecules (those molecules which are close to working electrode) from the photons, etc. At higher dye concentration, despite the availability of large numbers of dye molecules, the numbers of photo-excited dye molecules in nearby area of Platinum will not be high due to J/H aggregate formation. At very high concentration of dye, the proximity of dye sensitizer molecules causes the formation of statistical traps and aggregates. This aggregate formation induces the dissipation of the excitation energy and in turn leads to the lowering of the population of photo-excited states owing to the self-quenching process (Rodríguez & Román, 2013). It is reported that Allura Red also forms H/J aggregates at high concentration (Alamatsaz et al., 2016; Barber et al., 1991; Bordbar et al., 2002; Ribo et al., 1994). Therefore, in the present case of the high concentration of the Allura Red dye, the

aggregate formation will lead to the lowering of the numbers of the excited sensitizer species and in turn lowering of the electrical power output.

It is also to be noted that the molecules photo-excited in nearby area of Platinum electrode are able to reach within their life time to platinum-working electrode leading to the generation of photo-current. The dye molecules photo-excited in regions away from platinum electrode fails to reach this electrode within their life time, and in turn, such molecules also fail to generate the photo-current (Ameta et al., 1989; Bhimwal & Gangotri, 2011). At higher dye concentration, the higher numbers of dye molecules will always prevent sunlight photons from reaching to nearby area of Platinum electrode.

Effect of variation of didecyl dimethyl ammonium chloride (DDAC) surfactant concentration on the Allura Red-D-Galactose-DDAC-platinum photogalvanic system

The effect of variation of didecyl dimethyl ammonium chloride (DDAC) surfactant concentration on the photogalvanics of platinum electrode in the Allura Red-D-Galactose-DDAC-platinum photogalvanic system has been studied by constructing eight photogalvanic cells having all the factors (like chemical concentrations of dye, reductant, and alkali; electrode dimensions; light intensity; diffusion length; etc.) common for all the eight cells except the surfactant concentration (Table 2). The electrical parameters of the Allura Red-D-Galactose-DDAC-platinum photogalvanic system are observed by taking 35 ml of the total solution in each eight cells. Each cell has 0.5 ml of M/100 D-Galactose (reductant) with resultant concentration 1.42×10^{-4} M, 0.5 ml of M/500 Allura Red (dye) with resultant concentration 2.85×10^{-5} M, and

Table 2 Effect of variation of didecyl dimethyl ammonium chloride (DDAC) surfactant concentration on the Allura Red-D-Galactose-DDAC-Platinum photogalvanic system

Cell parameters	[Didecyl dimethylammonium chloride] $\times 10^{-3}$ M ^a							
	0.28	0.85	1.42	2.0	2.57	3.14	3.71	4.28
V_{dark} (mV)	458	444	435	462	439	456	453	444
V_{max} (mV)	766	780	726	740	732	709	771	731
V_{oc} (mV)	742	724	721	724	722	699	729	721
t (min.)	20	15	20	15	15	20	15	20
i_{max} (μ A)	4590	5920	5510	4720	5380	5170	5340	2720
i_{sc} (μ A)	2340	2820	2400	2400	2700	5080	2120	1570
P_{pp} (μ W)	380.8	388.8	443.8	354.1	343.6	307.0	325.1	345.8
V_{pp} (mV)	280	240	269	233	242	301	229	266
i_{pp} (μ A)	1360	1620	1650	1520	1420	1020	1420	1300
CE (%)	8.62	7.63	11.61	7.43	6.25	8.79	7.06	10.90
FF	0.219	0.19	0.025	0.20	0.17	0.27	0.210	0.305

^a At [D-Galactose] = 1.42×10^{-4} M, [Allura Red] = 2.85×10^{-5} M, Platinum electrode size = 0.3 cm \times 0.2 cm, Platinum electrode area = 0.1325 cm², Graphite electrode area = 4.1 cm \times 0.3 cm, Light intensity = 7.299 mWcm⁻², Diffusion length (D_L) = 4.5 cm, pH = 13.66

16 ml of 1N NaOH having resultant pH 13.66. The volume of M/10 surfactant for eight cells is 0.1 ml, 0.3 ml, 0.5 ml, 0.7 ml, 0.9 ml, 1.1 ml, 1.3 ml, and 1.5 ml, respectively, with resultant concentration 0.28×10^{-3} M, 0.85×10^{-3} M, 1.42×10^{-3} M, 2.0×10^{-3} M, 2.57×10^{-3} M, 3.14×10^{-3} M, 3.71×10^{-3} M, and 4.28×10^{-3} M, respectively. It has been observed in the study that various electrical parameters [like dark potential— V_{dark} (mV); maximum potential— V_{max} (mV); open-circuit potential— V_{oc} (mV); charging time (t); short-circuit current— i_{sc} (μA); maximum power— P_{pp} (μW); potential at power point— V_{pp} (mV); current at power point— i_{pp} (μA); solar conversion efficiency—CE (%); and fill factor—FF] were found different for each of the eight cells on changing the surfactant concentration. This shows that the surfactant concentration affects the cell performance. It means the cell performance is surfactant concentration dependent, and the cell shows highest performance at some optimal surfactant concentration. The study of effect of variation of concentration of surfactant for Allura Red-D-Galactose-DDAC-Platinum photogalvanic system shows optimum cell performance at 1.42×10^{-3} M surfactant concentration. It is found in the observations that at both the lower and higher side of the optimal surfactant concentration (1.42×10^{-3} M), the electrical power output is low. This trend of results can be explained considering particle nature of both the matter and sunlight. The sunlight consists of the tiny particles called photons, and the matter also consists of the tiny particles called the ions/atoms/molecules. High electrical performance of photogalvanic cells depends on the stability and solubility of the dye. The surfactant generally enhances both the solubility and stability of the dye sensitizer molecules. The solubilizing effect of the surfactant is generally highest at the critical micelles concentrations (CMC) of the surfactant. Therefore, on increasing the concentration of the surfactant up to CMC value, the dye solubility increases leading to the enhanced electrical performance of the cell. The CMC value of DDAC is reported in the order of 10^{-3} molar (Aiad et al., 2016). In present case, the CMC value may be the 1.42×10^{-3} M. The lower power output (at surfactant concentrations below and above of 1.42×10^{-3} M) is due to the fact that at lower concentration, a smaller number of surfactant molecules are available for solubilizing of available dye molecules. At higher surfactant concentration, the higher numbers of surfactant molecules will prevent sunlight photons from reaching to nearby area of platinum electrode. Therefore, at higher surfactant concentration also, despite the availability of large numbers of surfactant molecules, the numbers of photo-excited dye molecules in nearby area of Platinum will not be high. It is to be noted that the molecules photo-excited in nearby area of Platinum electrode are able to reach

within their life time to platinum working electrode but the high surfactant concentration will limit the numbers of such dye molecule and in turn, such molecules also fail to generate the photo-current.

Effect of variation of D-Galactose reductant concentration on the Allura Red-D Galactose-DDAC-platinum photogalvanic system

The effect of variation of D-Galactose reductant concentration on the photogalvanics of platinum electrode in the Allura Red-D-Galactose-DDAC-Platinum photogalvanic system has been studied by constructing eight photogalvanic cells having all the factors (like chemical concentrations of dye, surfactant, and alkali; electrode dimensions; light intensity; diffusion length; etc.) common for all the eight cells except the reductant concentration (Table 3).

The electrical parameters of the Allura Red-D-Galactose-DDAC-Platinum photogalvanic system are observed by taking 35 ml of the total solution in each eight cells. Each cell has 0.5 ml of M/500 Allura Red (dye) with resultant concentration 2.85×10^{-5} M, 0.5 ml of M/10 Didecyl Dimethyl Ammonium Chloride (surfactant) with resultant concentration 1.42×10^{-3} M, and 16 ml of 1N NaOH having resultant pH 13.66. The volume of M/100 reductant for eight cells is 0.1 ml, 0.3 ml, 0.5 ml, 0.7 ml, 0.9 ml, 1.1 ml, 1.3 ml, and 1.5 ml, respectively, with resultant concentration 0.28×10^{-4} M, 0.85×10^{-4} M, 1.42×10^{-3} M, 2.0×10^{-4} M, 2.57×10^{-4} M, 3.14×10^{-4} M, 3.71×10^{-4} M, and 4.28×10^{-4} M, respectively.

It has been observed in the study that various electrical parameters [like dark potential— V_{dark} (mV); maximum potential— V_{max} (mV); open-circuit potential— V_{oc} (mV); charging time (t); short-circuit current— i_{sc} (μA); maximum power— P_{pp} (μW); potential at power point— V_{pp} (mV); current at power point— i_{pp} (μA); solar conversion efficiency—CE (%); and fill factor—FF] were found different for each of the eight cells on changing the reductant concentration. This shows that the reductant concentration affects the cell performance. It means the cell performance is reductant concentration dependent, and the cell shows highest performance at some optimal reductant concentration. The study of effect of variation of concentration of reductant for Allura Red-D-Galactose-DDAC-Platinum photogalvanic system shows optimum cell performance at 1.42×10^{-4} M reductant concentration. It is found in the observations that at both the lower and higher side of the optimal reductant concentration (1.42×10^{-4} M), the electrical power output is low. This trend of results can be explained considering particle nature of both the matter and sunlight. The sunlight consists of the tiny particles called photons, and the matter also consists of the tiny particles called the ions/atoms/

Table 3 Effect of variation of the D-Galactose reductant concentration on the Allura Red-D-galactose-DDAC-platinum photogalvanic system

Cell parameters	[D-Galactose] × 10 ⁻⁴ M ^a							
	0.28	0.85	1.42	2.0	2.57	3.14	3.71	4.28
V _{dark} (mV)	460	445	435	435	437	407	433	458
V _{max} (mV)	787	752	726	755	736	713	722	718
V _{oc} (mV)	726	728	721	730	715	696	704	712
t (min.)	20	17	20	20	15	15	20	15
i _{max} (μA)	5850	5890	5510	6220	5030	6080	6040	5830
i _{sc} (μA)	3160	3930	2400	2770	1880	1950	1580	1520
P _{pp} (μW)	394.6	406.1	443.8	384.0	300.0	436.7	364.9	344.0
V _{pp} (mV)	276	269	269	240	250	251	231	253
i _{pp} (μA)	1430	1510	1650	1600	1200	1740	1580	1360
CE (%)	7.01	5.92	11.61	7.50	6.69	14.49	12.37	11.34
FF	0.17	0.14	0.025	0.18	0.22	0.32	0.32	0.31

^a At [Allura Red] = 2.85 × 10⁻⁵ M, [DDAC] = 1.42 × 10⁻³ M, Pt electrode size = 0.3 cm × 0.2 cm, Platinum electrode area = 0.1325 cm², Graphite electrode area = 4.1 cm × 0.3 cm, Light intensity = 7.299 mWcm⁻², Diffusion length (D_i) = 4.5 cm, pH = 13.66

molecules. The lower power output (at reductant concentrations below and above of 1.42 × 10⁻⁴ M) is due to the fact that at lower concentration, a smaller number of reductant molecules are available for donating electrons to the dye molecules. At higher reductant concentration, increased back electron combination reaction (electron returning back from the dye to the reductant) along with the increased hindrance from the reductant molecules fails to generate photo current. Therefore, it is viewed that very high concentration of D-Galactose will reduce probability of light absorption by dye molecules. And, also the power output is adversely affected by high reductant concentration because the photons are absorbed too far away from the illuminated electrode for the photo-generated semi/leuco sensitizer to reach it before decomposing (Gangotri et al., 1996; Murthy et al., 1996).

Effect of variation of NaOH (pH) concentration on the Allura Red-D-Galactose-DDAC-platinum photogalvanic system

The effect of variation of NaOH (pH) concentration on the photogalvanics of platinum electrode in the Allura Red-D-Galactose-DDAC-Platinum photogalvanic system has been studied by constructing ten photogalvanic cells having all the factors (like chemical concentrations of dye, reductant, and surfactant; electrode dimensions; light intensity; diffusion length; etc.) common for all the ten cells except the NaOH (pH) concentration (Table 4).

The electrical parameters of the Allura Red-D-Galactose-DDAC-Platinum photogalvanic system are observed by taking 35 ml of the total solution in each ten cells. Each cell has 0.5 ml of M/500 Allura Red (dye) with

resultant concentration 2.85 × 10⁻⁵ M, 0.5 ml of M/100 D-Galactose (reductant) with resultant concentration 1.42 × 10⁻⁴ M, and, 0.5 ml of M/10 Didecyl Dimethyl Ammonium Chloride (surfactant) with resultant concentration 1.42 × 10⁻³ M. The volume of 1N NaOH for ten cells is 8 ml, 9 ml, 10 ml, 11 ml, 12 ml, 13 ml, 14 ml, 15 ml and 16 ml with pH 13.36, 13.41, 13.46, 13.5, 13.54, 13.57, 13.61, 13.64, 13.66, and 13.69, respectively.

It has been observed in the study that various electrical parameters [like dark potential—V_{dark} (mV); maximum potential—V_{max} (mV); open-circuit potential—V_{oc} (mV); charging time (t); short-circuit current—i_{sc} (μA); maximum power—P_{pp} (μW); potential at power point—V_{pp} (mV); current at power point—i_{pp} (μA); solar conversion efficiency—CE (%); and fill factor—FF] were found different for each of the ten cells on changing the NaOH (pH) concentration. This shows that the NaOH (pH) concentration affects the cell performance. It means the cell performance is NaOH (pH) concentration dependent, and the cell shows highest performance at some optimal NaOH (pH) concentration. The study of effect of variation of concentration of NaOH (pH) for Allura Red-D-Galactose-DDAC-Platinum photogalvanic system shows optimum cell performance at 13.66 pH. It is found in the observations that at both the lower and higher side of the optimal NaOH concentration (13.66 pH), the electrical power output is low.

This trend of results can be explained considering particle nature of both the matter and sunlight. The sunlight consists of the tiny particles called photons, and the matter also consists of the tiny particles called the ions/atoms/molecules. High pH favors the stability and solubility of the dye materials, which increases the electrical

Table 4 Effect of variation of NaOH (pH) concentration on the Allura Red-D-galactose-DDAC-platinum photogalvanic system

Cell parameters	[NaOH] pH ^a									
	13.36	13.41	13.46	13.5	13.54	13.57	13.61	13.64	13.66	13.69
V_{dark} (mV)	446	467	483	471	472	447	462	452	435	414
V_{max} (mV)	769	764	759	757	769	760	738	720	726	754
V_{oc} (mV)	751	747	738	744	748	752	733	716	721	725
t (min.)	35	26	20	20	20	25	20	20	20	15
i_{max} (μA)	4650	4450	3900	4370	5470	6100	5050	5680	5510	5700
i_{sc} (μA)	2720	2200	1170	2020	2120	1700	2210	3750	2400	2300
P_{pp} (μW)	226.8	289.5	290.7	271.3	324.0	325.7	370.8	401.7	443.8	391.8
V_{pp} (mV)	214	197	285	204	225	267	244	227	269	263
i_{pp} (μA)	1060	1470	1020	1330	1440	1220	1520	1770	1650	1490
CE (%)	2.60	5.26	10.09	5.04	6.83	8.55	8.74	6.18	11.61	9.52
FF	0.11	0.17	0.33	0.18	0.20	0.25	0.22	0.14	0.253	0.23

^a At [Allura Red] = 2.85×10^{-5} M, [D-Galactose] = 1.42×10^{-4} M, [DDAC] = 1.42×10^{-3} M, Pt electrode size = 0.3 cm × 0.2 cm, Platinum electrode area = 0.1325 cm², Graphite electrode area = 4.1 cm × 0.3 cm, Light intensity = 7.299 mWcm⁻², Diffusion length (D_L) = 4.5 cm

output of the dye-sensitized photo-galvanic cells (Koli et al., 2021). The lower power output below 13.66 pH is due to the fact that at lower concentration, a smaller number of alkali molecules are available for solubilizing the available dye molecules and will produce limited number of excited and electron rich molecules so the numbers of photo-excited dye molecules in nearby area of Platinum will not be high which in turn fails to generate photocurrent. With the rise in NaOH concentration up to 13.66 pH, the number of alkali molecules to solubilize dye molecules increases leading to the corresponding rise in the power output. At NaOH concentration above the 13.66 pH, the alkalinity may inhibit the movement of molecule of the dye towards the electrodes in the desired time limit. This shows that dye stability, dye solubility, and dye electron donating tendency depends on the strength of the alkali medium of the electrolyte. Further, the cell performance is poor in acidic medium. The low ability of the dye and reductant to donate electrons to the Platinum could be caused by proton attachment to the heteroatom and double bonds in the dye and reductant. This effect is not present in alkali media, the anion formation of dye and reductant enhances their electron donation power. When the pH is extremely high, the OH (from the NaOH used in this system) can combine with the cationic reductant (produced when reductant donates electrons to dye), preventing reductant from regeneration in its original form and resulting in poor cell performance (Koli, 2017).

Effect of variation of light intensity on the Allura Red-D-Galactose-DDAC-platinum photogalvanic system

The effect of variation of light intensity on the photogalvanics of Platinum electrode in the Allura

Red-D-Galactose-DDAC-Platinum photogalvanic system has been studied by constructing five photogalvanic cells having all the factors (like chemical concentrations of dye, reductant, surfactant and alkali; electrode dimensions; diffusion length; etc.) common for all the five cells except the light intensity (Table 5).

The electrical parameters of the Allura Red-D-Galactose-DDAC-Platinum photogalvanic system are observed by taking 35 ml of the total solution in each five cells. Each cell has 0.5 ml of M/500 Allura Red (dye) with resultant concentration 2.85×10^{-5} M, 0.5 ml of M/100 D-Galactose (reductant) with resultant concentration 1.42×10^{-4} M, 0.5 ml of M/10 didecyl dimethyl

Table 5 Effect of variation of light intensity on the Allura Red-D-galactose-DDAC-platinum photogalvanic system

Cell parameters	Light intensity (mWcm ⁻²) ^a				
	12.87	12.00	7.29	6.16	3.76
V_{dark} (mV)	478	448	435	468	425
V_{max} (mV)	743	734	726	744	755
V_{oc} (mV)	715	721	721	739	725
t (min.)	15	20	20	20	20
i_{max} (μA)	7000	6190	5510	6020	4900
i_{sc} (μA)	4690	2520	2400	2830	2900
P_{pp} (μW)	420.5	474.2	443.8	460.8	411.0
V_{pp} (mV)	290	247	269	512	239
i_{pp} (μA)	1450	1920	1650	900	1720
CE (%)	7.91	7.77	11.61	12.41	16.05
FF	0.32	0.26	0.25	0.22	0.19

^a At [Allura Red] = 2.85×10^{-5} M, [D-Galactose] = 1.42×10^{-4} M, [DDAC] = 1.42×10^{-3} M, Pt electrode size = 0.3 cm × 0.2 cm, Platinum electrode area = 0.1325 cm², Graphite electrode area = 4.1 cm × 0.3 cm, Diffusion length (D_L) = 4.5 cm, pH = 13.66

ammonium chloride (surfactant) with resultant concentration 1.42×10^{-3} M and 1N NaOH of pH 13.66. The light Intensity of five cells is 12.87 mWcm^{-2} , 12.00 mWcm^{-2} , 7.29 mWcm^{-2} , 6.16 mWcm^{-2} , and 3.76 mWcm^{-2} , respectively.

It has been observed in the study that various electrical parameters [like dark potential— V_{dark} (mV); maximum potential— V_{max} (mV); open-circuit potential— V_{oc} (mV); charging time (t); short-circuit current— i_{sc} (μA); maximum power— P_{pp} (μW); potential at power point— V_{pp} (mV); current at power point— i_{pp} (μA); solar conversion efficiency—CE (%); and fill factor—FF] were found different for each of the five cells on changing the light intensity. This shows that the light intensity affects the cell performance. It means the cell performance is light intensity dependent, and the cell shows highest performance at some optimal light intensity. The study of effect of variation of light intensity on the Allura Red-D-Galactose-DDAC-platinum photogalvanic system shows optimum cell performance at the illumination intensity 12.00 mWcm^{-2} . It is found in the observations that at both the lower and higher side of the optimal light intensity (12.00 mW cm^{-2}), the electrical power output is low. This trend of results can be explained considering particle nature of both the matter and sunlight. The sunlight consists of the tiny particles called photons, and the matter also consists of the tiny particles called the ions/atoms/molecules. At illumination intensity below the 12.00 mWcm^{-2} , the number of the available photons shall be less in numbers for photo-exciting the dye molecules leading to the reduced cell power output. At illumination intensity above the 12.00 mWcm^{-2} , the numbers of available photons shall be larger than that of the available dye molecules available for absorbing the photons. Thus, the higher illumination intensity will not in effect cause the photo-excitation of the increased numbers of the dye sensitizers' molecules. Further, the excess illumination intensity will cause heating effect leading to the downfall in the electrical output of the cell (Koli et al., 2019).

Effect of variation of size of illumination window on the Allura Red-D-Galactose-DDAC-platinum photogalvanic system

The effect of variation of size of illumination window on the photogalvanics of platinum electrode in the Allura Red-D-Galactose-DDAC-Platinum photogalvanic system has been studied by constructing five photogalvanic cells having all the factors (like chemical concentrations of dye, reductant, surfactant and alkali; electrode dimensions; diffusion length; etc.) common for all the five cells except the size of illumination window (Table 6).

The electrical parameters of the Allura Red-D-Galactose-DDAC-Platinum photogalvanic system are observed

Table 6 Effect of variation of size of illumination window on the Allura Red-D-Galactose-DDAC-Platinum photogalvanic system

Cell parameters	Size of illumination window (cm × cm) ^a				
	1.0 × 1.0	1.5 × 1.0	1.5 × 1.5	2.0 × 1.0	2.0 × 1.5
V_{dark} (mV)	435	462	452	450	451
V_{max} (mV)	726	734	738	732	735
V_{oc} (mV)	721	719	728	720	720
t (min.)	20	20	15	20	15
i_{max} (μA)	5510	5850	5310	6090	5280
i_{sc} (μA)	2400	2520	2650	2680	2330
P_{pp} (μW)	443.8	333.9	421.1	386.5	392.5
V_{pp} (mV)	269	283	224	256	250
i_{pp} (μA)	1650	1180	1880	1510	1570
CE (%)	11.61	6.35	9.49	7.99	9.45
FF	0.25	0.18	0.21	0.20	0.23

^a At [Allura Red] = 2.85×10^{-5} M, [D-Galactose] = 1.42×10^{-4} M, [DDAC] = 1.42×10^{-3} M, Pt electrode size = $0.3 \text{ cm} \times 0.2 \text{ cm}$, Platinum electrode area = 0.1325 cm^2 , Graphite electrode area = $4.1 \text{ cm} \times 0.3 \text{ cm}$, Light intensity = 7.299 mWcm^{-2} , Diffusion length (D_L) = 4.5 cm , pH = 13.66

by taking 35 ml of the total solution in each five cells. Each cell has 0.5 ml of M/500 Allura Red (dye) with resultant concentration 2.85×10^{-5} M, 0.5 ml of M/100 D-Galactose (reductant) with resultant concentration 1.42×10^{-4} M, 0.5 ml of M/10 Didecyl Dimethyl Ammonium Chloride (surfactant) with resultant concentration 1.42×10^{-3} M, and 1N NaOH of pH 13.66. The size of illumination window for five cells is $1.0 \times 1.0 \text{ cm}^2$, $1.5 \times 1.0 \text{ cm}^2$, $1.5 \times 1.5 \text{ cm}^2$, $2.0 \times 1.0 \text{ cm}^2$, and $2.0 \times 1.5 \text{ cm}^2$, respectively.

It has been observed in the study that various electrical parameters [like dark potential— V_{dark} (mV); maximum potential— V_{max} (mV); open-circuit potential— V_{oc} (mV); charging time (t); short-circuit current— i_{sc} (μA); maximum power— P_{pp} (μW); potential at power point— V_{pp} (mV); current at power point— i_{pp} (μA); solar conversion efficiency—CE (%); and fill factor—FF] were found different for each of the five cells on changing the size of the illumination window. But there is no significant change in the electrical performance of the cell on variation of the illumination window size. This shows that the size of illumination window does not significantly affects the cell performance.

This trend of results can be explained considering the properties like diffraction, scattering and particle nature of the both sunlight and matter. For all window sizes (whether small or large), the whole body of the electrolyte is exposed to the illumination due to the diffraction and scattering of the sunlight. Therefore, the dye molecules present throughout the body of the electrolyte are exposed to the photons.

The photogalvanic cells uses very dilute solution of the dye. In present case, the resultant concentration of the dye is 2.85×10^{-5} M in total 35 ml volume of the electrolyte. It means that the whole electrolyte has nearly 17.157×10^{18} dye molecules. For Allura Red dye, absorbance is $\sim 60\%$ at 506 nm. Therefore, considering about $\sim 60\%$ absorbance of the sunlight by the dye nearly 17.157×10^{18} photons are required for effective photogalvanics. For window size 1×1 cm², the number of falling photons per seconds is nearly 2.027×10^{16} from illuminating intensity 7.299 mWcm⁻². It means lesser or greater numbers of the photons than the numbers of dye molecules present in the electrolyte shall not cause good photogalvanics. At small window size, the numbers of photons entering the electrolyte will be less in number to excite sufficient dye molecules leading to the lower power output. At larger window sizes, the numbers of photons entering the electrolyte shall be in excess and ineffective for photogalvanics leading no proportionate increase in power output. Further, larger window size and excess photons will cause heating effect affecting cell adversely.

Effect of variation of platinum electrode area on the Allura Red-D-Galactose-DDAC-platinum photogalvanic system

The effect of variation of Platinum electrode area in the Allura Red-D-Galactose-DDAC-Platinum photogalvanic system has been studied by constructing four photogalvanic cells having all the factors (like chemical concentrations of dye, surfactant, and alkali; light intensity; diffusion length; etc.) common for all the four cells except the Platinum electrode area (Table 7).

The electrical parameters of the Allura Red-D-Galactose-DDAC-Platinum photogalvanic system are observed by taking 35 ml of the total solution in each four cells. Each cell has 0.5 ml of M/500 Allura Red (dye) with resultant concentration 2.85×10^{-5} M, 0.5 ml of M/100 D-Galactose (reductant) with resultant concentration 1.42×10^{-4} M, 0.5 ml of M/10 Didecyl Dimethyl Ammonium Chloride (surfactant) with resultant concentration 1.42×10^{-3} M and 1N NaOH of resultant pH 13.66. The size of platinum electrode area for four cells is 0.13 cm², 1.57 cm², 2.2 cm², and 3.25 cm², respectively.

It has been observed in the study that various electrical parameters [like dark potential— V_{dark} (mV); maximum potential— V_{max} (mV); open-circuit potential— V_{oc} (mV); charging time (t); short-circuit current— i_{sc} (μ A); maximum power— P_{pp} (μ W); potential at power point— V_{pp} (mV); current at power point— i_{pp} (μ A); solar conversion efficiency—CE (%); and fill factor—FF] were found different for the different Platinum electrode area. This shows that the Platinum electrode area affects the cell performance. It means the cell

Table 7 Effect of variation of Platinum electrode area on the Allura Red-D-Galactose-DDAC photogalvanic-Platinum system

Cell parameters	Platinum electrode area (cm ²) ^a			
	0.13	1.57	2.2	3.25
V_{dark} (mV)	435	453	477	480
V_{max} (mV)	726	721	718	735
V_{oc} (mV)	721	712	710	727
t (min.)	20	20	20	20
i_{max} (μ A)	5510	5150	6110	7000
i_{sc} (μ A)	2400	2140	3200	5000
P_{pp} (μ W)	443.8	437.9	512.5	434.7
V_{pp} (mV)	269	272	255	247
i_{pp} (μ A)	1650	1610	2010	1760
CE (%)	11.61	1.09	0.53	0.21
FF	00.25	0.28	0.16	0.11

^a At [Allura Red] = 2.85×10^{-5} M, [D-Galactose] = 1.42×10^{-4} M, [DDAC] = 1.42×10^{-3} M, Graphite electrode area = $4.1 \text{ cm} \times 0.3 \text{ cm}$, Light intensity = 7.299 mWcm^{-2} , Diffusion length (D_L) = 4.5 cm, pH = 13.66

performance is Platinum electrode area dependent, and the cell shows highest performance at some optimal Platinum electrode area. The study of effect of the variation of Platinum electrode area for Allura Red-D-Galactose-DDAC-Platinum photogalvanic system shows optimum cell performance at Platinum electrode area of 2.2 cm² under the experimental limitations. For electrodes of the area larger than this 2.2 cm², the cell power output was found decreasing with the increase in the electrode area. For the observed effect of the electrode area, the better efficiency is supposed to be for small electrodes owing to relatively less hindrance to diffusion of ions as the photogalvanic cells are the diffusion-controlled cells depending on the diffusion of the ions in the bulk of the electrolytic solution.

The excited and reduced dye molecules collide with the Platinum electrode, and through this process, the excess electron from the dye molecule is transferred to the Platinum working electrode. The number of electrons transferred per second from the dye to Platinum constitutes the current in the external circuit. How many numbers of the dye molecules at a time may interact with the Platinum electrode depends on the electrode surface area. For larger electrode area, the numbers of dye molecules may not be sufficient to cover whole electrode surface and to use large surface area of electrode effectively. So, the larger electrode area will not be able to bring proportionate increase in the current under the experimental conditions. Further, the larger sized Platinum will affect cell adversely due to steric hindrance in the diffusion path of the dye molecules.

Study of potential variation with time during illumination of the cell, I–V characteristics, power storage capacity of the Allura Red-D-Galactose-DDAC-platinum photogalvanic cell, and mechanism

Study of potential variation with time during illumination of the NaOH-Allura Red-D-Galactose-DDAC-platinum photogalvanic system

In the Photogalvanic system of Allura Red-D-Galactose-DDAC-Platinum, the H-cell is filled with the known amount of electrolyte solution (total volume 35 ml, 0.5 ml of M/500 dye, 0.5 ml of M/100 reductant, 0.5 ml of M/10 surfactant, 16 ml of 1 N NaOH, and 17.5 ml of distilled water). In the dark condition, the cell is allowed to attain equilibrium potential (stable potential) called dark potential (V_{dark} , observed 435 mV in present case) while circuit is open. Thereafter, cell is charged by illuminating it with the artificial light with the intensity of 7.299 mWcm^{-2} while keeping the circuit open. During illumination, the potential is observed with a time intervals of 5 min. The observed potential at zero time is 439 mV. On illumination, the potential rises and reaches to a highest potential called as a maximum potential (V_{max} , 726 mV in present case), after some time, the potential goes down and attains a quasi-equilibrium potential (stable potential) called as the open-circuit potential (V_{oc} , 721 mV in present case) (Table 8, Fig. 5). The open-circuit potential (V_{oc} , 721 mV) was obtained after 20 min of the continuous illumination. Therefore, in present case, the time duration of 20 min has been designated as charging time of the cell.

Study of variation of current with potential (I–V characteristics of cell), and current with power for Allura Red-D-Galactose-DDAC-platinum photogalvanic system

Study of I–V characteristics of cell represents the relationship between the voltage and the current flowing through it. It is one of the most common methods of determining how an electrical device functions in a circuit. In the present work, after fully charging the Allura Red-D-Galactose-DDAC-Platinum photogalvanic system,

Table 8 Study of potential variation with time during illumination of the NaOH-Allura Red-D-Galactose-DDAC-Platinum photogalvanic system

S.No.	Time (min)	Potential (mV)
1	0	439
2	5	434
3	10	726 (V_{max})
4	15	721
5	20	721 (V_{oc})

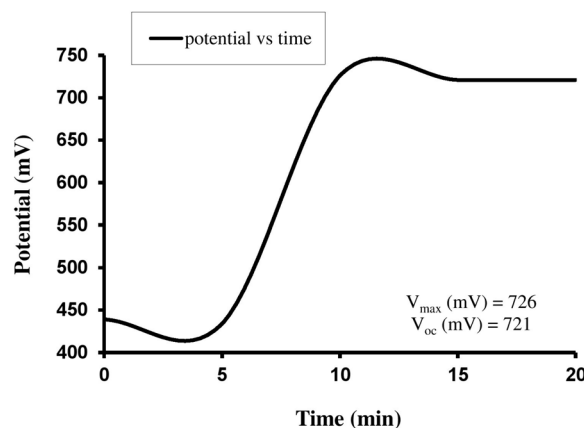


Fig. 5 Study of potential variation with time during illumination for NaOH-Allura Red-D-Galactose-DDAC-Platinum photogalvanic system

circuit is closed by circuit key to observe maximum current (I_{max}) $5510 \mu\text{A}$ at external resistance (load) zero. After some time, the current gradually decreases to a relatively stable value called as equilibrium current (I_{eq}) or short-circuit current (I_{sc}) $2400 \mu\text{A}$. The potential at (I_{sc}) is nearly zero. With the help of the potentiometer/rheostat, the resistance of the circuit is varied slowly from zero potential to maximum potential value along with their corresponding current values, i.e., from short-circuit current value till the current is zero to study the I–V characteristics of the cell (Table 9, Fig. 6). The point in the I–V curve called the power point (P_{pp}) $433.8 \mu\text{W}$ was determined where the product of potential and current was maximum.

For this Allura Red-D-Galactose-DDAC-Platinum photogalvanic system, the optimum value of the cell’s electrical parameters obtained at the experimental condition (Temp. $21.8 \text{ }^\circ\text{C}$, Humidity 47%, electrolyte Temp. $21.0 \text{ }^\circ\text{C}$, pH of solution 13.66) is summarized as: dark potential 435 mV, maximum potential (V_{max}) 726 mV, open-circuit potential (V_{oc}) 721 mV, charging time (min) 20 min, maximum current (I_{max}) $5510 \mu\text{A}$, short circuit current (I_{sc}) $2400 \mu\text{A}$, power at power point (P_{pp}) $443.8 \mu\text{W}$, current at power point (I_{pp}) $1650 \mu\text{A}$, potential at power point (V_{pp}) 269 mV, fill factor (FF) 0.25, and conversion efficiency (CE) 11.61%.

Study of power storage capacity of the Allura Red-D-Galactose-DDAC-platinum photogalvanic system (half change time)

Study of power storage capacity (half change time) of the NaOH-Allura Red-D-Galactose-DDAC-Platinum photogalvanic system has been studied through three

Table 9 Study of variation of current with potential (I–V characteristics of cell), and current with power for Allura Red-D-Galactose-DDAC-Platinum photogalvanic system

Current (μA)	Potential ^a (mV)	Power (μW)	Current (μA)	Potential ^a (mV)	Power (μW)
2430	028	068.0	1130	303	342.3
2100	083	174.3	1050	310	325.5
2040	113	230.5	910	320	291.2
1980	168	332.6	870	330	287.1
1840	220	404.8	720	357	257.0
1790	238	426.0	650	374	243.1
1750	249	435.7	500	428	214.0
1600	270	432.0	490	435	213.1
1650 (i_{pp})	269 (V_{pp})	443.8 (P_{pp})	380	463	175.9
1540	272	418.8	230	504	115.9
1430	278	397.5	140	584	81.7
1350	285	384.7	000	698	000
1230	296	364.0	–	–	–

^a CE = 11.61%, FF = 0.253, Dye = 0.5 ml, Reductant = 0.5 ml, Surfactant = 0.5 ml, pH = 13.66, Platinum electrode size = 0.3 cm × 0.2 cm, Platinum electrode area = 0.1325 cm², Graphite electrode area = 4.1 cm × 0.3 cm Room Temp. = 21.8 °C, Humidity = 47%, Solution Temp. = 21.0 °C, Distance from the bulb = 8 cm, Intensity = 924 × 10 lx (7.299 mWcm⁻²)

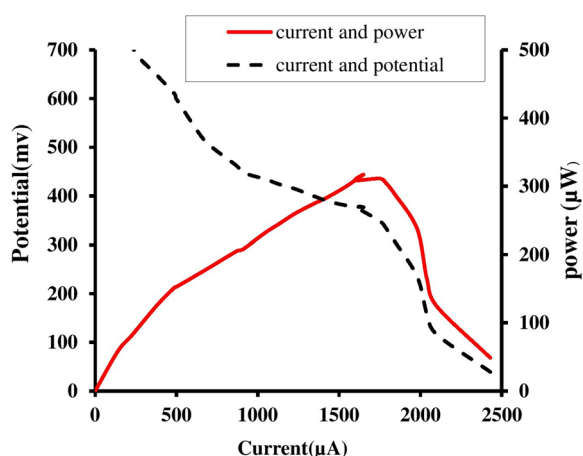


Fig. 6 Study of variation of current with potential (I–V characteristics of cell) (shown by dashed line), and current with power for Allura Red-D-galactose-DDAC-platinum photogalvanic system (shown by solid line)

experiments. For all three experiments, the cell fabrication variables and principles of the study were the same.

The additional advantage of photogalvanic cell is its inherent storage capacity of solar energy in the form of electrical energy. In the early stages of research, the scientists focused mainly on the enhancement of the conversion efficiency. But without storage of energy, it may be difficult to make these cells competitive with other cells. A detailed study on the storage of solar energy in the form of electrical energy was reported in the year 1972 (Daniels, 1972). Later on, various workers have reported photogalvanic cells with remarkable storage

capability (Breneman & Lichtin, 1981; Deb, 1978; Deb et al., 1978; Witzke, 1978; Witzke & Deb, 1978; Witzke et al., 1978). Therefore, the photogalvanic cell has an extra advantage of being capable of working in the dark.

The power storage capacity of the photo-galvanic cell is defined as its capacity to store the solar power obtained from the sunlight energy. This storage capacity may be attributed to the both photo processes and dark processes occurring in the electrolyte. The dye sensitizer molecules are photo-excited by absorbing the photon energy. The excited species have life ranging from zero time to infinite time. Statistically, the excited species have average life time. The average life of singlet and triplet species is 10^{-9} s and 10^{-3} s, respectively. So, because of the species having certain life, the cell continues to supply power in even dark conditions enabling power storage through the cell. In absence of the light, the dark processes also contribute in extraction of the power from the cell in post-illuminated dark conditions.

The power storage capacity of the cell has been studied in terms of the half change time ($t_{0.5}$). The half change time is defined as the time duration in which the power reduces to half of its initial value in the dark conditions. For study of the power storage capacity, the cell is fully charged and the power at point is determined with the help of the I–V characteristics. Thereafter, the resistance of the circuit is set to get again the potential and current corresponding to the power at point. Thereafter, the illumination is cut-off and the cell is put in the dark. The power at different time intervals is noted. The time (starting from the time at which

the illumination is cut-off) at which the power output becomes half of the initial power (power point) is called half time.

In the 1st experiment, the power reduces from 570.96 μW to 288.80 μW in 20 min, and therefore, the half-life ($t_{0.5}$) of cell is designated as 20 min in the 1st experiment (Tables 10, 11). In the 2nd experiment, the power reduces from 773.37 μW to 385.84 μW in 28 min, and therefore, the half-life ($t_{0.5}$) of cell is designated as 28 min in the 2nd experiment (Table 12). In the 3rd experiment, the power reduces from 343.22 μW to 156.80 μW in 04 min, and therefore, the half-life ($t_{0.5}$) of cell is designated as 04 min in the 3rd experiment (Table 13).

The mechanism for the storage of the energy in the photogalvanic cells can be explained on the basis of life time of the excited states (semi/leuco) of dye, and the rate of transfer of electron between dye and reducing agent. Average life time of photo excited states of the Allura Red dye is estimated to be $\sim 0.7 \times 10^{-12}$ s to 40×10^{-12} s (Hamburger et al., 2023). The photo-galvanic cells are the devices that go through the cycles of charging and discharging process that can only be charged in presence of illumination source and the cell will only get discharge when an external circuit is applied for electron transfer. The cell will continue to store light energy even in the absence of external circuit. The population of excited dye molecules and the stability of the excited state of the dye molecules determine how long the cell will store light energy. The storage capacity of the cell will be higher if the excited dye molecules are more stable due to its bulkiness or amount of delocalization of excited electrons on it. If for any reasons, say, due to recombination as a result of diffusion, the concentration of excited dye is reduced and the storage capacity of cell will also get reduced (Genwa et al., 2009; Malviya & Solanki, 2016).

Most plausible mechanism of the photo-generation of the current in the NaOH-Allura

Red-D-Galactose-DDAC-platinum photo-galvanic system

The following mechanism has been suggested for the photogeneration of the current in the NaOH-Allura Red-D-Galactose-DDAC-Platinum photogalvanic system on the basis of the present work and the already published literature (Fig. 7) (Koli, 2018; Gangotri et al., 1996; Murthy et al., 1996; Potter Jr. & Thaller, 1959; Rabinowitch, 1940a). Abbreviations-Allura Red dye (AR), D-Galactose Reductant (Gal).

Photo-processes occurring in the electrolyte and on the surface of the Pt electrode:

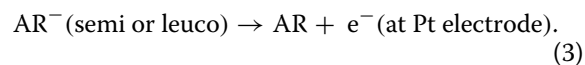
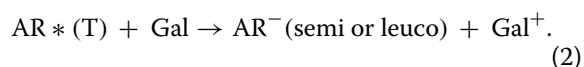
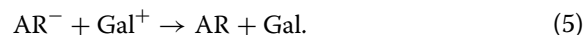
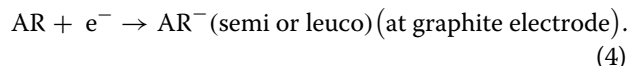


Photo-processes occurring in the electrolyte of the graphite region:



In illuminated region of the cell, the Allura Red dye photosensitizer molecule absorbs energy from the photons and gets photo-excited to higher energy level to form the excited state of Allura Red dye molecule, leaving a vacant space in its ground state. After photo-excitation, the Allura Red dye molecule gets reduced by receiving electrons in its ground state from the reductant D-Galactose. After that the excess of electrons produced in the higher energy state of the dye molecule is donated to an electron acceptor Pt electrode. This is because the dye molecule cannot accommodate this excess electron for a long time. Then, the electrons from the Platinum electrode flow through circuit to graphite electrode showing conversion of light into electricity. At graphite electrode, the dye molecule (present in the electrolyte solution) accepts electron in its ground state to form semi reduced form of the Allura Red dye molecule, which in turn reduces the oxidized reductant D-Galactose molecule, which has diffused to the electrolyte region nearby the graphite counter chamber. This way, the photo-galvanic cell enables solar energy conversion into solar power with inherent storage capacity.

Here, it is to be noted that the surfactant is not a necessary species required in the mechanism of photo-generation of the current. But, the presence of the surfactant generally enhances the dye stability and in turn the electrical output of the cell. The present research is based on the concept of light harvesting through the Allura Red dye sensitizer material. The light-induced dye decay is imminent. In other words, the dye stability is lowered in the presence of the sunlight. The monomeric dye species are open for the sunlight and photo-decay. The presence of the surfactant enhances the photo-stability of the dye molecule as the exposure of dye molecules to sunlight photon is prevented by incorporation of dye molecule in micelles (Oakes et al., 2003; Tehrani-Bagha & Holmberg, 2013). Therefore, only interactions between the surfactant and dye molecules will not be able to keep the dye stable. The dye-surfactant interaction leading to the incorporation of dye molecules in micelles will be able to keep dye stable.

Further, the role of dye is in absorbing light and also working as electro- active species at both the electrodes. The whole mechanism of current generation is

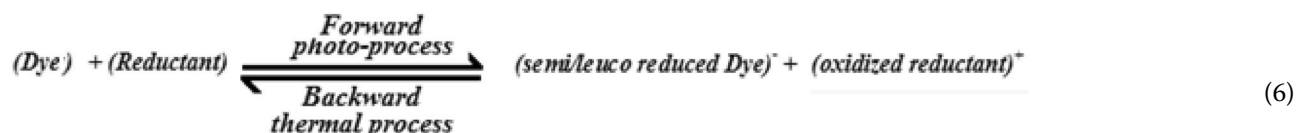
Table 10 Change of power with time in dark (study of cell performance) for the NaOH-Allura Red-d-Galactose-DDAC-Platinum photo-galvanic cell (1st experiment)

Time (h)	Current (μA)	Potential (mV)	Power (μW)	Time (h)	Current (μA)	Potential (mV)	Power (μW)	Time (h)	Current (μA)	Potential (mV)	Power (μW)
<i>Day 1</i>											
0.00	1560	366	570.96	0.60	820	273	223.86	70.83	232	89	20.64
0.01	1276	356	454.25	0.63	805	269	216.54	71.16	234	89	20.82
0.03	1168	348	403.68	0.65	798	267	213.06	71.53	235	90	21.15
0.05	1129	346	390.63	0.66	789	264	208.29	71.98	231	89	20.55
0.06	1061	341	361.80	0.68	780	262	204.36	72.36	235	90	21.15
0.08	1055	337	355.53	0.75	756	255	192.78	72.50	235	90	21.15
0.10	1071	333	356.64	1.50	463	163	75.46	<i>Day 5</i>			
0.11	1075	329	353.67	1.65	437	154	67.29	<i>Day 6</i>			
0.13	1077	324	348.94	1.73	427	151	64.47	119.05	26	10	0.26
0.15	1074	323	345.61	1.85	417	148	61.71	120.60	24	10	0.24
0.16	1066	320	341.12	<i>Day 2</i>				121.15	24	10	0.24
0.18	1057	319	337.18	23.00	273	102	27.84	121.36	24	09	0.21
0.20	1040	317	329.68	23.13	273	102	27.84	121.58	24	09	0.21
0.21	1026	316	324.21	23.20	272	101	27.47	121.95	24	09	0.21
0.23	1014	315	319.41	23.46	272	101	27.47	<i>Day 7</i>			
0.25	1005	313	314.56	23.63	270	101	27.27	145.76	07	03	0.02
0.26	989	311	307.57	23.73	268	100	26.80	<i>Day 8</i>			
0.28	979	310	303.49	23.83	265	99	26.23	167.58	07	03	0.02
0.30	971	308	299.06	23.95	264	98	25.87	169.85	07	09	0.06
0.31	960	306	293.76	24.06	262	98	25.67	170.15	08	04	0.03
0.33	950	304,288.80 (t _{0.5} 20 min)	293.76	24.36	261	97	25.31	<i>Day 9</i>			
0.35	940	302	283.88	24.48	260	97	25.22	190.53	07	03	0.02
0.36	923	301	277.82	24.73	259	97	25.12				
0.38	919	298	273.86	25.46	257	96	24.67				
0.40	910	296	269.36	25.95	256	95	24.32				
0.41	899	294	264.30	26.03	257	96	24.67				
0.43	891	292	260.17	<i>Day 3</i>							
0.45	884	290	256.36	<i>Day 4</i>							
0.46	879	289	254.03	69.98	232	89	20.64				
0.48	870	287	249.69	70.11	232	89	20.64				
0.50	864	286	247.10	70.50	231	88	20.32				

Table 11 Variation of power with time (stability of cell under dark) of NaOH-Allura Red-d-Galactose-DDAC-Platinum photogalvanic system (1st experiment)

S. No.	Time (h)	Power (μ W)
1	0	570.90
2	24	25.67
3	70	20.64
4	190	0.00

based on the photo-physical processes taking place in following sequence: absorption of photon by dye molecule, photo-excitation of electron in dye molecule to form excited singlet state of the dye molecule, intersystem crossing to form triplet excited state of the dye molecule, reductant reduces excited dye molecule to semi/leuco forms, interaction of semi/leuco form of dye molecule with platinum working electrode, electron transfer from semi/leuco dye molecule to platinum, flow of this electron from working electrode to counter electrode through the external circuit, ground state dye molecule interaction with counter electrode and transfer of electron from this electrode to dye molecule (formation of semi reduced form of the dye molecule), interaction of this semi-reduced dye molecule with oxidized state of reductant molecule to form the original molecules of dye and reductant. The photo-induced electrochemical changes occurring in the electrolyte may be represented by following equilibrium (Eq. 6):



The electron affinity of the ground state dye molecule is lower than that of the reductant molecule, but the electron affinity of the excited dye molecule is higher than that of the reductant molecule. Therefore, the electron transfer from the ground state reductant molecule to the photo-excited dye molecule easily takes place in the illuminated conditions (forward photo-process shown in Eq. 6). Further, the electron affinity of the oxidized state of reductant (oxidized state being an electron and energy deficient state) is higher than that of the semi/leuco reduced dye state (this state is an energy and electron rich state) (Koli, et al., 2024; Rohtagi-Mukherjee, 1986).

Therefore, the electron transfer from the semi/leuco reduced dye state molecule to the oxidized state of reductant molecule easily takes place in the thermal

conditions to regenerate electronically original dye molecule (backward thermal-process shown in Eq. 1) (Schmidt et al., 1990). This way the original dye molecule is assumed to be regenerated. It is to be noted that the photogalvanic process involves only electron exchange among sensitizer, reductant and electrodes (Rabinowitch, 1940a, 1940b). During photo-galvanic process, the photo-physical events lead to the conversion of solar energy into solar electricity in a cyclic manner. There is ideally no chemical change in the molecules of sensitizer and reductant molecules. Ideally, the photogalvanic system acts as a (cyclic) light-driven electricity generator (Albery et al., 1979). The photogalvanic behaviour has been found reversible for several cycles (Suresh et al., 1999). The reducing agents and their oxidized products behave as the electron carriers in the cell diffusing through the path (Albery et al., 1979). But, in the course of time, the photo-induced decay of sensitizer molecule and reductant molecule is imminent. Further, the reductant molecule is supposed to be a non-electro-active sacrificial reductant species (Albery et al., 1979). Thus, the mechanistic aspect of the photo-generation of the current through the photogalvanic cells as has been reported time to time does not show any reported information on the role of Fluorescence resonance energy transfer (FRET). However, the authors foresee the occurrence of FRET in the photogalvanic systems. Further, the photogalvanic systems are favoured by the increased population of the excited sensitizer species. The energy re-absorption as a result

of FRET by the dye sensitizer molecules is expected to enhance the efficiency of these cells. The authors would try to investigate this aspect of science in the future research.

The photo-galvanic cells are based on the principle of photo-galvanic effect (a special Becquerel effect). In 1925, the scientists Rideal and Williams observed the photo-galvanic effect which, later on in 1940, was systematically investigated by the scientist Rabinowitch in Fe (II)-Thionine system (Rabinowitch, 1940a, 1940b; Rideal & Williams, 1925). Rabinowitch suggested that the photo-galvanic effect might be used to convert sunlight into electricity. In photo-galvanic effect, the generation of potential difference between two electrodes is attributed to the photo-physical processes occurring in the body of the electrolyte. In photo-galvanic effect, the generation of

Table 12 Change of power with time in dark (study of cell performance) for the NaOH-Allura Red-o-Galactose-DDAC-Platinum photo-galvanic cell (2nd experiment)

Time (h)	Current (μA)	Potential (mV)	Power (μW)	Time (h)	Current (μA)	Potential (mV)	Power (μW)	Time (h)	Current (μA)	Potential (mV)	Power (μW)
<i>Day 1</i>											
0.00	1983	390	773.37	0.58	1244	259	322.19	22.66	250	59	14.75
0.01	1950	378	737.10	0.60	1226	256	313.85	23.36	247	59	14.57
0.03	1932	374	722.56	0.61	1209	253	305.87	23.80	247	59	14.57
0.05	1916	370	708.92	0.65	1170	250	297.75	23.86	247	58	14.32
0.06	1881	365	686.56	0.66	1146	246	287.82	23.96	247	59	14.57
0.08	1872	362	677.66	0.68	1132	240	277.33	24.91	250	59	14.75
0.10	1847	357	659.37	0.70	1120	238	271.68	<i>Day 3</i>			
0.11	1832	355	670.17	0.71	1109	236	266.56	<i>Day 4</i>			
0.13	1817	352	637.12	0.73	1085	231	261.72	68.20	281	67	18.82
0.15	1794	348	622.92	0.75	1071	228	250.63	68.90	280	66	18.48
0.16	1764	344	606.81	0.76	1064	227	244.18	69.41	280	66	18.48
0.18	1739	339	589.52	0.78	1044	224	241.52	70.21	279	66	18.41
0.20	1685	331	557.73	0.80	1030	221	233.85	70.33	280	65	18.20
0.21	1684	331	557.40	0.81	1015	218	227.63	<i>Day 5</i>			
0.23	1667	328	546.77	0.83	998	215	221.27	92.33	321	78	25.03
0.25	1649	324	534.27	0.85	983	212	214.57	93.03	318	77	24.48
0.26	1625	321	521.62	0.86	965	209	208.39	94.21	324	78	25.27
0.28	1607	317	509.41	0.88	961	208	201.68	94.26	328	78	25.58
0.30	1574	313	492.66	0.90	949	206	199.88	94.71	330	113	41.92
0.31	1556	310	482.36	0.91	938	204	195.49	95.53	371	97	30.36
0.33	1520	303	460.56	0.93	926	202	191.35	95.65	313	97	27.16
0.35	1509	302	455.71	0.95	916	200	187.05	95.83	280	108	27.10
0.36	1489	299	445.21	0.96	905	198	183.20	95.96	251		
0.38	1467	295	432.76	0.98	896	196	179.19	<i>Day 6</i>			
0.40	1441	291	419.33	1.00	888	194	175.61	116.36	329	110	36.19
0.41	1430	289	413.27	1.01	877	192	172.27	118.91	253	103	26.05
0.43	1411	286	403.54	1.03	871	191	168.38	120.91	266	84	22.34
0.45	1398	283	395.63	1.28	751	168	166.36	<i>Day 7</i>			
0.46	1378	280,385.84 (t _{0.5} 28 min)					126.16	141.38	25	03	0.07
				<i>Day 2</i>				141.58	22	03	0.06
				19.53	255	60	15.30	142.68	00	03	0.00
0.48	1359	277	375.88	20.65	254	60	15.24				
0.50	1344	275	369.60	21.21	253	60	15.18				
0.51	1325	271	359.07	21.40	253	60	15.18				
0.53	1306	268	350.00	21.46	252	60	15.12				

Table 12 (continued)

Time (h)	Current (μA)	Potential (mV)	Power (μW)	Time (h)	Current (μA)	Potential (mV)	Power (μW)	Time (h)	Current (μA)	Potential (mV)	Power (μW)
0.55	1284	265	340.26	22.00	250	59	14.75				
0.56	1260	261	328.86	22.26	250	59	14.75				

Table 13 Change of power with time in dark (Study of cell performance) for the NaOH-Allura Red-d-Galactose-DDAC-Platinum photo-galvanic cell (3rd experiment)

Time (h)	Current (µA)	Potential (mV)	Power (µW)	Time (h)	Current (µA)	Potential (mV)	Power (µW)	Time (h)	Current (µA)	Potential (mV)	Power (µW)
<i>Day 1</i>											
0.00	1816	189	343.22	25.25	214	22	4.70	<i>Day 7</i>			
0.01	1631	170	277.27	25.40	214	22	4.70	<i>Day 8</i>			
0.03	1515	158	239.37	25.43	214	22	4.70	<i>Day 9</i>			
0.05	1382	144	199.00	25.63	213	22	4.68	<i>Day 10</i>			
0.06	1225	128	156.80	25.83	213	22	4.68	<i>Day 11</i>			
		($t_{0.5}$ 4 min)		26.31	213	22	4.68	215.85	396	54	21.38
0.10	1082	112	121.18	26.73	214	22	4.70	215.98	369	50	18.45
0.11	980	102	99.96	<i>Day 3</i>				216.41	320	40	12.80
0.13	906	94	85.16	<i>Day 4</i>			6.47	216.83	301	37	11.13
0.15	864	90	77.76	46.58	250	26	6.50	217.16	292	36	10.51
0.16	815	85	69.27	48.10	260	27	7.02	217.53	281	34	9.55
0.18	785	82	64.37	48.35	261	27	7.04	218.10	255	31	7.90
0.20	753	78	58.73	49.36	262	27	7.07	218.81	229	28	6.41
0.21	725	76	55.10	49.45	261	27	7.04	219.45	219	27	5.91
0.23	700	73	51.10	49.51	259	28	7.25	219.85	218	26	5.66
0.25	660	69	45.54	49.63	262	27	7.07	<i>Day 12</i>			
0.26	647	67	43.34	49.68	262	27	7.07	241.08	36	04	0.14
0.28	628	65	40.82	49.91	262	27	7.07	241.90	33	04	0.13
0.30	615	64	39.29	50.20	262	27	7.07	242.41	34	04	0.13
0.31	609	63	38.36	50.58	261	27	7.04	242.76	32	05	0.16
0.41	531	55	29.20	<i>Day 5</i>				243.15	32	04	0.12
0.46	500	52	26.00	70.73	226	23	5.19	243.43	29	03	0.08
0.50	482	50	24.10	71.21	121	13	1.57	244.05	28	04	0.11
0.53	469	49	22.98	71.33	156	16	2.49	<i>Day 13</i>			
0.60	452	47	21.24	71.70	210	22	4.62	264.81	19	02	0.03
0.65	437	45	19.66	72.03	226	24	5.42	265.00	14	02	0.03
<i>Day 2</i>											
22.35	213	22	4.68	72.40	236	25	5.90				
22.50	213	224.68		72.96	240	25	6.00				
22.90	211	224.64		73.13	241	25	6.02				
23.35	212	22	4.66	73.60	244	26	6.34				
23.50	214	22	4.70	74.38	246	26	6.39				
23.95	214	22	4.70	74.63	247	26	6.42				
24.10	212	22	4.66	<i>Day 6</i>							
				94.26	256	27	6.91				
				94.86	263	27	7.10				

Table 13 (continued)

Time (h)	Current (μA)	Potential (mV)	Power (μW)	Time (h)	Current (μA)	Potential (mV)	Power (μW)
24.75	210	22	4.62	95.20	262	27	7.07
24.91	212	22	4.66	95.78	263	27	7.10

potential difference between two electrodes is not attributed to the electrode processes. The photo-galvanic cells are quite different than the emf cells in which the chemical energy is converted into the electricity through the spontaneous chemical reactions. In photo-galvanic cells, the solar energy is converted into the current through photo-induced migration of the electrons. Therefore, no chemical interaction is expected between electrode and electrolyte in the photo-galvanic systems. In these cells, the electrodes are estimated to be inert just to facilitate only electron exchange between the electrolyte and external circuit. In present research, the inert materials platinum and graphite have been used as working and counter electrodes, respectively. The platinum is a well-known inert electrode. The graphite material is also an inert electrode as is evident from the working of the Leclanché cell. The present research has used graphite extracted from the discarded Leclanché cell. The inertness of the graphite material may also be attributed to the peculiar electronic structure of the carbon. The electronic configuration of the carbon (atomic number 6) in graphite is the $1s^2, 2s^2, 2p_x^1, 2p_y^1, 2p_z^0$, and this is the naturally occurring electronic state, i.e., neutral carbon atom. It means, the carbon will tend to be in this natural neutral stable electronic state. The carbon is a very popular inert electrode, and this is enabled by its peculiar electronic configuration. On getting one electron from the external source, the carbon atom will have the half-filled orbital, i.e., $1s^2, 2s^2, 2p^3$. But this $2p^3$ state (one negative charged) is not the most stable naturally occurring state of the carbon. Therefore, the carbon sheds excess electron to the electrolyte (to dye). This way, the carbon acts as a good inert electron exchanger between external circuit and the electrolyte by taking electron from the circuit and giving this electron to the electrolyte. Thus, in view of all these scientific facts, the interaction between the graphite and the electrolyte is not expected to cause the electrolyte decomposition or intercalation.

Here, the estimated formation of the photo-excited Allura Red dye (AR)* molecule in the proposed mechanism is based on the two facts: 1st, the proposed mechanism is based on the already published works in which the dye sensitizer material has been reported as the light absorbing agent through photo-excitation to form the photo-excited dye molecule (Gangotri et al., 1996; Murthy et al., 1996; Potter Jr. & Thaller, 1959; Rabinowitch, 1940a); and the 2nd, the experimental data of the present work also supports the formation of the photo-excited Allura Red dye (AR)* molecule. In present research, the illuminating source emits wavelengths 300–3000 nm (Koli et al., 2012). The spectral study of aqueous electrolyte solution (consisting of the Allura Red D dye-Galactose-Didecyl Dimethyl Ammonium Chloride-NaOH

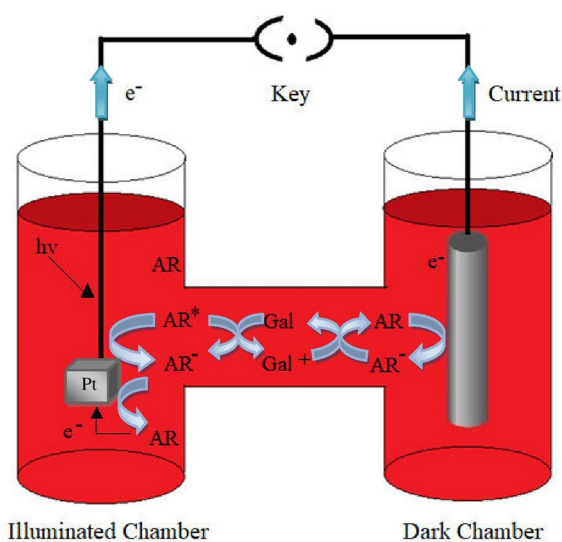


Fig. 7 Mechanism of the photo-generation of the current [Here, $h\nu$, photon; Gal, D-Galactose reductant molecule; Gal+, oxidized form of D-Galactose reductant molecule; e, electron; AR-, Allura Red dye photosensitizer molecule; AR*, Allura Red molecule in excited state; and Pt, platinum working electrode]

electrolyte) in present research has shown absorption maxima at wavelength ~ 500 nm. This absorption maxima at wavelength ~ 500 nm is due to the absorption of the light by the Allura Red D dye molecule to form its photo-excited species (AR*). In literature, the reported absorption maximum of the Allura Red-D dye is 504 nm (Aldrich, 2003). The other electrolyte constituents like Galactose, didecyl dimethyl ammonium chloride, NaOH, and water absorbs in UV region only, and on that basis, it can be verified that it is the only the Allura Red D dye present in the electrolyte which is absorbing wavelength ~ 500 nm in visible region. No absorption is observed for didecyl dimethyl ammonium chloride above 290 nm in neutral/acidic/basic medium (Directive 98/8/EC Assessment Report, 2015). The NaOH absorb wavelength ~ 200 nm in UV region (Tong et al., 2020). The D-Galactose absorbs wavelength ~ 255 nm in UV region (SpectraBase Wiley, 2024).

Power stability of the NaOH-Allura Red-D-Galactose-DDAC-platinum photogalvanic system (complete discharge of the cell)

The power stability of the NaOH-Allura Red-D-Galactose-DDAC-Platinum photo-galvanic system has been studied through three experiments. For all three experiments, the cell fabrication variables and principles of the study were the same.

For the study of the power stability of the NaOH-Allura Red-D-Galactose-DDAC-Platinum photo-galvanic cell,

first of all, the cell was fully charged and the power at point was determined with the help of the I–V characteristics. Thereafter, the resistance of the circuit was set to get again the potential and current corresponding to the power at point. In present case, the power at power point was determined as 570.90 μW in the 1st experiment (Tables 10, 11). Thereafter, the illumination was cut-off, and the cell was then put in the dark i.e., the illumination of the cell was cut-off, and the time of cutting the illumination was designated as zero time. The power at different time intervals was noted.

The observed power after 24.06 h was 25.67 μW in the 1st experiment. After 70.11 h, the observed power was 20.64 μW . After 190.53 h, the power was 0.02 μW . From these observations, it can be inferred that the cell has power storage capacity, and it can supply power in the dark conditions. Despite it, the observation also shows that there is power decay and power becomes almost zero in 190.53 h of cutting illumination (Tables 10, 11). Regarding power decay, one interesting fact has been noted that the power decay rate is higher at initial power value. After that the power decay rate decreases and power remain almost constant for a long-time duration and then it becomes almost zero in 190.53 h in the 1st experiment (Table 10; Fig. 8a–c).

In the 2nd experiment, the power reduces from 773.37 μW to 385.84 μW in 28 min, and therefore, the half-life ($t_{0.5}$) of cell is designated as 28 min in the 2nd experiment. The observed power after 24.91 h was 14.75 μW . After 70.21 h, the observed power was 18.41 μW . After 142.68 h, the power was 0.00 μW . From these observations in the 2nd experiment also, it can be inferred that the cell has power storage capacity, and it can supply power in the dark conditions. Despite it, the observation also shows that there is power decay and power becomes almost zero in 142.68 h of cutting illumination. Regarding power decay, one interesting fact has been noted that the power decay rate is higher at initial power value in 2nd experiment also. After that the power decay rate decreases and power remain almost constant for a long-time duration and then it becomes almost zero in 142.68 h in the 2nd experiment (Table 12).

In the 3rd experiment, the power reduces from 343.22 μW to 156.80 μW in 04 min, and therefore, the half-life ($t_{0.5}$) of cell is designated as 04 min in the 3rd experiment. The observed power after 24.10 h was 4.66 μW . After 70.73 h, the observed power was 5.19 μW . After 265.0 h, the power was 0.03 μW . From these observations in 3rd experiment also, it can be inferred that the cell has power storage capacity, and it can supply power in the dark conditions. Despite it, the observation also shows that there is power decay and power becomes

almost zero in 265 h of cutting illumination. Regarding power decay, one interesting fact has been noted that the power decay rate is higher at initial power value in 3rd experiment also. After that the power decay rate decreases and power remain almost constant for a long-time duration and then it becomes almost zero in 265.0 h in the 3rd experiment (Table 13).

Photo-absorption and photostability of NaOH-Allura Red-D-Galactose-DDAC-platinum photogalvanic system: a UV-Visible spectral study

In literature, the reported absorption maximum of the Allura Red-D dye is 504 nm (Aldrich, 2003). The electrolyte used in the present spectral study consists of the Allura Red-D photo-sensitizer, Galactose reductant, DDAC surfactant, NaOH alkali, and distilled water. The photo-absorption property of the Allura Red sensitizer in pure form and in the electrolyte has been studied in the present work, and is shown in Fig. 9a–c. The Allura Red dye sensitizer is the main component for the fabrication of the cell as it has the light absorbing property where its light absorbing property can be characterized by the position and the intensity of the UV-Visible spectral band. Therefore, the pre-illuminated and post-illuminated spectrum of the pure Allura Red dye sensitizer has been studied in the aqueous medium as well as in the electrolyte. The UV-Visible spectra have been taken with the help of Micro spectrophotometer (Model-MT 129; purchased from the Manti Lab Solution, Haryana, India; wavelength accuracy ± 2 nm, spectral scan range 320–900 nm). In the present study, the pre-illuminated and post-illuminated spectrum of the Allura Red dye sensitizer in the electrolyte has been studied to explain the photoelectrochemical phenomenon of the photo-galvanic cells. The spectra of aqueous solution of Allura Red dye solution have been determined by taking 0.5 ml of M/500 Allura Red in sample cuvette and distilled water in the reference cuvette cell. The spectra of dye electrolyte solution has been determined by taking sample solution (0.5 ml of M/500 Allura Red, 0.5 ml of M/100 D-Galactose, 0.5 ml of M/10 didecyldimethylammonium chloride, 16 ml of 1 N NaOH, and 17.5 ml of singly distilled water; total 35 ml solution) in sample cuvette cell and reference solution (0.5 ml of M/10, 0.5 ml of M/10 didecyldimethylammonium chloride, 16 ml of 1 N NaOH, and 18 ml of singly distilled water; total 35 ml solution) in reference cuvette cell.

The spectrum of pure dye (in water) shows absorption maximum at 504–506 nm (Table 14, Fig. 9a). The observed maxima 504–506 nm is quite in conformity with the reported absorption maxima at 504 nm of

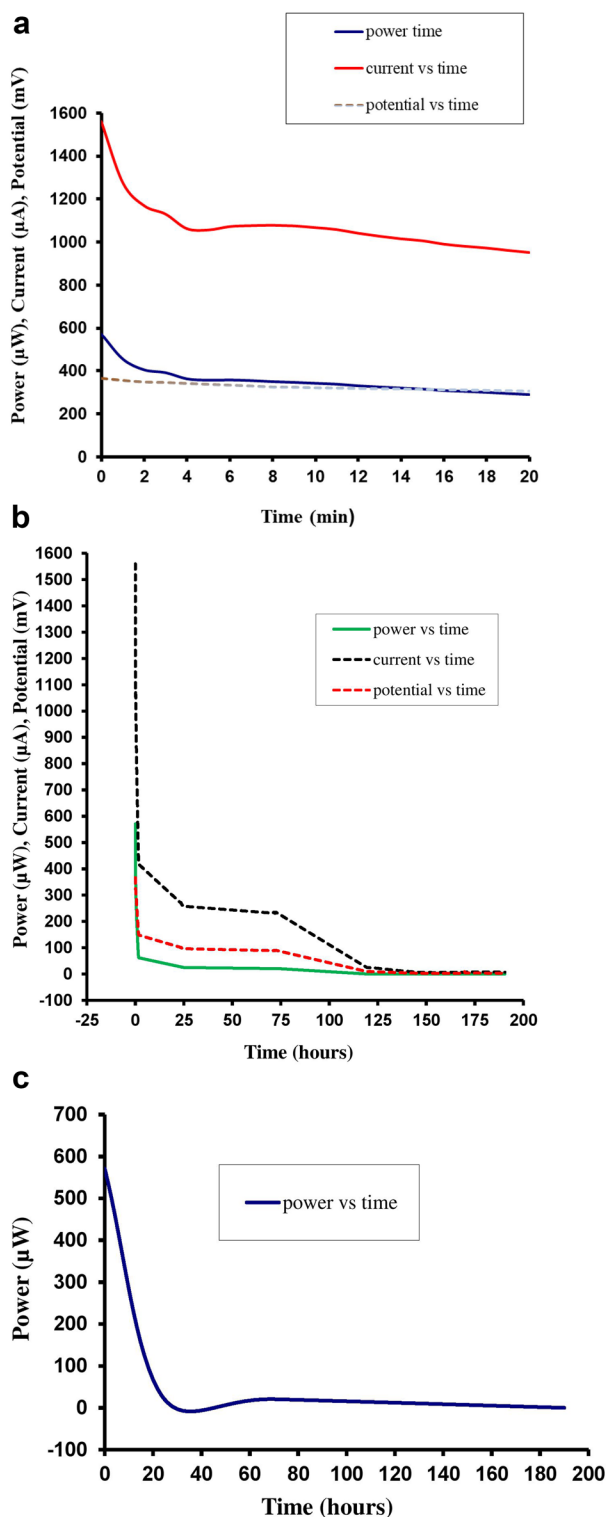


Fig. 8 **a** Change of power with time in dark (Study of cell performance in initial 20 min) for the NaOH-Allura Red-d-Galactose-DDAC-Platinum photogalvanic cell (1st experiment). **b** Change of power with time in dark (Study of cell performance till its complete discharge) for the NaOH-Allura Red-d-Galactose-DDAC-Platinum photo-galvanic cell (1st experiment). **c** Variation of power with time (stability of cell under dark) of NaOH-Allura Red-d-Galactose-DDAC-Platinum photogalvanic system (1st experiment)

the Allura Red dye (Aldrich, 2003). It shows that the purchased sample of the dye belongs to the Allura Red dye. Further, the absorbance spectra of the post-illuminated dye solution show maxima at 504–506 nm with same band intensity as it is for pre-illuminated spectra (Table 14, Fig. 9a). In totality, the spectral curves of the post-illuminated dye solution and pre-illuminated dye solution resemble with each other, and also overlaps with each other in almost whole scanned spectral range. It shows that the pure dye solution (aqueous medium) is quite photo-stable.

The pre-illuminated spectra of the electrolyte show absorption maxima at 496–500 nm (Table 15, Fig. 9b). The spectral pattern and absorption maxima (496–500 nm) of the pre-illuminated electrolyte solution resembles with spectra of pure dye. It shows that the light absorbing material present in the electrolyte is the Allura Red dye. It means the chemical Allura Red dye is working as photosensitizer and light harvesting material in the photo-galvanic cell studied in present research. But, the intensity of the dye band in the electrolyte is lower than that of pure dye (hypo-chromic shift of dye band due to electrolyte).

The post-illuminated spectra of the electrolyte show absorption maxima at 464 nm (band intensity same as in pre-illuminated state), i.e., bathochromic shift of dye band in electrolyte due to illumination). The nearly same band intensity of the pre-illuminated and post-illuminated electrolyte solution also shows quite good photo-stability of the dye in electrolyte form (Fig. 9c). But, one special point to be noted here is that the absorption of all rest wavelengths (other than 464 nm) by electrolyte is lowered in the post illuminated state in comparison to that in pre-illuminated state of the electrolyte (Fig. 9c). The photo-stability and power stability of cell can be explained on the basis of the spectral property and photo-stability of the Allura Red dye.

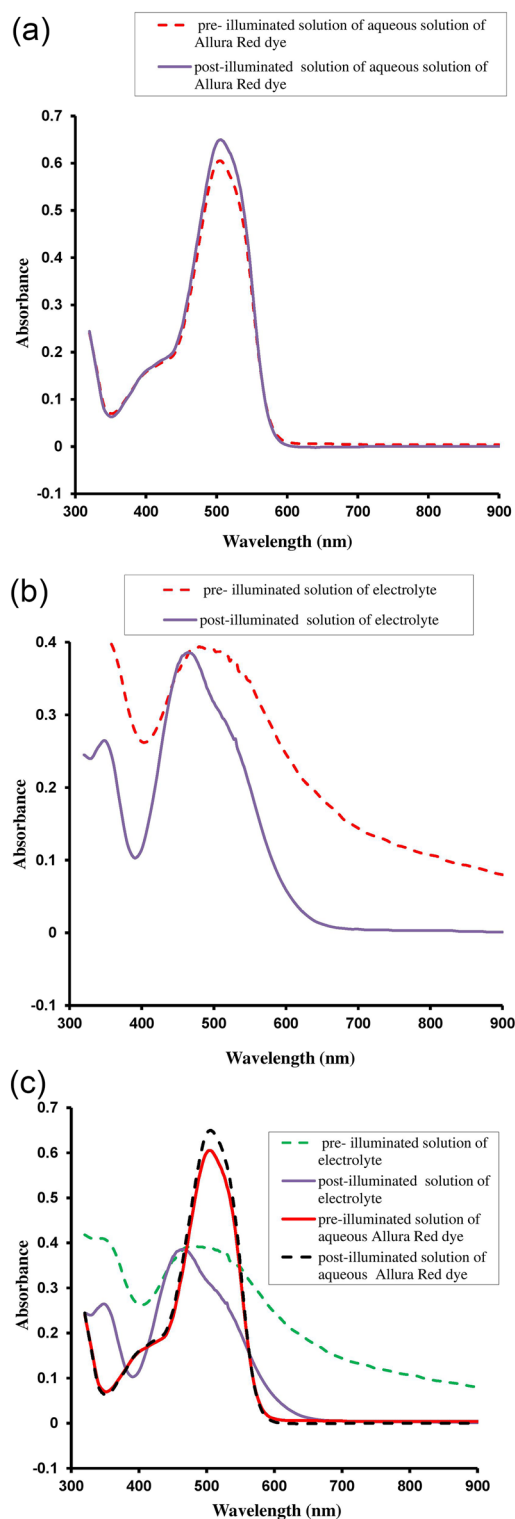


Fig. 9 **a** UV-Visible spectra of the aqueous solution of the pure Allura Red Dye [Sample cuvette having the dye concentration at 0.5 ml of M/500 dye 34.5 ml distilled water; reference cuvette having distilled water]. **b** UV-Visible spectra of the complete electrolyte [Sample cuvette having dye concentration at 0.5 ml of M/500, reductant concentration at 0.5 ml of M/100, surfactant concentration at 0.5 ml of M/10, NaOH concentration at 16 ml of 1 N and distilled water 17.5 ml distilled water; reference cuvette having reductant concentration at 0.5 ml of M/100, surfactant concentration at 0.5 ml of M/10 surfactant, NaOH concentration at 16 ml of 1 N and distilled water 18 ml distilled water]. **c** Comparison of UV-Visible spectra of Allura Red in aqueous solution and Allura Red dye in alkali electrolyte solution

Comparison of present photogalvanics of platinum electrodes with published work

In present study, the photogalvanics of the platinum electrode in the Allura Red photosensitizer-D-Galactose reductant-DDAC surfactant is summarized as- power, short circuit current, open circuit potential, conversion efficiency and storage capacity (as half time) are of the order of 443.8 μW , 2400 μA , 721 mV, 11.61%, and 28 min, respectively.

Some of the published photogalvanics of the platinum electrodes in various photo-galvanic chemical systems are as follows. For photogalvanics of Pt electrode in the Toluidine blue photo-sensitizer-Glucose-reductant-CTAB surfactant electrolyte; the reported maximum power, short-circuit current, open-circuit potential, and conversion efficiency are of the order of 6.26 μW , 35 μA , 175 mV, and 0.0578%, respectively (Gangotri et al., 1999). For photogalvanics of Pt electrode in the Brilliant Cresyl Blue photosensitizer-D Xylose reductant-SLS surfactant electrolyte; the reported maximum power, photocurrent, photo-potential, conversion efficiency and storage capacity of the cell is as 413.16 μW , 440.0 μA , 940.0 mV, 1.1057%, and 140 min, respectively (Gangotri & Bhimwal, 2010b). For photogalvanics of Pt electrode in the Sudan-I photosensitizer-Fructose reductant-SLS surfactant electrolyte; the reported power point, open circuit potential, equilibrium current, conversion efficiency and storage capacity (as half time) is as 367.8 μW , 1014 mV, 1350 μA , 11.49%, and 30 min, respectively (Koli, 2021). For photogalvanics of Pt electrode in the Sunset Yellow FCF photosensitizer-Ascorbic acid reductant-CTAB surfactant electrolyte; the reported power point, short-circuit current, open-circuit potential, conversion efficiency and storage capacity are as 552.0 μW , 5400 μA , 806 mV, 11.19%, and 7 min, respectively (Koli et al., 2023). For photogalvanics of the Pt electrode in the Bromo cresol

Table 14 UV–Visible spectra of the aqueous solution of the pure Allura Red Dye

Wavelength (nm)	Absorbance		Wavelength (nm)	Absorbance		Wavelength (nm)	Absorbance	
	Before illumination	After illumination		Before illumination	After illumination		Before illumination	After illumination
320	0.241	0.244	490	0.553	0.588	580	0.038	0.033
330	0.165	0.161	492	0.565	0.601	590	0.017	0.011
340	0.089	0.082	494	0.577	0.615	600	0.010	0.003
350	0.070	0.063	496	0.587	0.627	610	0.007	0.000
360	0.077	0.072	498	0.595	0.635	620	0.006	– 0.001
370	0.097	0.095	500	0.600	0.642	630	0.006	– 0.001
380	0.119	0.117	502	0.604	0.647	640	0.006	– 0.002
390	0.142	0.143	504	0.605	0.649	650	0.006	– 0.001
400	0.158	0.160	506	0.605	0.650	660	0.006	– 0.001
410	0.167	0.170	508	0.603	0.648	670	0.005	– 0.001
420	0.176	0.181	510	0.599	0.646	680	0.005	– 0.001
430	0.184	0.189	512	0.594	0.641	690	0.005	– 0.001
440	0.196	0.204	514	0.589	0.636	700	0.005	– 0.001
450	0.234	0.248	516	0.583	0.630	710	0.004	0.000
452	0.246	0.259	518	0.576	0.624	720	0.004	0.000
454	0.259	0.274	520	0.570	0.619	730	0.004	0.000
456	0.274	0.290	522	0.564	0.611	740	0.004	0.000
458	0.287	0.305	524	0.555	0.603	750	0.004	0.000
460	0.305	0.321	526	0.548	0.594	760	0.004	0.000
462	0.318	0.334	528	0.538	0.582	770	0.004	0.000
464	0.332	0.354	530	0.526	0.572	780	0.004	0.000
466	0.349	0.372	532	0.516	0.557	790	0.004	0.000
468	0.368	0.390	534	0.503	0.544	800	0.004	0.000
470	0.384	0.410	536	0.486	0.525	810	0.004	0.000
472	0.399	0.429	538	0.471	0.505	820	0.004	0.000
474	0.420	0.445	540	0.452	0.485	830	0.004	0.000
476	0.438	0.465	542	0.432	0.460	840	0.004	0.000
478	0.454	0.483	544	0.407	0.436	850	0.004	0.000
480	0.472	0.503	546	0.381	0.410	860	0.004	0.000
482	0.490	0.518	548	0.356	0.380	870	0.004	0.000
484	0.507	0.538	550	0.325	0.346	880	0.004	0.000
486	0.523	0.556	560	0.188	0.193	890	0.004	0.000
488	0.540	0.571	570	0.088	0.086	900	0.004	0.000

green photosensitizer-Formaldehyde reductant-SLS surfactant electrolyte; the reported power point, short-circuit current, open-circuit potential, conversion efficiency and storage capacity are as 1170 μ W, 8000 μ A, and 1130 mV, 9.02%, and 70 min, respectively (Koli et al., 2022a). The comparison of the already published work with the present work has been listed in the (Table 16).

A comparison of the already published results with the results of the present work (Pt-Allura Red-D-Galactose-DDAC system) show both higher and lower results than reported data. The results of the present study are higher than results of the some reported studies. This

can be explained on the basis of different factors like dye and reductant concentrations, dye stability, pH, light intensity; electrodes used, Pt electrode area, and diffusion length, etc., as all these factors have great impact on the cell performance (Koli, 2021). The higher results of the present Pt-Allura Red-D-Galactose-DDAC photogalvanic system than the results of the already published Pt-Brilliant Cresyl Blue-D Xylose-NaLS, Pt-Toluidine blue-Glucose-CTAB, and Pt-Sudan-I-fructose-SLS photogalvanic systems may be attributed to the use of small sized Pt electrode, cationic surfactant, anionic dye sensitizer and graphite counter electrode in present work (Koli

Table 15 UV–Visible spectra of the aqueous solution of electrolyte having Allura Red dye, D-Galactose, DDAC and NaOH

Wavelength (nm)	Absorbance		Wavelength (nm)	Absorbance		Wavelength (nm)	Absorbance	
	Before illumination	After illumination		Before illumination	After illumination		Before illumination	After illumination
320	0.418	0.245	490	0.391	0.338	580	0.284	0.102
330	0.410	0.240	492	0.391	0.334	590	0.263	0.078
340	0.410	0.256	494	0.391	0.329	600	0.246	0.059
350	0.408	0.264	496	0.390	0.325	610	0.231	0.044
360	0.393	0.237	498	0.390	0.320	620	0.215	0.032
370	0.359	0.177	500	0.390	0.317	630	0.204	0.023
380	0.313	0.123	502	0.387	0.313	640	0.195	0.016
390	0.279	0.103	504	0.387	0.310	650	0.184	0.012
400	0.263	0.115	506	0.387	0.307	660	0.175	0.009
410	0.265	0.155	508	0.387	0.304	670	0.167	0.007
420	0.280	0.209	510	0.387	0.300	680	0.156	0.006
430	0.304	0.274	512	0.385	0.296	690	0.150	0.005
440	0.334	0.329	514	0.384	0.294	700	0.144	0.005
450	0.361	0.369	516	0.384	0.291	710	0.138	0.004
452	0.362	0.372	518	0.382	0.287	720	0.134	0.004
454	0.366	0.377	520	0.380	0.283	730	0.131	0.004
456	0.370	0.381	522	0.374	0.278	740	0.127	0.004
458	0.373	0.382	524	0.376	0.274	750	0.121	0.003
460	0.377	0.384	526	0.376	0.270	760	0.119	0.003
462	0.379	0.385	528	0.375	0.266	770	0.116	0.003
464	0.383	0.386	530	0.375	0.267	780	0.112	0.003
466	0.387	0.385	532	0.370	0.256	790	0.109	0.003
468	0.389	0.385	534	0.361	0.250	800	0.107	0.003
470	0.390	0.384	536	0.359	0.245	810	0.105	0.003
472	0.391	0.382	538	0.360	0.239	820	0.100	0.003
474	0.391	0.379	540	0.356	0.233	830	0.097	0.003
476	0.392	0.375	542	0.354	0.228	840	0.094	0.002
478	0.393	0.371	544	0.353	0.221	850	0.093	0.002
480	0.394	0.366	546	0.349	0.214	860	0.090	0.002
482	0.393	0.362	548	0.347	0.207	870	0.088	0.002
484	0.393	0.356	550	0.346	0.201	880	0.085	0.001
486	0.392	0.350	560	0.323	0.165	890	0.082	0.001
488	0.391	0.345	570	0.303	0.131	900	0.080	0.001

et al., 2022a). The saturated calomel electrode SCE was exploited in published works. The photo-galvanic cells are based on the ion's diffusion throughout the bulk of the electrolytic solution (Bisquert et al., 2004). Therefore, one of the primary factors influencing the electrode's efficiency is the diffusion of ions. Thus, in order to generate optimum diffusion, using small sized Platinum electrode which less hinders the ions mobility has successfully enhanced the photo-galvanic performance of the present work. Further, the increased stability and solubility of dye molecules might also have promoted the enhanced electrical performance of photo-galvanic cell in the present

study. The molecular interaction between the dye and the surfactant molecules is important for the solubility and stability of dye molecules. For the molecules of surfactant and dye that have opposite charges, the dipole–dipole interaction is strong (Mall et al., 2018).

In the present study, the cationic surfactant DDAC molecule exhibits strong dipole–dipole interaction with the anionic dye Allura Red, resulting in increased electrical output of the cell in present study. Whereas, the decreased electrical output of three reported photo-galvanic systems is due to the similar charges on the dye and surfactant molecules. Also, the use of graphite in place

Table 16 Comparison of present photogalvanics of platinum working electrode with already published work

Literature	Electrodes ^a	Photo-sensitizer ^a	Reductant	Surfactant ^a	Power (μ W)	Short circuit current (μ A)	Open circuit potential (mV)	Conversion efficiency (%)	Storage capacity (min)
Gangotri et al. (1999)	Pt-SCE	Toluidine Blue	Glucose	CTAB	6.26	35	175	0.0578	–
Gangotri and Bhimwal ()	Pt-SCE	Brilliant Cresyl Blue	D-Xylose	SLS	413.16	440.0	940.0	1.1057	140
Koli (2021)	Pt-SCE	Sudan-I	Fructose	SLS	367.8	1350	1014	11.49	30
Koli et al. (2023)	Pt-Graph	Sunset Yellow FCF	Ascorbic acid	CTAB	552.0	5400	806	11.19	07
Koli et al., (2022a, 2022b)	Pt-Graph	Bromo cresol green	Formaldehyde	SLS	1170	8000	1130	9.02	70
Present research	Pt-Graph	Allura Red	D-Galactose	DDAC	443.8 μ W	2400 μ A	721 mV	11.61%	28

^a Saturated calomel electrode, Graphite (Graph), Cetyl trimethyl ammonium bromide (CTAB), Sodium lauryl sulphate (SLS), Didecyl Dimethyl Ammonium Chloride (DDAC)

of SCE electrode in the present work has shown better outcomes (due to the inert properties of both the graphite and Platinum electrodes) when utilized as the counter and working electrodes, respectively.

The lower results of the (Pt-Allura Red-D-Galactose-DDAC) system from (Pt-Sunset Yellow FCF-Ascorbic acid-CTAB) and (Pt-Bromo cresol green-Formaldehyde-SLS) system may be due to the use of H-shaped tube cells in the present work whereas simple glass tube is used over H-shaped tube in other two systems with highest results. This could be explained by the diffusion length of the H-cell tube and the glass tube cell. The diffusion length of the simple glass tube length is small than that of H-cell tube which increases the possibilities of the excited dye sensitizer species reaching the Platinum electrode during their lifetime, which leads to better electrical performance of these systems in cylindrical cell design (Koli et al., 2022a).

Conclusion

The photogalvanics of platinum working electrode with the novel electrolyte (Allura Red photosensitizer-D-Galactose reductant-DDAC surfactant) has been explored for solar power generation and storage through the photogalvanic cells. The observed power, current, potential, efficiency and storage capacity (as half time) are of the order of 443.8 μ W, 2400 μ A, 721 mV, 11.61%, and 28 min, respectively. These observed results are higher than some reported data. The higher results of the present Pt photogalvanics may be attributed to the use of small sized Pt electrode, cationic surfactant, anionic dye sensitizer, and graphite counter electrode (instead of saturated calomel electrode) in the present work. The lower results of the photogalvanics of Pt in the present system from reported

Pt photogalvanics may be due to the use of H-shaped cell design in the present work whereas the cylindrical cell design was used in reported studies. The lengthy diffusion length of H-shaped cell design disfavors the photogalvanics whereas the shorted diffusion length of cylindrical cell design favors the photogalvanics. In the spectral study, nearly same band intensity of the pre-illuminated and post-illuminated electrolyte solution shows quite good photo-stability of the Allura Red dye in electrolyte form. This new combination of Platinum-electrolyte still has the scope to achieve the enhanced cell performance of photogalvanic cell for future development.

Supplementary Information

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Supplementary Material 1.

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Author contributions

Authors, PK and JS, have contributed in every aspect of this research work including the conception, design of the work, the acquisition, experimentation, analysis, interpretation of data, original writing of manuscript, review of manuscript, editing and finalization of manuscript, etc. Additionally, author PK has also contributed as corresponding author, mentor and supervisor of the research work. All authors have approved the submitted version (including the final version).

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Data availability

All data have been incorporated in the manuscript file.

Declarations**Ethics approval and consent to participate**

Not applicable.

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