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Investigation of the Effect of Type and Concentration of Dye on the Performance of Tio2 Based Dye-Sensitized Solar Cells

Aghareed M. Tayeb[1,] , Amr Harfoush[2], Tamer M. Abu el-Ella[3].*

1 chemical Department, Faculty of Engineering, Minia University, Minia, Egypt, email: aghaereed1@yahoo.com
2 former head, solar energy labtecnical research center, Cairo, Egypt, email: amrharfoosh8@gmail.com
3 former head, protection lab CWA, Cairo, Egypt, email: eng.tamer13280@gmail.com
** Aghareed M. Tayeb, Email: aghaereed1@yahoo.com,* *DOI: 10.21608/pserj.2022.94940.1141*

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ABSTRACT

Dye-Sensitized Solar Cells (DSSCs) have been paying much attention due to their low cost and high efficiency. In this work, high-performance dye-sensitized solar cells (DSSCs) made of a combination of TiO_2 nanoparticles and dye were fabricated and tested. Three types of Ruthenium dyes; N3, N719, and N749 Black Dye were used. Three concentrations of each dye; 30, 40, and 50% were tested. Under optimized conditions, the solar energy conversion efficiencies were measured. The short-circuit current density (J_{SC}), the open-circuit voltage (V_{OC}), the fill factor (FF), and the overall efficiency (η) of the DSSCs was measured. Results indicated N3 dye resulted in the most efficient DSSC. When working in the voltage range 0 - 0.577V, values of the resulting current were 5.711, 4.836, and 3.965 mA for N3, N719, and N749 Black Dye, respectively. These values of current remained constant with increasing voltage until voltage values of 0.436, 0.4, and 0.47V; for the three dyes, respectively. The values of the maximum power got were 2.223, 1.832, and 1.748 mW for N3, N719, and Black Dye, respectively. The efficiency of the TiO_2 cells was 5.56, 4.58, and 4.37% when using N3, N719, and N749 Black Dye, respectively. Experimentation on different dye concentrations showed N3 dye with a concentration of 50% gives the best performance for DSSC with an FF value of 79.21 and photoconversion efficiency of 6.002%.

Keywords: Solar cell, Dye-sensitized solar cell (DSSC), dye, current, photoconversion efficiency.

1 . INTRODUCTION

The enhancement of photovoltaic effects through dyes returns to the 19th century; when Dr. Moser of the University of Vienna made his first study on the dye-sensitized photoelectric action. The first experiment was performed in the 1960s with a monocrystalline semiconductor electrode; which has been dipped in a dye solution. This device has conversion efficiencies less than 0.5% while its long-term stability was poor when applied in water division systems. In 1976, Tshubomura et al. used highly porous colored multicrystalline ZnO cell which had a 1.5% energy conversion. They also concluded that a system of the iodide / triiodide redox shuttle performed very well to reach high conversion efficiencies. [1].

Gratzel's group at EPFL (Switzerland) has been considered to be the driving force for the development of dye-sensitized solar cells since the Mid. 1980. In 1991 they invented cells with conversion efficiencies greater than 10% in inexpensive nanoporous TiO_2 deposited on conductive glass [2].

The cell is constructed in a sandwich configuration as shown in Figure (1).[3].

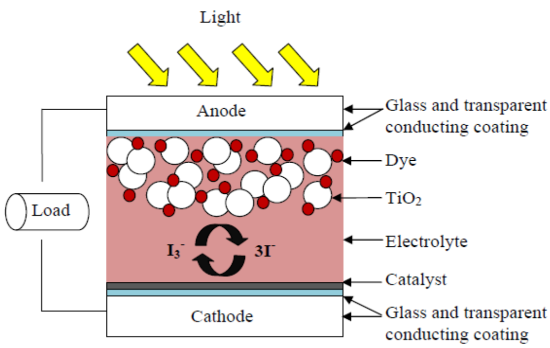

Figure 1: Schematic of the energy flow in a dye-sensitized solar cell

The carrier substrate must be transparent in the visible range and close to UV rays, since it is through it that the light is coupled to the cell. The anode electrode consists of a thin film of transparent conductive material deposited within the carrier substrate. An indium fine oxide (ITO) semiconductor is often used for this purpose. However, other semiconductors such as fluorine-doped fine oxide (SnO_2: F) can also be used. The actual photoanode consists of a film made of three layers of nanocrystalline semiconductors (TiO_2). These sheets are typically a few microns thick (between 1 10 μm) and can be produced in different ways. The most common method of making thin films is by pouring a suspension of the nanocrystals using a spray or drag coating and then calcining the film at 400°C. The working electrode; the nano-porous TiO_2 (three layers) is applied to the conductive glass and is separated from the counter electrode only by a thin layer of electrolyte solution. The dye is chemisorbed on the surface of TiO_2. The counter electrode is also made of conductive glass, onto which thin clear platinum is sprayed to catalyze the regeneration process of the mediator. A DSSC is configured by filling an electrolyte solution between the dye-sensitized TiO_2 electrodes and a carbon black coated counter electrode. The two electrodes were held together and a cyanoacrylate adhesive was used as a sealant to prevent the ionic liquid electrolyte solution from leaking out [4, 5].

A very difficult step in the working process of color-sensitive nanocrystalline solar cells. When the solar cell works, there are multiple simultaneous chemical processes. These are the key chemical processes between the two glass plates of the semiconductor when the cell functions [6]:

TiO_2 | S + hv → TiO_2 | S* **(1)**

TiO_2 | S* → TiO_2 + e-| S+ **(2)**

TiO_2 | S+ + red → TiO_2 + ox (red=the reduced form ox = the oxidized form) **(3)**

S* + I- reduced form (mediator) → S + I. (Radicle) 2I. → I2 **(4)**

I2 + I-→I3 **(5)**

If S is the color molecule when S is touched by light, then S absorbs the photon energy and then S* is the agitated color molecule. Once the excited coloration molecule releases the ions, S* is oxidized to S+ by TiO_2. It is then reduced by the I to the original form [4].

The 'fill factor' is a parameter which with Voc and Isc determines the maximum energy of a solar cell, more generally known by its 'FF' abbreviation. The FF is defined as the maximum energy ratio of the solar cell to the Voc and Isc product.

The PV DSSC test is performed by measuring the J-V character curves in the environmental atmosphere with a simulated AM 1.5 photovoltaic light at 100 mW/cm^2 of a xenon arc lamp (XQ-500W) [5, 6].

The overall efficiency of the dye-sensitized solar cell is determined by the photocurrent density (Isc) measured in the event of a short circuit, the no-load photovoltage (Voc), the cell fill factor (ff), and the intensity of the incident light (Is) [7].

$$\eta = \frac{I_{sc} V_{oc} (ff)}{Is} \quad \textbf{(6)}$$

Isc, Voc is determined from the photocurrent-photovoltage curve of the cell. The fill factor was calculated using the following equation:

$$FF = \frac{IV}{I_{sc} V_{oc}} \quad \textbf{(7)}$$

Where V, I are the voltage and current determined from the point of the curve that has maximum power.

2. EXPERIMENTAL WORK

Manufacture of Dye Sensitized Solar Cells

The experimental work of the present study is carried out in the Renewable Energy Laboratory. From the Technical Research Center (TRC), Cairo, Egypt to manufacture and test advanced types of nanocrystalline solar cells, i.e. H. dye-sensitized nanocrystalline solar cells.

The dye-sensitized solar cell is manufactured in the lab. using three different dyes (N3, N719, and N749 Black Dye) for dyeing the coated electrode, at three different concentrations (50, 40, and 30%). The original 5 × 10^{-4} M N3 dye concentration in ethanol (100%) was changed to get 50%, 40%, 30% concentrations through further dilution by the addition of various amounts of ethanol [8]

The fabricated cell is integrated into an electric cell and its performance is evaluated by recording the values of Filling Factor (FF) and efficiency (η, %) obtained.

The step-by-step procedures for the fabrication of dye-sensitized solar cells are displayed in Figure (2). Each picture depicts one step in the fabrication process, from the structuring of TCO to the complete assembly of the devices.

The steps are summarized as follows [9]:

- Preparation of fluorine-doped SnO_2 (F-SnO_2 glass)
- Deposition of the blocking layer of TiO_2 (5:10 nm) on F-SnO_2
- Deposition of the nanoporous layer of TiO_2
- Deposition of reflecting layer of TiO_2
- Deposition of platinum paste on the counter electrode
- Dye sensitization of TiO_2 layers by soaking TiO_2 film in the concentrated dye solution
- Assembly of electrode and counter electrode
- Filling of sandwich cell with the electrolyte solution

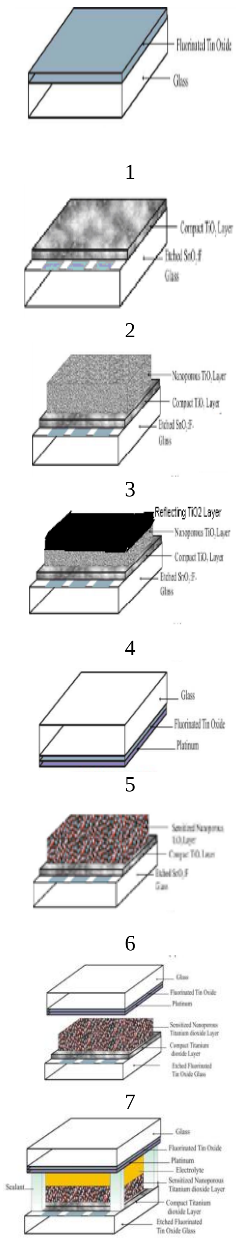

Figure 2: Details of dye-sensitized solar cells fabrication

2.1 Materials and Method:

2.1.1 Materials

TiO_2 nanoparticles are used for preparing a layered electrode as a semiconductor for manufacturing the cell. **An SEM micrograph of a nanocrystalline TiO2 film is shown in Figure (3) and its characteristics are given in Table (1).**

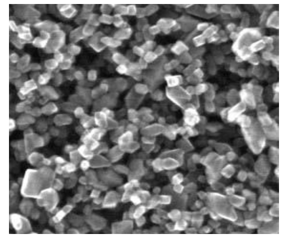

Figure 3: SEM micrograph of a nanocrystalline TiO2 film (viewed from the top)

Table 1. Characterization of nanocrystalline TiO2

Description	R3008 is a white fluffy powder, with fine particle diameter and wide surface area. The products come on through organic and inorganic enveloping.
Typical Properties	Appearance: Odor-free, white powder TiO2 Content %:95%~98% Rutile relative Content %:≥98% Silicon Oxide Content %:1%~4% Alumina Content %:1%~3% H2O Content %:≤3% Ignition Loss:≤15% pH Value:6.0~10.0 Grain Size:10~100nm

The dyes used are Ruthenium based dyes
(N3): C26H16N6O8RuS2 (Figure: 4)

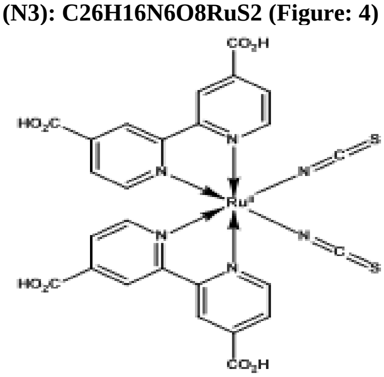

Figure 4: Structure of N3 dye molecule
(N719): (Bu4N)2[Ru(dcbpyH)2(NCS)2] (Figure 5)

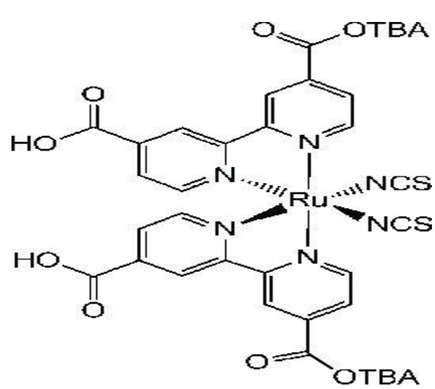

Figure 5: Structure of N719 Dye [10]

(N749) Black Dye, Sigma- Aldrich (Figure. (6):

With visible absorption extending into the near-IR region up to 920 nm with IPCE 80%, producing an overall efficiency of 10.4%

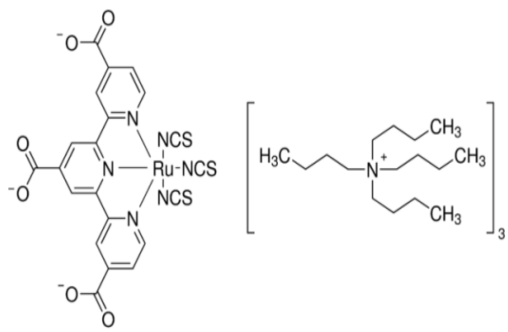

Figure 6: Structure of N749 Black Dye [11]

2.1.2 Method

Cells are manufactured using different types of dyes with different concentrations, different nanoparticles and different particle sizes. The effect of these parameters is evaluated by measuring the cell performance with respect to its filling factor (FF) and photoconversion efficiency

2.1.3 Equipment and tools used

The following equipment and tools are used throughout the experimental work.

Ultra Sonic device, tapes, well finished spreader, blower, air dryer, para-film, different sizes of beakers, furnace up to 500°C, gifts, halogen lamp, ammeter, voltmeter, variable resistance box, clamps and solar power meter.

3 . RESULTS AND DISCUSSION

This section presents the results obtained from experimentation on three different dyes with three different concentrations for determining FF and photoconversion efficiency of the Lab.- fabricated DSSC.

3.1 Effect of dye type

Three different dyes; N3, N.719, and N749 Black Dye are used under the fixed operating conditions shown in Table (2). The results given by the three types of dyes are presented in the following tables and figures.

Table 2. Operating parameters of experiments run on TiO_2 cell

Variable	Value
Type of semi-conductor	TiO_2
Type of dye	N3 or N719 or Black Dye
The particle size of the semiconductor	50 nm
The thickness of the semiconductor layer	0.1 mm
Concentration of dye	40%
Heat treatment temp	100 °C

3.1.1 Results of using N3 dye

The cell behavior is measured considering the same operating parameters, i.e., (T_{op}), (T_{ref}), (G), (A), (I_{sc}), (V_{oc}), (V_{max}), (I_{max}), (F.F), and efficiency (eff).

The experimental results for N.3 dye are given in Table (3) and are presented graphically in Fig. (7) as a relation between voltage, (V), and current, (mA), or power, (mW).

Table 3. Cell behavior of TiO_2 as a semiconductor with N3 dye

Variable	Value
T_{op}, °C	30
T_{ref}, °C	25
G, W/m²	1000
A, m²	0.04
I_{sc}, mA	5.711
V_{oc} volt	0.577
V_{maxm} volt	0.436
I_{max}, mA	5.1
P_{max}, mA	2.223
FF	67.10
eff. %	5.56

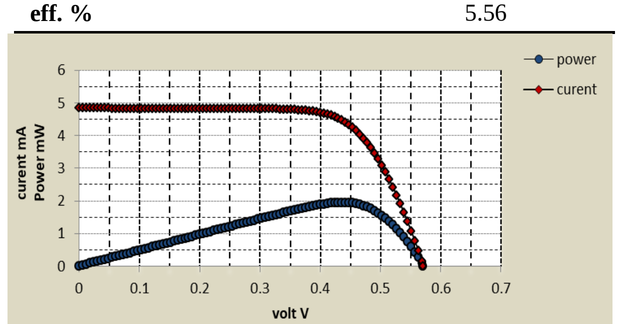

Figure 7: TiO_2 cell behavior when using N.3 dye

Examination of the figures in Table (3) and the shape of Fig. (7) shows that increasing voltage in the initial stages of the experiment does not affect the value of current, which keeps constant at 5.711 mA. When the voltage reaches a value of 0.436 current gradually decreases till it reaches a zero value at voltage 0.577 (V_{max}).

The attitude of the change of power with voltage was different. The value of power increased gradually with increased voltage till it reaches 2.223 mW (P_{max}) at 0.436 Volt after which the value of power decreases with increasing voltage till it reaches a zero value at the maximum voltage of o.577 V.

Values of 67.10 and 5.56% are accomplished for FF and photo-conversion efficiency, respectively.

3.1.2 Results of using N.719 dye

Similar tests to those of the previous section are run at the same values of parameters but with using N.719 dye.

The results of the present test are given in Table (4) and presented graphically in Fig. (8)

Table 4. Cell behavior of TiO_2as a semiconductor with N719 dye

Variable	Value
T_{op}, °C	30
T_{ref}, °C	25
G, W/m^2	1000
A, m^2	0.04
I_{sc}, mA	4.836
V_{oc} volt	0.571
V_{maxm} volt	0.4
I_{max}, mA	4.58
P_{max}, mA	1.832
FF	66.32
eff. %	4.58

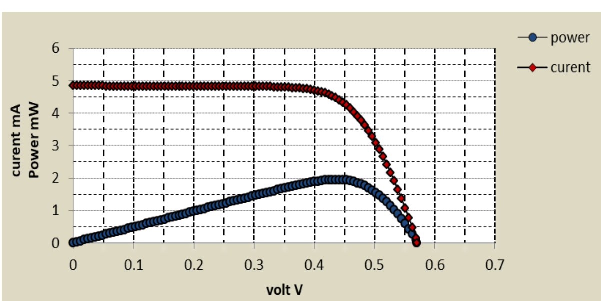

Figure: 8 TiO_2 cell behavior when using N.719 dye

At a zero voltage value, the resulting current was 4.836 mA (I_{sc}) and it remained constant until the voltage reached 0.4V, where the current gradually decreased to zero at 0.571 Volt. Power started at zero value and it increased with increasing voltage until it reached 1.832 mW (P_{max}) at 0.4 Volt before it decreases again until it reaches zero at 0.571 Volt.

Values of 66.32 and 5.56 are accomplished for FF and photoconversion efficiency for this type of DSSC.

3.1.3 Results of using N. 749 black dye

The experimental results of the tests run using black dye are shown in Table (5) and represented graphically in Fig. (9).

Table 5. Cell behavior of TiO_2as a semiconductor with N749 black dye

Variable	Value
T_{op}, °C	30
T_{ref}, °C	25
G, W/m^2	1000
A, m^2	0.04
I_{sc}, mA	3.965
V_{oc} volt	0.569
V_{maxm} volt	0.47
I_{max}, mA	3.72
P_{max}, mA	1.748
FF	77.46
eff. %	4.371

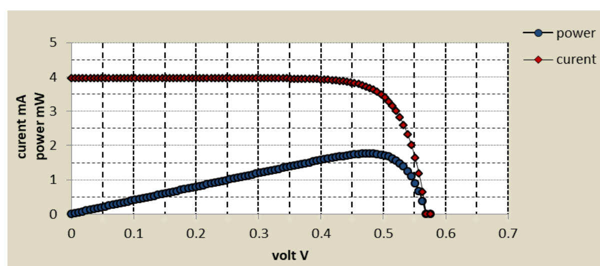

Figure: 9 TiO_2 cell behavior when using N749 Black Dye

Examination of the results given in Table (5), and represented in Fig. (9) shows that the resulting current begins with a value of 3.965 mA (Isc) and it remains constant until the voltage reaches 0.47 (V_{max}.); when current gradually decreases till it reaches a zero value at 0.569 Volt. On the other side, power starts at zero and it increases gradually until it reaches its maximum value of 1.748 mW (P_{max}) at 0.569 Volt and then it gradually decreases to zero.

Thus, experimentation on different dyes shows that when working in the voltage range 0 - 0.577V, values of the resulting current were 5.711, 4.836, and 3.965 mA for N.3, N.719, and N.749 Black Dye, respectively. These values of current remained constant with increasing voltage until voltage values of 0.436, 0.4, and 0.47V; for the three dyes, respectively. This means that a higher current is obtained from N.3 dye followed by N.719 dye and finally by the black dye. The values of the maximum power obtained were 2.223, 1.832, and 1.748 mW for N.3, N.719, and black dye, respectively and this confirms the previous finding of Nam, et al. [12].

The efficiency of the TiO_2 cells was 5.56, 4.58, and 4.37% when using N.3, N.719, and N.749 Black Dye, respectively. Thus, the efficiency of N.3 cell is 21.39% higher than that of N.719 and is 27.2% higher than the efficiency of the cell manufactured with black dye.

3.2 Effect of dye concentration:

3.1.4 Results of using TiO2 as a semiconductor with dye concentration 50%:

The results of this test are given in Table (6) and Fig. (10).

Table 6. Cell behavior of TiO_2 as a semiconductor with dye concentration 50%

Variable	Value
T_{op}, °C	20
T_{ref}, °C	0
G, W/m^2	1000
A, m^2	0.04
I_{sc}, mA	5.226
V_{oc} volt	0.58
V_{maxm} volt	0.49
I_{max}, mA	4.9
P_{max}, mA	2.401
FF	79.21
eff. %	6.002

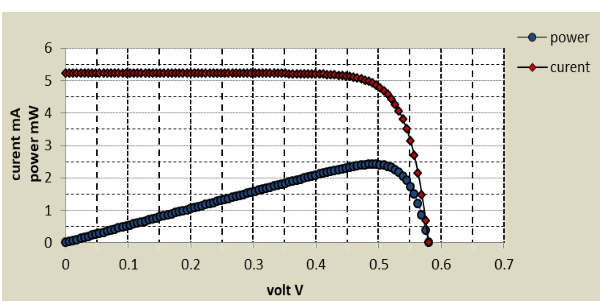

Figure 10: Cell behavior of TiO_2 as a semiconductor with dye concentration 50%

Examination of the figures in Table (6) and the shape of Figure (10) indicates that increasing voltage in the initial stages of the experiment does not affect the value of current which keeps constant at 5.712 mA (I_{sc}). When the voltage reaches a value of 0.581V (V_{oc}) current gradually decreases till it reaches a zero value at voltage 0.46V (V_{max}).

The attitude of the change of power with voltage was different. The value of power increased gradually with increasing voltage till it reaches 2.438 mW (P_{max}) at 0.581 Volt (V_{oc}) after which the value of power decreases with increasing voltage till it reaches a zero value at the maximum voltage of 0.46V (V_{max}).

3.1.5 Results of using TiO2 as a semiconductor with dye concentration 40%:

The results of this test are given before in Table (2) and represented graphically in Figure (7).

3.1.6 Results of using TiO_2 as a semiconductor with dye concentration 30%:

The results of this test are given in Table (7) and are represented graphically in Fig. (11).

Table 7. Cell behavior of TiO_2 as a semiconductor with dye concentration 30%

Variable	Value
T_{op}, °C	30
T_{ref}, °C	0
G, W/m^2	1000
A, m^2	0.04
I_{sc}, mA	4.838
V_{oc} volt	0.574
V_{maxm} volt	0.44
I_{max}, mA	4.61
P_{max}, mA	2.028
FF	73.03
eff. %	5.071

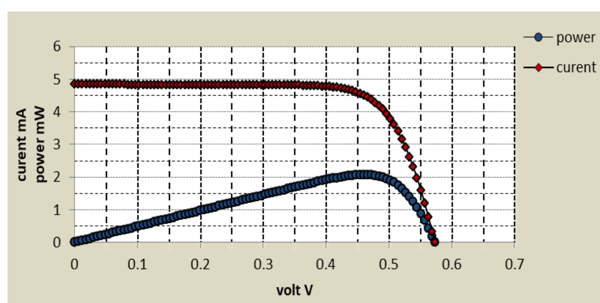

Figure 11: Cell behavior of TiO_2 as a semiconductor with dye concentration 30%

Examination of the figures in Table (7) and the shape of Figure 11 indicates that increasing voltage in the initial stages of the experiment does not affect the value of current which keeps constant at 5.712 mA (I_{sc}). When the voltage reaches a value of 0.581V (V_{oc}) current gradually decreases till it reaches a zero value at voltage 0.46V (V_{max}).

The attitude of the change of power with voltage was different. The value of power increased gradually with increasing voltage till it reaches 2.438 mW (P_{max}) at 0.581 Volt (V_{oc}) after which the value of power decreases with increasing voltage till it reaches a zero value at the maximum voltage of 0.46V (V_{max}).

The results of all tests run on different concentrations of dye are summarized in Table (7).

Table 8. Comparison behavior of different concentrations of dye

Table No.	**6**	**2**	**7**
Concentration of dye	50%	40%	30%
Isc	5.226	5.711	4.838
V_{oc}	0.58	0.577	0.574
V_{max}	0.49	0.436	0.44
I_{max}	4.9	5.1	4.61
P_{max}	2.401	2.223	2.028
FF	79.21	67.10	73.03
Eff.	6.002	5.56	5.071

From Table (8) it is clear that a DSSC fabricated with the use of 50% dye solution gives the highest performance; represented by a value for Filling Factor, FF, of 79.21 and a photoconversion efficiency of 6.002%. The attitude of the results of this test agrees with the work of Nabeel et. al, [13] and Kabir et. al, [14]; who worked on N.719 dye and found that increasing dye concentration positively affects the photoconversion efficiency of DSSC.

4 CONCLUSION:

The main achievements of the present study can be summarized in the following points:

1. Titanium dioxide nanoparticles have proved to be a good enough semiconductor for manufacturing Dye Sensitised Solar Cells (DSSCs)
2. Experimentation on three different dyes; N.3, N.719, and N.749 Black Dye showed that N.3 dye is the most efficient one; giving the highest FF and highest photoconversion efficiency. This is followed by N719 dye and finally by Black Dye".
3. Experimentation on different dye concentrations; 30, 40 and 50% showed that dye concentration 50% gives the best results with respect to the values of FF and conversion efficiency.
4. Thus, N.3 dye with a concentration of 50% gives the best performance for DSSC with FF value of 79.21 and photoconversion efficiency of 6.002%.

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Credit Authorship Contribution Statement

Aghareed M. Tayeb: Conceptualization, Review and editing, Investigation, Supervision.

Amr K. Harfoush: Methodology, Investigation, Supervision.

Tamer Melegy: Methodology, Writing an original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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