

Study to Enhancing the Performance of Photogalvanic Cells for Solar Energy Conversion and Storage by Using Micelles

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Abstract - Photogalvanic cell containing rose bengal as photosensitizer, D-Xylose as electron donor and dioctyl sodium sulphosuccinate (DSS) as micelles species, was used for conversion of solar energy into electric power through a H shape type solar cell of 25.0 ml volume only. The optimum performance in terms of photo potential, photocurrent, storage capacity and conversion efficiency were observed as 715.0 mV, 395.0 μ A, 55.0.0 min., and 0.95%, respectively in absence of micelles (DSS), whereas 910.0 mV, 590.0 μ A, 142.0 min., and 1.54%, respectively in presence of micelles. The micelles species dioctyl sodium sulfosuccinate (DSS) promote the separation of photoproducts via hydrophilic-hydrophobic interactions between the products, thus improving the efficiency and storage capacity of the photogalvanic cell. However, considerable challenges must be addressed before photogalvanic cells can be employed for both solar power generation and storage. Some challenges include dye photo degradation, platinum (Pt) corrosion, liquid evaporation, breaking the weakness of the SCE/combination electrode, and the necessity to enhance the conversion efficiency and storage capacity.

Index Terms - Solar Energy; Conversion efficiency; Storage Capacity; Photogalvanic cell.

Highlights:

- Rose Bengal as dye, D-Xylose as reductant and DSS as micelles has been used.
- We have compared the electrical output of the cell with and without micelles.
- Micelles not only increase electric power and potential but also increase storage capacity.
- Conversion efficiency 1.54% and storage capacity 142.0 min have been observed.

INTRODUCTION

Photochemistry offers an obvious potential route to the practical use of solar energy. The photosynthesis reaction, driven by sunlight, consumes water and CO₂ to produce oxygen and plant matter. The stored solar energy in this "biomass" represents 0.10% of the total annual solar energy reaching the Earth. This is over 10 times the total amount of energy consumed by human activities in twelve months. The possibility of utilizing the sunlight [1] that reaches the earth's surface each day as a source of energy was a major challenge to modern science and technology in 1995. The move to explore photochemical methods for the conversion and storage of solar energy was part of the general search for alternative energy sources following the oil crisis of 40 years ago. With photosynthesis as a practical example of the success of this approach, many scientists have started to search for both practical and fundamental work of practical schemes toward the goal of solar energy conversion and storage. Since the primary photochemical reaction of photosynthesis involves photo-induced electron transfer (PET) reactions, there has naturally been a great deal of interest in building electron transfer models and in the theoretical understanding of the factors that influence photo-induced electron transfer. Primitive photo electrochemical (PEC) cells and PEC cells with Fe-thionine were studied by Jana [2]. Jana observed maximum wavelength (λ_{max}) of different dyes like as Thionine (596 nm), Toluidine blue (630 nm) Methylene blue (MB) (665 nm), Azure A (635 nm), Azure B (647 nm), Azure C (620nm), Phenosafranin (PSF) (520 nm), Safranin-O (Saf-O) (520 nm), Safranin-T (Saf-T) (520 nm), Neutral red (NR) (534 nm, Fluorescein (490 nm), Erythrosin (530 nm), Erythrosin B (525 nm), Rhodamine B (Rh. B)

(551 nm), Rose bengal (550 nm), Pyronine Y (PY) (545nm), Eosin (514 nm), Rhodamine 6G (524 nm), Acridine orange (AO) (492 nm), Proflavin (PF) (444 nm), Acridine yellow (AY) (442 nm), Fuchsin Triphenyl methane (545 nm), Crystal violet Triphenyl methane (578 nm), Malachite green (423, 625nm), Methyl violet (580 nm) with reducing agent. The use of inorganic semiconductor electrode (e.g. SnO₂, In₂O₃ and ZnO) and utilization of semiconducting properties of organic dyes in PEC cell have been mentioned. Optimum donor density of semiconductor ZnO was few times larger than of SnO₂ for enhancement of the quantum yield of the dye-sensitized photocurrent. The stability of a PEC cell depends on the photoanodic corrosion of an n-type semiconductor. The corrosion can be suppressed if the electron supply from a reductant to the electrode is faster. Furthermore, utilization of surfactant media for storage of solar energy and production of hydrogen from solar cell using dye are also studied. Gangotri and Lal [3] were observed the photogalvanic effect in a photogalvanic cell containing Ethylenediaminetetra-acetic acid as reductant and methylene blue and thionine as photosensitizers. The photopotential, photocurrent and conversion efficiency generated were 752.0 mV and 90.0 μ A, and 0.43%, respectively. The maximum output of cell was 67.68 μ W. The photogalvanic cell can be used for 30 min in the dark. The effects of different parameters on electrical output of the cell were observed. Meena et al. [4] were developed a photogalvanic system consisting thymole blue as photosensitizer and ascorbic acid as reducing agent. Observed photopotential and photocurrent generated by the system were 810.00 mV and 150.0 μ A, respectively. The observed conversion efficiency, maximum power of cell and storage capacity were 0.8038%, 82.06 μ W and 54.0 minute in dark. The effect of variation of diffusion length (distance between the two electrodes) on the current parameters of the cell was studied using H- cells of different dimensions. It was observed that there was a sharp increase in photocurrent (i_{max}) in the first few minutes of illumination and then there was a gradual decrease to a stable value of photocurrent. This kind of behavior of photocurrent indicates that there is an initial rapid reaction followed by slow rate determining step at a later stage. Gangotri and Gangotri [5] studied the micellar effect on photogalvanic cells for solar energy conversion and

storage in cell containing Tween-80 as neutral micellar species, EDTA as reductant and Safranin O as photosensitizer. The generated photopotential, and photocurrent were 785.0 mV and 300.0 μ A, respectively. The observed conversion efficiency, fill factor and maximum power of the cell were 0.9769%, 0.34 and 235.50 μ W, whereas the power at the power point of the photogalvanic cell was 101.60 μ W. The rate of initial generation of current was 80.0 μ A min⁻¹. The photogalvanic cell can be used for 60.0 minutes in the dark. Yadav and Lal [6] studied a mixed dyes system containing methylene blue and fast green as a photosensitizer in photogalvanic cell for improved the efficiency of the photogalvanics. They used Ethylene diaminetetra acetic acid as an electron donor and photopotential and photocurrent were observed as 738.0 mV and 120.0 μ A, respectively. The observed conversion efficiency for the system was 0.564 % if it irradiated for 90.0 min only. Genwa and Sagar [7] used a photogalvanic system containing ascorbic acid as a reductant with Amido black 10B as photosensitizer and Tween 60 as surfactant in aqueous solution for solar energy conversion and storage. The generated photopotential, photocurrent, and power for the system were 996.0 mV, 420 μ A , and 84.68 μ W, respectively. The conversion efficiency and fill factor were 1.62 and 0.38% respectively. The cell performance was 130 min. in dark. Photogalvanic cell containing Amido Black 10B – Tween 60 – Ascorbic acid system was found to be quite sensitive for pH of the used solutions also. The photopotential and photocurrent were increased with increases the pH value of the cell. At pH 11.17, a maxima was obtained. On further increase in pH, photopotential and photocurrent were decreased gradually. The optimum electrical output was obtained at particular pH 11.17 due to better availability of reductant's donor form. Neniwal and Gangotri [8] used an efficient photogalvanic cell containing Ascorbic acid as an electron donar, Bismark brown as photosensitizer for solar energy and storage. The photopotential, photocurrent and power generated by the photogalvanic cell were 810.0 mV, 175.0 μ A and 70.0 μ W respectively. The determined conversion efficiency of cell was 0.6646%. The current voltage characteristics of the cell have also been studied. It was observed that i-V curve deviated from their regular rectangular shapes. A point in i-V curve, called power point was determined where the product of current and

potential was maximum and the fill factor was calculated as 0.3743. The performance of the photogalvanic cell (determined as 35 min. in terms of $t_{1/2}$) was observed by applying an external load (necessary to have current at power point) after termination the illumination as soon as the potential reaches a constant value. Bhimwal and Gangotri [9] were observed the comparative performance of photogalvanic cells for solar energy conversion and storage by using Methyl Orange, Rose Bengal, Toluidine Blue and Brilliant Cresyl Blue as different photosensitizers with d-Xylose as reductant and Sodium Lauryl Sulphate (NaLS) as surfactant in the different systems. The generated photopotential for Methyl Orange, Rose Bengal, Toluidine Blue and Brilliant Cresyl Blue systems were observed for comparative study as 890.0, 885.0, 945.0, 940.0 mV and photocurrent 625.0, 575.0, 510.0 and 480.0 μA , respectively. The shortcircuit current or photocurrents at equilibrium for above systems were 480.0, 460.0, 430.0 and 440.0 μA , respectively. The observed conversion efficiencies and fill factors for Methyl Orange, Rose Bengal, Toluidine Blue and Brilliant Cresyl Blue with d-Xylose and Sodium Lauryl Sulphate systems were 1.6245%, 1.5261%, 1.4323%, 1.1057%, and 0.3244, 0.3151, 0.3120, and 0.2408, respectively. Koli et al.[10] were studied the Rhodamine B dye as photo sensitizer, Fructose as reductant and NaOH as alkaline medium to enhance electrical performance of the cell. They quote that the observed cell performance was radically high than previous work which was found fortuitously. The observed cell performance in terms of maximum potential, maximum photocurrent, short-circuit current, power at power point, conversion efficiency and storage capacity in terms of half change time were 1071 mV, 1049 μA , 972 μA , 244.02 μW , 7.58% and 3.6 h, respectively. It is concluded that Rhodamine B - Fructose based cells have radically enhanced performance. Genwa and Singh [11] studied optimum efficiency of photogalvanic cell for solar energy conversion containing Lissamine Green B-Ascorbic Acid-NaLS System and the generated photo potential and photocurrent were 850.0 mV and 375.0 μA respectively. The observed conversion efficiency, fill factor and discharging time were 1.0257%, 0.2598% and 170.0 minutes in dark, respectively. The effects of different parameters on the electrical output of the photogalvanic cell were observed. Nadeem and

Gunsaria [12] were studied role of reductant and dye sensitizer for solar energy conversion and storage in photogalvanic cell containing Indigo carmine as dye and ascorbic acid as electron donor for the enhancement of the electrical output and overall performance of the photogalvanic cell with reduce the cost of construction for commercial viability. The observed photo potential and photocurrent were 580.0 mV and 160.0 μA respectively. The conversion efficiency and fill factor of the system were observed as 0.45%, and 0.27, respectively. The cell performance of Indigo Carmine - Ascorbic Acid system was determined in term of $t_{1/2}$ as 40.0 min. Whereas Meena et al. [13] studied the role of heterocyclic dye (Methylene blue) with reductant and micelles in photogalvanic cell containing Methylene blue-EDTA-TX-100 system for solar energy conversion and storage. The photopotential and photocurrent of the cell were observed as 845.0 mV and 420.0 μA respectively. The conversion efficiency and fill factor of the cell are determined 1.08 % and 0.2488 respectively. The storage capacity (performance) was determined in terms of $t_{1/2}$ as 160.0 minutes, on irradiation for 130.0 minutes only. The observed storage capacity of the cell was 123.07%. Mahmoud et al. [14] used Rose Bengal as photosensitizer with Oxalic acid as reductant and Tween 80 as surfactant for the enhancement of the conversion efficiency and storage capacity of photogalvanic cell for its commercial viability. The observed photogeneration of photopotential and photocurrent were 666.0 mV and 119.5 μA , respectively whereas, maximum power at power point (22.308 μW) was 79.58 μW . Experimentally determined conversion efficiency and fill factor of the system at the power point were 0.258% and 0.328, respectively. The photogalvanic cell so developed can work for 230 min in dark on irradiation for 72 min. The photogalvanic cell was subjected to the solar energy in Egypt on summer. A higher photovoltage of 815 mV was obtained. The cell can keep the energy for a longer time. On the recycling using solar energy for seven days using the same cell solution, the same photovoltage and photocurrent were obtained which show longer use of the cell. Koli [15] observed that photogalvanic cells are photoelectrochemical devices involving ions as mobile charges moving in solution through diffusion process. These photoelectrochemical are capable of solar power generation at low cost with inherent

storage capacity. This property of photogalvanic cell needs to be exploited as this technology is cleaner and promising for application in daily life. Therefore, a photogalvanic cell containing Fast Green as photosensitizer, Fructose as reductant in alkaline medium has been studied with observed value of maximum photocurrent $431\mu\text{A}$, maximum potential 1083mV , power at power point $138.60\mu\text{W}$, conversion efficiency 1.33% , and storage capacity (as half change time) 70min . The observed results are higher and encouraging enough for ultimate aim of development of applicable and affordable photogalvanic cells in future. Mahmoud and Mohamed [16] were studied solar energy conversion and storage through photogalvanic effect using photogalvanic cell containing Rose Bengal – Oxalic acid – CTAB System. The oxalic acid used as reductant, Rose Bengal as photosensitizer and Cetyl hexadecyl ammonium bromide as charge transfer carrier in aqueous solution. The photopotential, photocurrent and power generated were 550.0 mV , $75.0\ \mu\text{A}$, and $41.3\mu\text{W}$, respectively. The conversion efficiency and fill factor was determined as 0.067% and 0.169 respectively. The cell storage capacity was 175.0 min . in dark. A detailed review about solar energy conversion and storage was discussed by Ameta and Ameta [17]. They acknowledge that the solar age began in the 1950s in Bell Laboratories with the development of silicon technology. They described the first high-power silicon photovoltaic cell with 6% efficiency. This cell was much more efficient than the previous selenium solar cell. Due to the energy crisis in 1970, many technologies introduced for producing energy from renewable energy sources and photovoltaic devices. A photovoltaic device or solar cell is a solid-state electrical device that directly converts solar light energy into electricity but has nil storage capacity. The light energy is transmitted in the form of small packets of photons or quanta of light, and electrical energy generated is stored in batteries. Materials are normally classified into three categories, depending on energy of conduction band (CB) and valence band (VB). The conduction band is the lowest unoccupied molecular orbital (LUMO), while the valence band is the highest occupied molecular orbital (HOMO). The conducting materials have a bandgap less than 1.0 eV or, sometimes, there may even be almost an overlap between these two bands, so that there is smooth conduction of electricity. The

insulators (nonconducting material) have a wide bandgap that is more than 5.0 eV ; therefore, they do not conduct electricity. There are some materials that have a band gap of the medium order that is $1.5 - 3.0\text{ eV}$. These are basically non conducting in nature, but in the presence of some energy source, they become conducting. Therefore, such materials are called semiconductors.

Energy conversion and storage are considered two of the most important technologies in today's green and sustainable energy science. Mahmoud et al. [18] used ionic liquid as electrolyte in photogalvanic cell for solar energy conversion and storage. They used 1-Butyl-3-methylpyridinium

bis(trifluoromethylsulfonyl)imide ($[\text{C}_4\text{3mpy}][\text{NTf}_2]$) ionic liquid as electrolyte in photogalvanic cell. Rose Bengal, oxalic acid and ($[\text{C}_4\text{3mpy}][\text{NTf}_2]$) were used as a novel system for photo-electrochemical conversion of solar energy to electrical energy. The generated photopotential, photocurrent, and power were 670.0 mV , $61.2\mu\text{A}$, and $8.06\ \mu\text{W}$ respectively. Whereas the observed conversion efficiency was 0.077% and fill factor was 0.196 . The storage capacity of the cell was 109.0 min . Low values of the electrical output could be attributed to the fast mobility of the cation and aggregation motives. There are also several reasons related to the structure of the ionic liquid. Self-powered electrochemical energy storage systems (SEES) that harvest their operating energy from the environment hold great promise to power future portable and wearable electronics. SEESs are defined by the connection module between the energy storage system and the energy conversion system. Next-generation portable and wearable smart electronics hold great promise for wire-structured SEES. Advances in SEES powered by various energy conversion technologies with an emphasis on solar cells are reviewed by Huige et al.[19]. SEESs are defined by the connection module between the energy storage system and the energy conversion system. SEESs generally fall into three categories: (1) module I, (2) module II or (3) module III. The first two modules are independent, i.e. the scavenged energy is converted into electricity and then transferred to a SC or LIB for storage. The third module combines the two processes into one step in which the energy is directly converted and simultaneously stored as electrochemical energy without any intermediate processes. Saini et al. [20] studied the system

containing orange G with sodium lauryl sulphate as surfactant and EDTA as an electron donor species in a photogalvanic cell. The current-voltage relations of the cell were measured in the dark and light in both forward and reverse directions. The generated photo potential, photocurrent, and maximum power of the cell were observed to be 960.0 mV, 350.0 μ A, and 158.9 μ W, respectively. The observed conversion efficiency and fill factor of the system were 1.52% and 0.47 μ A, respectively. The storage capacity of the cell was 80.0 minutes in the dark for orange G-sodium lauryl sulphate and EDTA systems. Singh et al. [21] analyzed that the photogalvanic cells have inbuilt storage capacity and stored energy can be used in the absence of light, whereas photovoltaic cells need extra hardware such as batteries for energy storage. Photogalvanic cells are more economical than photovoltaic cells because low-cost materials are used in these cells. The conversion efficiency, storage capacity and fill factor are recorded as 1.02980%, $t_{1/2}$ 170.0 min and 0.2598 respectively in the Nephthol Blue Black-Ascorbic acid-NaLS system. Whereas Pooran [22] observed the power, short-circuit current, open-circuit potential, conversion efficiency, and storage power (in terms of half change time) for photogalvanic cells are reported to be of the order of 1159 μ W, 4500 μ A, 1.07 V, 14, and 260 min, respectively. However, to make photogalvanic cells a reality in life for simultaneous solar power and storage, some challenges have to be tackled. Some of the challenges are photodecay of dye, corrosion of platinum (Pt), evaporation of liquid, breaking vulnerability of SCE/combination electrode, further need to increase the power and efficiency and storage, assembly operation of cells for augmentation of power, cell study in natural sunlight, and so on. Cationic oxazine dye (brilliant cresyl blue, BCB) with anionic (sodium lauryl sulphate, SLS), cationic (hexadecyltrimethylammonium bromide, CTAB) and nonionic (tween 80) surfactants were studied [23] by spectrophotometric and conductometric methods. An absorbance maximum (λ_{max}) for only BCB solution was observed at 624.5 nm at room temperature. The λ_{max} value of BCB was shifted towards a higher wavelength (644.5 nm) with SLS and towards a lower wavelength (517.5 nm) with tween 80. But there was no any type of shifting observed with CTAB. Shifting in BCB is due to the complex formation of BCB with SLS and tween 80. A decrease in specific conductance

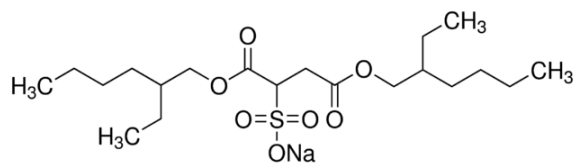
was caused by the slow moving or non-moving larger dye-surfactant complex. Christian et al. [24] demonstrated the potential of centrifugal particle receivers to provide hot particle streams of temperatures above 950°C as heat transfer fluids and solar energy storage materials. Proppant NO₂ at 850°C and under a low sulphuric acid flow rate, demonstrated conversions exceeding 70%. The accuracy of the applied iodometry method is estimated based on a detailed analysis assuming a Gaussian distribution of the different influencing factors (e.g. pipette, balance, graduated flask, pump, etc.). But due to the changing concentration of the titration solution during the measurement, the accuracy is not constant. A device that comprises inorganic kesterite solar cells and Li-ion batteries has been proposed by Jihun et al. [25] for application in fast photo-charging power systems. Photo-charging was conducted at a rate of 1.790 mAh g⁻¹ at 2.1 V, and energy conversion and storage efficiency of 3.87% was acquired in the integrated device. A storage efficiency of over 70% was observed in LIBs. By synchronizing the charging voltage of the solar cell and LIB, more than 70% of the capacity was obtained at the speed of 1C while preventing overvoltage during long-term charging. Koli et al. [26] used congo red as dye and formaldehyde as photo sensitizer and reductant couple for enhanced simultaneous solar energy conversion and storage by photogalvanic cells at low and artificial sun intensity. The electrical cell performance of the PG cell as power at power point was 782 μ W, i_{sc} 3200 μ A, V_{oc} 1074 mV, and CE 11.02% at artificial and low illumination intensity. The storage capacity ($t_{0.5}$) of the photogalvanic cell was observed for 120 min in the dark. Mahesh [27] also discussed the use of solar cells for solar energy conversion in electricity generation in India. The issue of the securities of energy in India is the same as that of oil securities for the country. In India, when the geopolitical implications of the increased requirement for hydrocarbons and the dependency of the country on its oil resources are important, the matter of the security of energy should be kept at the top of the priority list for energy supplies, commercial and non-commercial, and it should not be stopped by just thinking about the availability of the hydrocarbons only. Our energy demand is increasing by 5.4 billion kW per year, and non-commercial energy sources such as biomass, fuel, wood, and animal waste account for nearly a quarter

of our total primary energy demand. Recently, Bendary et al.[28] investigated the conversion of solar energy to electricity in a photogalvanic cell using a Tris (2,2'-bipyryl) ruthenium (II) chloride hexahydrate-diethyl ammonium tetrachloroferrate-oxalic acid system. Gautam [29] acknowledges that the impact of photogalvanic cells containing the best combination of dyes, reductants, and surfactants was studied. The photosensitizers employed in his research were Methyl Orange-Glucose-Cetyl Trimethyl Ammonium Bromide, Thymole Blue-Glucose-Cetyl Trimethyl Ammonium Bromide, Victoria Blue-Glucose-Cetyl Trimethyl Ammonium Bromide, and Methyl Orange-EDTA-Cetyl Trimethyl Ammonium Bromide. Cell conversion efficiency has been reported as 0.55 to 1.01%, which can be used in the dark for 32-68 min. only. No attention has been paid to the use of the DSS-D-Xylose-Rose Bengal system to enhance the electrical output, conversion efficiency and power.

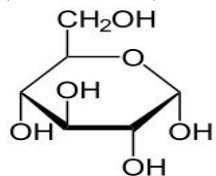
2. MATERIALS AND METHOD

2.1 Materials

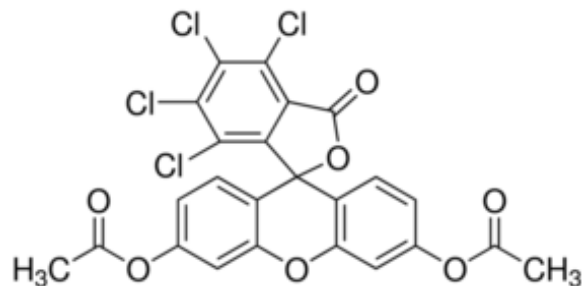
- (i) Dioctylsodiumsulphosuccinate (DSS) (Loba Chemie) –Used as surfactant



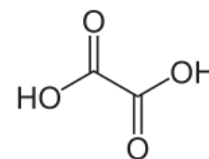
- (ii) D-Xylose (Loba Chemie)- Used as reductant



- (iii) Rose Bengal (Merck Spec. Pvt. Ltd.)- Used as (dye) photosensitizer



- (iv) Oxalic Acid (used for standardization of NaOH)



- (v) Sodium hydroxide (Merck Spec. Pvt. Ltd) - Used as basic medium

2.2 Experimental Method

A mixture of very dilute solutions (prepared in double distilled water) of surfactant, reductant, photosensitizer and sodium hydroxide were taken in a 'H' type glass tube, blackened except for a window. A platinum electrode (area 1.0 X 1.0 cm²) was dipped in one limb of the H-tube having a window, and a Saturated Calomel Electrode (SCE) was immersed in another limb of the tube. The whole cell was first placed in the dark till a stable potential was obtained, then the limb containing the platinum electrode was exposed to a 200 W tungsten lamp (Philips) as a light source. Employing a lamp of different wattage varies the light intensity of the cell. Where, the intensity of light was measured in terms of mW cm⁻² with the help of a solarimeter (CEL Model SM 203). A water filter was placed between the illuminated chamber and the light source to cut off infra-red radiation. According to Gangotri et al. [30], the generated photopotential and photocurrent of the systems were measured with the help of the Digital pH meter (Systronics model-335) and microammeter (Ruttonsha Simpson), respectively. Microammeter was also connected through a key to close one circuit and open the other circuit. The current-voltage characteristics of photogalvanic cells were studied by applying an external load with the help of a resistance (a carbon pot log 470 K) connected with the circuit. The experimental set-up of the photogalvanic cell is given in figure 1.

3. RESULTS AND DISCUSSION

3.1 Variation of DSS (dioctylsodiumsulphosuccinate) Concentration

The reliable electrical output of the photogalvanic cell was observed around the critical micelle concentration (cmc) of the dioctyl sodium sulphosuccinate as anionic micelles, i.e., 6.60 X 10⁻³ M (volume of DSS 1.60 ml) and on further increase in micelle concentration or volume, i.e., 1.60 ml to 1.65 ml, a decrease in electrical

power, conversion efficiency, $t_{0.5}$ and storage capacity of the cell has been observed. The observed results are summarized in table 1.

3.1.1 Role of Micelles (DSS): The role of micelles species was investigated as paramount to enhancing the solubility of photosensitizer molecules in the photogalvanic systems. The photoejection of electrons from excited photosensitizer molecules depends on the charge on the micelles. The micelles help to achieve the separation of photoproducts by hydrophilic-hydrophobic interaction of the products to enhance the conversion efficiency and storage capacity of the photogalvanic cell. The photogalvanic cell containing the D-Xylose-Rose Bengal system (without DSS) shows conversion efficiency and storage capacity as 0.95% and 75.0 min., respectively. The addition of DSS as micelles, on the other hand, acts as a suitable combination with D-Xylose and Rose Bengal to improve the overall performance of the cell, as measured by maximum photocurrent, photopotential, conversion efficiency, and percentage storage capacity, which are 1095.0 mV, 590.0 mA, 1.54%, and 97.93%, respectively. All comparative results are summarized in table 6. The usefulness of micelles [31] in photogalvanic cells with respect to their nature have been investigated by Gangotri and Gangotri [32] and found the following order of the micelle: anionic micelle > neutral micelle > cationic micelle in order of better performance.

3.2 Variation of D-Xylose Concentration

With the increase in concentration of the reductant (D-Xylose) in the present system, the photopotential was found to increase till it reaches its maximum value. On a further increase in the concentration of reductant (i.e., 1.84×10^{-3} M), a decrease in the electrical output of the cell was observed. The observed results of the system are summarized in Table 2. The decrease in power output was also caused by a decrease in reductant concentration due to a lower number of molecules available for electron donation to the cationic form of dye. However, the movement of dye molecules may be hampered by the higher concentration of reductant reaching the electrode within the time limit, resulting in a decrease in electrical output.

3.3 Variation of Rose Bengal Concentration

The effect of variation of photosensitizer (Rose Bengal) concentration was studied in the present system. With the increase in concentration of the photosensitizer, the photopotential and photocurrent were found to increase until they reached a maximum at 8.40×10^{-5} M. On further increase in concentration of the photosensitizer, a decrease in the electrical output of the cell was found. The effects of the variation of Rose Bengal concentration on the photogalvanic system are summarized in table 3. The reason for the change in photopotential is that on the lower side of the concentration range of photosensitizers, there are a limited number of photosensitizer molecules to absorb the major portion of the light in the path and, therefore, there is low electrical output, whereas the higher concentration of the photosensitizer does not permit the desired light intensity to reach the molecules near the electrodes and, hence, there is a corresponding fall in the power of the cell.

3.4 Effect of change of pH, diffusion length and temperature

The photogalvanic cell containing DSS- D-Xylose-Rose Bengal system, was found to be quite sensitive to pH of the solutions i.e. 12.76, 12.79, 12.81, 12.85, 12.87 and 13.00. It was observed that there is an increase in the photopotential and photocurrent of this system with the increase in pH value (In the alkaline range). At pH 12.85 a maxima was obtained. On further increase in pH, there was a decrease in photopotential and photocurrent. It was observed that the pH for the optimum condition [33] has a relation with pKa of the reductant and the desired pH is higher than the pKa value i.e. 5.2 ($\text{pH} > \text{pKa}$). The reason may be the availability of the reductant in its anionic form, which is a better donor form. The effect of variation of pH on cell potential and current are summarized in **table 4**. If diffusion length i.e. distance between the saturated calomel electrode (SCE) and Pt electrode applied as 35.0 mm, 40.0 mm, 45.0 mm, 50.0 mm, and 55.0 mm of H cell then it was observed that there was a sharp increase in photocurrent (i_{max}) in the first few min. of illumination and then, there was a gradual decrease to a stable value of photocurrent. Such behavior of photocurrent (i_{eq}) is due to an initial rapid reaction followed by a slow rate-determining-step at a later stage. On behalf of the observations, it may be concluded that the leuco or semi reduced form of used

dye (Rose Bengal), and the dye itself is the main electro active species at the illuminated and dark electrodes, respectively. However, the reducing agents and their oxidized products behave as the electron carriers in the cell, diffusing through the path. On this way, it was observed that with the increasing in temperature (temperature range under observation) the electrical power output of the photogalvanic cell increases gradually irrespective of the rapid fall in photo potential.

3.5 Current-Voltage (i-V) Characteristics, Conversion Efficiency and Storage Capacity-

The short circuit current (i_{sc}) and open circuit voltage (V_{oc}) of the photogalvanic cells were measured with the help of a micro ammeter (keeping the circuit closed) and with a digital pH meter (keeping the other circuit open), respectively. The current and potential values in between these two extreme values were recorded with the help of a carbon pot (log 470 K) connected in the circuit of microammeter, through which an external load was applied. The Current-Voltage (i-V) characteristics of the photogalvanic cell containing DSS- D-Xylose- Rose Bengal system is graphically represented in figure 2. It was observed that i-V curve deviated from their regular rectangular shapes. A point in i-V curve, called Power Point (pp) was determined where the product of current and potential was maximum. The value of fill factor (η) = 0.3144 was obtained and the determined power point of cell was (pp) = 160.12 μ W.

The conversion efficiency of the cell was calculated as 1.5261% using the electrical output at power point and the power of incident radiations.

$$\text{Conversion efficiency} = \frac{V_{pp} \times i_{pp}}{10.4mWcm^{-2} \times \text{Electrode area}(cm^2)} \times 100\% \dots\dots (1)$$

Whereas the storage capacity of the photogalvanic cell was observed by applying an external load (necessary to have current at power point) after termination the illumination as soon as the potential reaches a constant value. The storage capacity was determined in terms of $t_{0.5}$, i.e., the time required in fall of the electrical output (power) to its half at power point in dark. It was observed that the photogalvanic cell can be used in dark for 142.0 min. on irradiate for 145.0 min., so observed storage capacity was 97.93%. Conversion

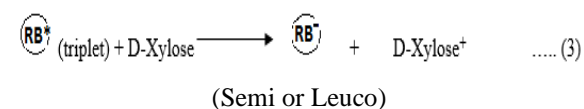
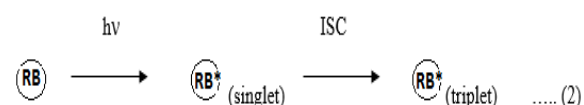
efficiency and storage capacity results are summarized in Table 5.

4. REACTION MECHANISM IN THE CELL

On the basis of obtained observations, a mechanism for the generation of photocurrent in the photogalvanic cell is discussed as-

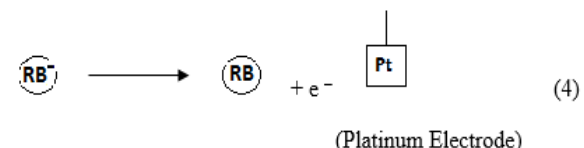
4.1 Illuminated Chamber

On illumination, the photosensitizer or dye (Rose Bengal) molecules get excited. The excited dye molecules accept an electron from reductant and get converted into Semi or Leuco form of dye [34] and reductant into its oxidized form-



4.1.1 At platinum electrode:

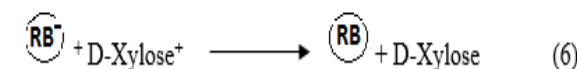
Dye molecules lose an electron to electrode and become original dye molecule.



4.2 Dark Chamber

4.2.1 At counter electrode

Dye molecules accept electron from the electrode and converted into Semi or Leuco form of the dye molecules



Finally the Semi or Leuco form of dye molecules and oxidized form of the reductant recombine to produce original dye molecules and reductant molecules and cycle will go on. Where RB, RB^* , RB^- , D-Xylose and $D\text{-Xylose}^+$ are the photosensitizer (Rose Bengal), its excited form, Semi or Leuco form, reductant and its oxidized form, respectively

5. CONCLUSION

The micelles help to achieve the separation of photoproducts by hydrophilic-hydrophobic interaction of the products to enhance the conversion efficiency and storage capacity of the photogalvanic cell. The photogalvanic cell containing D-Xylose- Rose Bengal system (without DSS) shows conversion efficiency and storage capacity as 0.95% and 75.0 min., respectively. On the other side, addition of DSS as micelles act as suitable combination with D-Xylose and Rose Bengal to enhancement of overall performance of the cell like as maximum photocurrent, photopotential, conversion efficiency and percentage storage capacity i.e. 1095.0 mV , 590.0 μ A, 1.54% and 97.93%, respectively. The current and potential values in between these two extreme values i.e. short circuit current (i_{sc}) and open circuit voltage (V_{oc}) were recorded with the help of a carbon pot (log 470 K) connected in the circuit of microammeter, through which an external load was applied. It was observed that i-V curve deviated from their regular rectangular shapes. The error in observed values of potential (from digital pH meter) and current (from micro-ammeter) are ± 5 mV and ± 10 μ A, respectively. The developed cell can work for 142.0 min. in dark if it irradiate for 145.0 min. so the storage capacity is 97.93%. The observed overall performance of this system i.e. DSS- D-Xylose- Rose Bengal system is radically high and has enough scope to increases the conversion efficiency and storage capacity of the photogalvanic cells. These solar cells are capable of solar power generation at low cost (due to use of very dilute solutions and cheap chemicals) with inherent storage capacity. This property of photogalvanic cell needs to be exploited as this technology is cleaner and promising for application in daily life for future.

APPENDIX

I_{eq} = photocurrent at equilibrium
 I_{max} = maximum photocurrent
 i_{pp} = photocurrent at power point
 i_{sc} = short circuit current
ml = milliliter
mV = millivolt
M = molarity
 V_{oc} = open circuit voltage
 V_{pp} = photopotential at power point

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DISCLOSURE STATEMENT

Authors acknowledge that there was no any financial interest or benefit that has arisen from the direct applications of our research.

DATA AVAILABILITY

The data that supports the findings of this study are available within the article.

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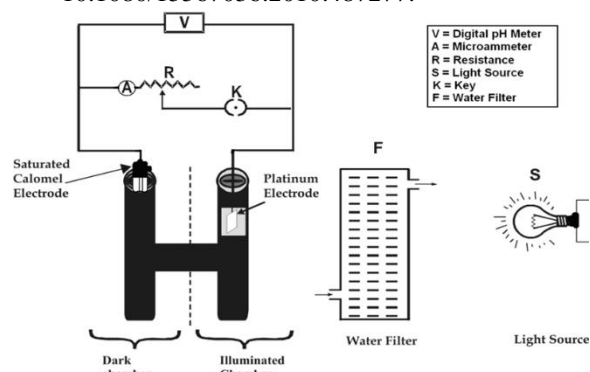


Figure: 1 Experimental Set-up of Photogalvanic Cell

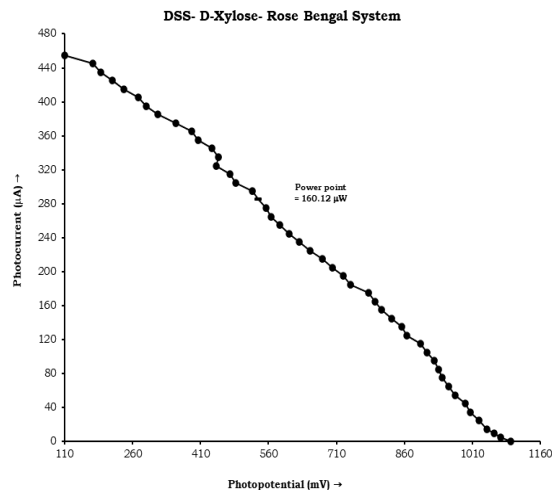


Figure 2. CURRENT-VOLTAGE (i-V) CURVE OF THE CELL

Table – 1 Effect of Variation of Micelles (dioctyl sodium sulphosuccinate, DSS) Concentrations

S. No.	Concentration of DSS X 10 ⁻³ M	Used Volume of DSS(ml)	Photo-potential (mV)	Photo-current (μA)	Power (μW)	Irradiated time in min.	Performance (t _{0.5}) min.	Storage capacity in %
1.	6.24	1.56	778.0	318.0	247.40	220.0	105.0	47.72
2.	6.36	1.59	835.0	377.0	314.79	185.0	95.0	51.35
3.	6.48	1.62	880.0	420.0	369.60	160.0	100.0	62.50
4.	6.60	1.65	910.0	465.0	423.15	145.0	142.0	97.93
5.	6.72	1.68	865.0	375.0	324.37	170.0	80.0	47.05

6.	6.84	1.71	790.0	315.0	248.85	185.0	92.0	49.72
7.	6.96	1.74	740.0	290.0	214.60	190.0	64.0	33.68

Used Concentrations*: [Rose Bengal] = $7.28 \times 10^{-5}M$; [D-Xylose] $1.02 \times 10^{-3}M$; [DSS] = $6.60 \times 10^{-3}M$, Light Intensity = 10.4 mW cm^{-2} ; Temperature = 299 K; pH = 12.85

Table – 2 Effect of Variation of D-Xylose Concentrations on the Photogalvanic System

S. No.	Concentration of D-Xylose $\times 10^{-3}M$	Used Vol. of D-Xylose	Photo-potential (mV)	Photo-current (μA)	Power (μW)	Irradiated time in min.	Performance ($t_{1/2}$) min.	Storage capacity in %
1.	0.90	2.38	736.0	334.0	245.82	190.0	85.0	44.73
2.	0.94	2.42	790.0	375.0	296.25	205.0	90.0	43.90
3.	0.98	2.46	840.0	405.0	340.20	146.0	110.0	75.34
4.	1.02	2.50	910.0	465.0	423.15	145.0	142.0	97.93
5.	1.06	2.54	856.0	415.0	355.24	135.0	65.0	48.14
6.	1.10	2.58	812.0	386.0	313.43	185.0	75.0	40.54
7.	1.14	2.62	765.0	320.0	244.80	215.0	90.0	41.86

Used Concentrations*: [Rose Bengal] = $7.28 \times 10^{-5}M$; [D-Xylose] $1.02 \times 10^{-3}M$; [DSS] = $6.60 \times 10^{-3}M$, Light Intensity = 10.4 mW cm^{-2} ; Temperature = 299 K; pH = 12.85

Table – 3 Effect of Variation of Rose Bengal Concentrations on the Photogalvanic System

S. No.	Concentration of Rose Bengal $\times 10^{-5}M$	Used Volume of Rose Bengal	Photo-potential (mV)	Photo-current (μA)	Power (μW)	Irradiated time in min.	Performance ($t_{1/2}$) min.	Storage capacity in %
1.	7.04	1.76	754.0	325.0	245.05	215.0	55.0	25.58
2.	7.12	1.78	828.0	390.0	322.92	200.0	75.0	37.50
3.	7.20	1.80	885.0	445.0	393.82	175.0	70.0	40.00
4.	7.28	1.82	910.0	465.0	423.15	145.0	142.0	97.93
5.	7.36	1.84	865.0	425.0	367.62	185.0	95.0	51.35
6.	7.44	1.86	768.0	380.0	316.16	220.0	68.0	30.90
7.	7.52	1.88	732.0	345.0	252.54	235.0	45.0	19.14

Used Concentrations*: [Rose Bengal] = $7.28 \times 10^{-5}M$; [D-Xylose] $1.02 \times 10^{-3}M$; [DSS] = $6.60 \times 10^{-3}M$, Light Intensity = 10.4 mW cm^{-2} ; Temperature = 299 K; pH = 12.85

Table – 4 Effect of Variation of pH on the Photogalvanic System

pH	DSS- D-Xylose- Rose Bengal System				
	Photopotential (mV)	Photocurrent (μA)	Power (μW)	Conversion Efficiency (Percent)	Storage Capacity in Dark (Min.)
12.76	765	340	260.10	0.94	60.0
12.79	790.0	352.0	278.08	1.00	55.0
12.81	845.0	405.0	342.22	1.06	65.0
12.85	910.0	465.0	423.15	1.54	142.0
12.85	822.0	382.0	314.00	1.24	80.0
12.87	790.0	335.0	264.65	1.07	65.0
13.00	660.0	320.0	211.20	0.75	40.0

Used Concentrations*: [Rose Bengal] = $7.28 \times 10^{-5}M$; [D-Xylose] $1.02 \times 10^{-3}M$; [DSS] = $6.60 \times 10^{-3}M$, Light Intensity = 10.4 mW cm^{-2} ; Temperature = 299 K; pH = 12.85

Table- 5 Sunlight Conversion Data and Conversion Efficiency of the Photogalvanic Cells

Concentration of Photosensitizer (Rose Bengal $\times 10^{-5}M$)	DSS- D-Xylose- Rose Bengal System				
	Fill Factor (η)	Conversion Efficiency in %	Storage capacity in %	Sunlight Conversion Data	
				Photopotential (mV)	Photocurrent (μA)
7.04	0.2984	0.76	25.58	1885.0	815.0
7.12	0.3105	0.98	37.50	2070.0	975.0

7.20	0.3210	1.12	40.00	2210.0	1115.0
7.28	0.3144	1.54	97.93	2275.0	1160.0
7.36	0.2840	1.05	51.35	2165.0	1060.0
7.44	0.2790	0.81	30.90	1920.0	950.0
7.52	0.2972	0.62	19.14	1830.0	865.0

Used Concentrations*: [Rose Bengal] = 7.28×10^{-5} M; [D-Xylose] 1.02×10^{-3} M; [DSS] = 6.60×10^{-3} M , Light Intensity = 10.4 mW cm^{-2} ; Temperature = 299 K; pH = 12.85

Table -6 Comparative Performance of the Photogalvanic Cell

S.N.	Parameters	Observed Results of the Present System	
		Without DSS	With DSS
1.	Dark Potential	287.0 mV	185.0 mV
2.	Open Circuit Voltage (V_{OC})	1002.0 mV	1095.0 mV
3.	Photopotential (ΔV)	715.0 mV	910.0 mV
4.	Equilibrium Photocurrent (i_{eq})	240.0 μ A	465.0 μ A
5.	Maximum Photocurrent (i_{max})	395.0 μ A	590.0 μA
6.	Time of Illumination	210.0 min.	145.0 min.
7.	Storage Capacity ($t_{1/2}$)	55.0 min.	142.0 min.
8.	Conversion Efficiency (CE)	0.95 %	1.54 %

Used Concentrations*: [Rose Bengal] = 7.28×10^{-5} M; [D-Xylose] 1.02×10^{-3} M; [DSS] = 6.60×10^{-3} M , Light Intensity = 10.4 mW cm^{-2} ; Temperature = 299 K; pH = 12.85