The Effect of Eriochrome Black T Concentrations on the Efficiency of Dye-sensitized Solar Cells

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Authors’ contributions

This work was carried out in collaboration between all authors. Authors MAA and SMHA designed the study, performed the experimental work and wrote the first draft of the manuscript. Author MD managed the study and edit the manuscript. Author MAS managed the literature searches and edit manuscript. All authors read and approved the final manuscript.

ABSTRACT

**Aims:** To investigate The effect of concentration on organic solar cell efficiency.

**Study Design:** Polymer and natural dye Eriochrome black T were deposited on ITO glass substrate, and then the resulted cells were tested for $I-V$ characteristics.

**Place and Duration of Study:** International University of Africa Faculty of Pure and applied science-Department of Physics collaboration with University Medical Science and Technology-Alawiya Centre and AlNilain University – Faculty of Science and Technology – Department of Physics, between March 2016 and May 2017.

**Methodology:** we have dye of different colour, we select three colours the dye, and then UV-visible spectrometer used for absorption spectra. After that, the relation between absorption and wavelength, absorption coefficient, and energy band gap were found graphically. Finally, cells were designed on ITO glass substrate by using spin coating deposition. $I-V$ Characteristics measured.

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Results: The relation between the Eriochrome black T concentration of dye for three samples are 6.67, 6.03, and 5.43 g/L, and the corresponding efficiencies for dark blue are 0.091, 0.090 and 0.229 respectively. The efficiencies of yellow Eriochrome Black T are 0.228, 0.193 and 0.181. And the efficiencies of red Eriochrome Black T are 0.246, 0.235 and 0.193. The decreases of efficiency due to the decreases of Eriochrome Black T concentration is related to the direct relation between Eriochrome Black T concentration and solar cell.

Conclusion: The efficiency of dye-sensitised solar cells can be increased by increasing the Eriochrome Black T dye concentrations at least within the examined range. The Eriochrome Black T dye type also affect efficiency. This includes the transparency of the Eriochrome Black T dye beside the value of the Fermi energy. In addition to the relative positions of highest occupied molecular orbitals (HOMO) and lowest unoccupied molecular orbitals (LUMO) to nearby layers.

Keywords: Dye; concentration; solar cells; polymer; voltage; current.

ABBREVIATIONS

\[ P_{\text{op}} \equiv \text{Output power} \]
\[ P_{\text{in}} \equiv \text{Incident power density (sunlight)} \]
\[ V_{\text{oc}} \equiv \text{Open circuit voltage} \]
\[ J_{\text{sc}} \equiv \text{Current density} = \frac{I_{\text{sc}}}{A} \]
\[ I_{\text{sc}} \equiv \text{Short circuit current} \]
\[ A \equiv \text{cross sectional Area of the cell} \]
\[ FF \equiv \text{fill factor} = \frac{I_{\text{max}}V_{\text{max}}}{I_{\text{sc}}V_{\text{oc}}} \]
\[ I_{\text{max}} \text{ and } V_{\text{max}} \text{ are maximum current and maximum voltage respectively.} \]

1. INTRODUCTION

Renewable energy sources are gaining more interest in recent years and will be an increasingly important part of power generation in the coming years [1]. Solar cells or photovoltaic (PV) are solid state devices that directly convert sunlight energy into electrical energy through the photovoltaic e process [2]. French physicists Henri Becquerel was first observed of the photovoltaic which presents the basic concept behind solar cells [3]. The generation of electricity from sunlight started since the 1950s when the first PV cell was invented. Photovoltaic cells consist of a junction between two thin layers, a positive layer (p-type) and a negative layer (n-type) semiconductor materials. When photons of light of a suitable wavelengths fall within the p-n junction, they transfer their energy to some of the electrons in the material so taking them to a higher energy level, and then a p-n junction will forming. The absorption of sunlight will create free minority carries, which determine the solar cell current. These carriers are collected and separated by the junction of the diode, which determines the voltage. To increase the voltage, individual cells are combined in a panel form [4].

The first practical solar cell was developed in 1954 at Bell laboratories by Daryl M. Chapin, Calvin S. Fuller, and Gerald L. Pearson [5]. Solar cells have given rise to a global industry capable of producing many GWs of Additional installed capacity per year. Although much of the solar radiation reaching the earth is comprised of wavelengths with energies greater than the band gap of silicon. Therefore, it becomes essential to searching alternative materials for low-cost photovoltaic technologies. Recently, organic photovoltaic cells have attracted more attention as new energy sources due to their light weight, ease for designing, low cost, flexible and efficient solar cells [6]. The power conversion efficiency of polymer organic solar cells device has increased steadily over the last decades. [7]. Organic photovoltaic cell (OPVC) is a class of solar cell that uses conductive organic polymers such as MEH-PPV, its structure as shown below in figure 1 [8]; or small organic molecules for light absorption and charge transport [9], since they possess the base property of required to activate the fundamental mechanism to transform the radiative energy of light into an electric current [10]. They are a less expensive alternative to an inorganic semiconductor like Silicon [11]. Recently thin film based dye-sensitized solar cells (DSSCs), which was first proposed by O’Breon and Gratzel in 1991, which working as the principle of photosynthesis, it appears to be highly potential alternatives to more expensive solar cell technologies because of their high light-to-electricity conversion efficiencies, inexpensive production cost, and ease of fabrication [12, 13, 14, 15]. The performance of DSSCs depends upon many factors such as absorption efficiency of the sensitising dye for the solar light spectrum. The electron transfer and separation of a charge play important roles in the dye performance of DSSCs [16]. The sensitisser is one of the most important components to achieving high photoconversion efficiency (PCE) and stability of DSSCs [17]. Synthesized such as
TEMPO (TEMPO-I = \(2-(2,2,6,6\text{-tetramethyl}-1\text{-}(1\text{-oxidanyl})\text{piperidin}-4\text{-yl})\text{oxy})\) ethan-1-amine and TEMPO-III = tris(2-(2,2,6,6-tetramethyl-1-(1-oxidanyl)piperidin-4-yl)oxy)ethyl)amine)-based redox couple electrolytes incorporated with BIMI (1-buty1-3-methyl imidazolium iodide) was used in the application of dye-sensitised solar cells (DSSCs). Such type TEMPO-III/BIMI hybrid redox couple displayed the highest photo-current density (Jsc) and enhanced photo-voltage (Voc) and an efficiency (\(\eta = 5.12\%\)) upon 1 sunlight illumination [18]. The Erio Chrome Black T used as sensitisier due to the intense charge transfer in the whole visible spectrum range [19]. This work aims to investigate the effect of Eriochrome Black T Concentrations on the efficiency of Dye-sensitized Solar Cells.

2. MATERIALS AND METHODS

2.1 The Selection of Dye Colours

The three different colours were selected from Eriochrome Black T dye. An amount of 0.2 g from each colour was dissolved in distilled water of volume 30 mL. For each colour of Eriochrome Black T, the concentration is changed to assume the values 6.67, 6.03 and 5.43 g/L respectively. Thus, one has three samples for each colour. The chemical structure of the Eriochrome Black T dye was shown below (Fig. 2 [20]).

2.2 The Analysis of Dye Colour Using UV- Visible Spectrometer

The analysis of the spectrum of each Eriochrome Black T dye colours was achieved by using UV-visible spectrometer at the University of Medical Science and Technology. The absorption spectra of the Eriochrome Black T dye were taken when Eriochrome Black T dye samples put in UV-visible spectrometer. The relation between wavelengths and absorption (a. u), were represented graphically.

2.3 Cells Preparation and \(I - V\) Characteristics

Cells prepared by cleaning the ITO 2.5x2.5cm glass substrate using chloroform, then semiconductor polymer (MEH-PPV) was deposited on the glass using spin coating machine and applying operating current 0.03A at a voltage of 2.3V. The three different colors of Eriochrome Black T dyes were deposited by using also spin coating machine and applying operating current 0.03A at a voltage of 1.9V. After cells prepared, \(I - V\) characteristics were measured.

3. RESULTS AND DISCUSSION

| \(V(V)\) | \(I(mA)\) |
|-------|--------|
| 0.171 | 5.410^{-3} |
| 0.180 | 5.410^{-3} |
| 0.192 | 5.410^{-3} |
| 0.201 | 5.410^{-3} |
| 0.202 | 5.310^{-3} |
| 0.210 | 5.310^{-3} |
| 0.216 | 5.310^{-3} |
| 0.425 | 5.210^{-3} |

| \(V(V)\) | \(I(mA)\) |
|-------|--------|
| 0.171 | 5.410^{-3} |
| 0.181 | 5.410^{-3} |
| 0.193 | 5.410^{-3} |
| 0.204 | 5.410^{-3} |
| 0.214 | 5.410^{-3} |
| 0.216 | 5.310^{-3} |
| 0.217 | 5.310^{-3} |
| 0.217 | 5.2310^{-3} |
Table 3. $I - V$ Characteristics for dark blue colour dye (Sample 3)

| $V(V)$   | $I(mA)$   |
|----------|-----------|
| 0.533    | 5.2 x 10^{-3} |
| 0.537    | 5.1 x 10^{-3} |
| 0.542    | 5.1 x 10^{-3} |
| 0.549    | 5.1 x 10^{-3} |
| 0.556    | 5.7 x 10^{-3} |
| 0.562    | 5.0 x 10^{-3} |
| 0.572    | 5.0 x 10^{-3} |

Table 4. $I - V$ Characteristics for yellow colour dye (Sample 1)

| $V(V)$   | $I(mA)$   |
|----------|-----------|
| 0.506    | 4.9 x 10^{-3} |
| 0.577    | 4.9 x 10^{-3} |
| 0.588    | 4.8 x 10^{-3} |
| 0.592    | 4.8 x 10^{-3} |
| 0.593    | 4.6 x 10^{-3} |
| 0.593    | 4.5 x 10^{-3} |

Table 5. $I - V$ Characteristics for yellow colour dye (Sample 2)

| $V(V)$   | $I(mA)$   |
|----------|-----------|
| 0.733    | 3.11 x 10^{-3} |
| 0.741    | 3.11 x 10^{-3} |
| 0.749    | 3.11 x 10^{-3} |
| 0.758    | 3.11 x 10^{-3} |
| 0.772    | 3.11 x 10^{-3} |
| 0.782    | 3.07 x 10^{-3} |
| 0.782    | 3.02 x 10^{-3} |
| 0.783    | 2.98 x 10^{-3} |

Table 6. $I - V$ Characteristics for yellow colour dye (Sample 3)

| $V(V)$   | $I(mA)$   |
|----------|-----------|
| 0.066    | 5.17 x 10^{-3} |
| 0.150    | 5.17 x 10^{-3} |
| 0.261    | 5.17 x 10^{-3} |
| 0.378    | 5.17 x 10^{-3} |
| 0.493    | 5.13 x 10^{-3} |
| 0.523    | 5.06 x 10^{-3} |
| 0.540    | 4.94 x 10^{-3} |

3.1 Solar Cells Efficiency ($\eta$) - Second Level Heading

$\eta = \frac{P_{cell}}{P_{in}} = \frac{V_{oc}I_{sc}FF}{P_{in}}$  \hspace{1cm} (1)

Where

$J_{sc} = \frac{I_{sc}}{A}$  \hspace{1cm} (2)

\[ FF = \frac{I_{max}}{I_{scVoc}} \]  \hspace{1cm} (3)

Table 7. $I - V$ Characteristics for red colour dye (Sample 1)

| $V(V)$   | $I(mA)$   |
|----------|-----------|
| 0.599    | 4.66 x 10^{-3} |
| 0.598    | 4.85 x 10^{-3} |
| 0.597    | 5.08 x 10^{-3} |
| 0.591    | 5.24 x 10^{-3} |
| 0.575    | 5.24 x 10^{-3} |
| 0.565    | 5.24 x 10^{-3} |
| 0.558    | 5.24 x 10^{-3} |
| 0.599    | 4.66 x 10^{-3} |

Table 8. $I - V$ Characteristics for red colour dye (Sample 2)

| $V(V)$   | $I(mA)$   |
|----------|-----------|
| 0.518    | 5.36 x 10^{-3} |
| 0.522    | 5.36 x 10^{-3} |
| 0.529    | 5.36 x 10^{-3} |
| 0.537    | 5.37 x 10^{-3} |
| 0.547    | 5.37 x 10^{-3} |
| 0.557    | 5.21 x 10^{-3} |
| 0.558    | 4.99 x 10^{-3} |
| 0.558    | 4.81 x 10^{-3} |

Table 9. $I - V$ Characteristics for red colour dye (Sample 3)

| $V(V)$   | $I(mA)$   |
|----------|-----------|
| 0.534    | 4.7 x 10^{-3} |
| 0.532    | 4.76 x 10^{-3} |
| 0.528    | 4.89 x 10^{-3} |
| 0.520    | 5.03 x 10^{-3} |
| 0.427    | 5.13 x 10^{-3} |
| 0.244    | 5.13 x 10^{-3} |
| 0.122    | 5.13 x 10^{-3} |
| 0.055    | 5.13 x 10^{-3} |

3.2 Discussion

The three figures (Fig. 3a, Fig. 3b, Fig. 3c,) below are showed the optical absorption spectrum of Eriochrome Black T dye. This spectrum were taken by using UV visible spectrometer from Alawia Centre at the University of Medical Science and technology. The spectrum of the Fig. 3a is ranging between 250 up to 550 nm, that including in visible light wavelengths range. Which represent the spectrum of Eriochrome Black T (yellow) dye. The maximum of yellow recorded is 400 nm. Fig. 3b, explaining the spectrum of Eriochrome Black
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T (dark blue) dye, its wavelengths ranging between 250 nm up to 650 nm. The maximum peak recorded for this colour is at 618 nm. Finally, Fig. 3c, is the spectrum of Eriochrome Black T (red) dye, its wavelengths ranging between 250 nm up to 568 nm and the maximum peak recorded for colour is at 482. It is clear that the dark blue colour showed high absorption comparing to the yellow and red colours. These three figures showing that the Eriochrome Black T has very good optical properties, and hence is responsible for sunlight spectrum and using it as sensitisers for designing solar cells that can convert visible light into electricity in the range of 250 – 650 nm wavelengths [21]. Photovoltaic parameters are summarised in table 10, and they were measured under 200 mWcm$^{-2}$ light illumination. The efficiency of Eriochrome Black T dye ranges from 0.090 up to 0.246% [22,23]. Table 1, Table 2, and Table 3 are explaining the $I - V$ characteristics for the dark blue colour of Eriochrome Black T dye as is shown in Fig. 4, Fig. 5, and Fig. 6. The values of the current and voltage were taken when solar cells tested with incident light 200 mWcm$^{-2}$, the efficiencies recorded for dark blue are 0.091, 0.090, and 0.229% as is shown in table 10. Table 4, Table 5, and Table 6 they are explaining the $I - V$ characteristics for the yellow colour of Eriochrome black T dye, and hence the values of the current and voltage represented graphically as they appear in Fig. 7, Fig. 8, and Fig. 9. Yellow color recorded efficiencies 0.228, 0.193, and 0.181%. Finally, Table 7, Table 8, and Table 9, are also explaining the $I - V$ characteristics for the red colour of Eriochrome black T dye. The recorded efficiencies of the red colour from Fig. 10, Fig. 11, and Fig. 12 were 0.246, 0.235, 0.191 Table 10. The designed cell shows low efficiency 0.090% in Table 10 when the current density of 0.864mA cm$^{-2}$ generated an open circuit voltage 0.217V [24,25]. In the view Table 11, it is clear that decreasing the concentration of dark blue Eriochrome Black T dye 6.67, 6.03 and 5.43 increases the efficiency Table 11, 0.091, 0.090 and .229. And yellow Eriochrome Black T dye table 12, 6.67, 6.03 and 5.43 decreases the efficiency table 12, 0.228, 1.93 and 0.181 respectively. This may be due to fact that the decrease of Eriochrome Black T dye concentration decreases the number of free electrons that are liberated by photons from each dye atoms. This decrease in the number of electrons decreases the current flow thus decreases $Im$, which in turn decreases the efficiency $\eta$ of the cell. The same thing, table 13 shows that, the decreasing of the concentration of a red Eriochrome Black T dye Table 13, 6.67, 6.03 and 5.43, decreases the efficiency Table 13, 0.246, 0.235 and 0.191 respectively. This decrease in efficiency can be explained by using the same arguments used for yellow dyes. Figs 13a, 13b and 13c, they represent the relation between efficiency and concentration of yellow, dark blue and red colour dye. Fig. 13b has Plank prediction of the black body radiation, in this figure, the efficiency increasing when concentration increases and break down.

![Fig. 3a. Optical absorption spectrum of yellow colour dye](image-url)
Fig. 3b. Optical absorption spectrum of dark blue colour dye

Fig. 3c. Optical absorption spectrum of dye red colour dye

Table 10. Photovoltaic parameters for all Eriochrome Black T dye colors samples

| Sample  | $I_{sc}$ | $I_{max}$ | $V_{oc}$ | $V_{max}$ | $J_{sc}$ | FF  | $\eta$ % |
|---------|----------|-----------|----------|-----------|----------|-----|---------|
| Darkblue1 | 5.4      | 5.38      | 0.216    | 0.21      | 0.864    | 0.97| 0.091   |
| Darkblue2 | 5.4      | 5.38      | 0.217    | 0.209     | 0.864    | 0.96| 0.090   |
| Darkblue3 | 5.18     | 5.13      | 0.563    | 0.559     | 0.829    | 0.98| 0.229   |
| Yellow1  | 4.9      | 4.85      | 0.593    | 0.584     | 0.784    | 0.98| 0.228   |
| Yellow2  | 3.11     | 3.09      | 0.783    | 0.776     | 0.498    | 0.99| 0.193   |
| Yellow3  | 5.17     | 5.14      | 0.540    | 0.442     | 0.827    | 0.81| 0.181   |
| Red1     | 5.24     | 5.17      | 0.599    | 0.593     | 0.838    | 0.98| 0.246   |
| Red2     | 5.36     | 5.29      | 0.558    | 0.551     | 0.858    | 0.98| 0.235   |
| Red3     | 5.13     | 5.08      | 0.532    | 0.469     | 0.821    | 0.87| 0.191   |
Fig. 4. $I-V$ Characteristics for dark blue colour dye (sample 1)

Fig. 5. $I-V$ Characteristics for dark blue colour dye (sample 2)

Fig. 6. $I-V$ Characteristics for dark blue colour dye (sample 3)
Fig. 7. *I* – *V* Characteristics for yellow colour dye (sample 1)

Fig. 8. *I* – *V* Characteristics for yellow colour dye (sample 2)

Fig. 9. *I* – *V* Characteristics for yellow colour dye (sample 3)
Fig. 10. $I - V$ Characteristics for red colour dye (sample 1)

Fig. 11. $I - V$ Characteristics for red colour dye (sample 2)

Fig. 12. $I - V$ Characteristics for red dye (sample 3)
Table 11. Relation between concentration of dark blue colour of Eriochrome black T dye and efficiency

| Eriochrome black T | Efficiency % | Concentration g/l |
|--------------------|--------------|-------------------|
| Dark Blue dye 1    | 0.091        | 6.67              |
| Dark Blue dye 2    | 0.090        | 6.03              |
| Dark Blue dye 3    | 0.229        | 5.43              |

Fig. 13a. Relation between concentration of dark blue colour dye and efficiency ($\eta$)

Fig. 13b. Relation between concentration of yellow colour dye and efficiency ($\eta$)
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Fig. 13c. Relation between concentration of red colour dye and efficiency (η)

Table 12. Relation between concentration of yellow colour of Eriochrome black T dye and efficiency

| Eriochrome black T | Efficiency (%) | Concentration |
|--------------------|----------------|---------------|
| Yellow dye 1       | 0.228          | 6.67          |
| Yellow dye 2       | 0.193          | 6.03          |
| Yellow dye 3       | 0.181          | 5.43          |

Table 13. Relation between concentration of red colour of Eriochrome black T dye and efficiency

| Eriochrome black T | Efficiency (%) | Concentration |
|--------------------|----------------|---------------|
| Red dye 1          | 0.246          | 6.67          |
| Red dye 2          | 0.235          | 6.06          |
| Red dye 3          | 0.191          | 5.43          |

4. CONCLUSION

The efficiency of dye-sensitised solar cells can be increased by increasing the Eriochrome Black T dye concentrations at least within the examined range. The Eriochrome Black T dye type also affect efficiency. This includes the transparency of the Eriochrome Black T dye beside the value of the Fermi energy. In addition to the relative positions of highest occupied molecular orbitals (HOMO) and lower unoccupied molecular orbitals (LUMO) to nearby layers.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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