Green Dyes as Photosensitizers for Dye-Sensitized Solar Cells

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ABSTRACT

Dye-sensitized solar cells were fabricated using six natural dyes extracted from plant sources, namely: madder, khella, turmeric, alkanet, blood leaf, and lemon leaves. N3 dye and one of the eco-friendly organic dyes (Pyronin) have also been used in this study for the sake of comparison. The light absorption spectrum of the dye extract solutions as well as the wavelength of the maximum absorbance of the dye-loaded TiO2 film have been studied. The difference in the absorption characteristics is due to the different type of chromophores and colors of the extracts. Transmission electron microscopy analysis and the scanning electron microscope of the images of TiO2 film made with doctor blade technique shows that the diameter of the TiO2 particles was found in range of less than 25 nm. The electrical performance of the cells was investigated via current-voltage characteristic measurements. The fill factor of the cells sensitized with those natural dyes is close to that of the cell fabricated using the N3 dye.

Key words: Green Dyes, photosensitizers, Solar Cells.

Introduction

The conversion of solar energy to electricity appears as one of the technologies that can replace fossil fuels. The dye-sensitized solar cell is at present the only serious competitor to solid state junction devices for the conversion of solar energy into electricity (Otaka et al. 2004) and (Choi et al., 2007).

The dye sensitized solar cell (DSSC) is a photovoltaic device for the conversion of visible light into electricity, based on the sensitization of wide band gap semiconductors (Balraju et al., 2009). Light is absorbed by the dye sensitizer, which is anchored to the surface of a wide-band-gap semiconductor. Charge separation takes place at the interface via photoinduced electron injection from the dye into the conduction band of the nanocrystalline solids which are metal oxides, especially titanium dioxide. The performance of the cell mainly depends on the dye used as sensitizer. The absorption spectrum of the dye and the anchorage of the dye to the surface of TiO2 are important parameters determining the efficiency of the cell (Otaka et al. 2004).

Transition metal coordination compounds (ruthenium polypyridyl complexes) are used as the effective sensitizers, due to their intense charge-transfer absorption in the whole visible range and highly efficient metal to ligand charge transfer. However, ruthenium polypyridyl complexes contain a heavy metal, which is undesirable from point of view of the environmental aspects. Moreover, the process to synthesize the complexes is complicated and costly (Wongchareea et al., 2007). Alternatively, natural dyes can be used for the same purpose with an acceptable efficiency. The advantages of natural dyes include their availability, environmental compatibility and low cost (Hao et al., 2006), (Yamazaki et al., 2007) and (Lai et al., 2008).

The purpose of this study is to manufacture dye sensitized solar cells by means of a simple technique and to examine whether it is possible to sensitize them with plant extract-based dyes instead of the commonly used ruthenium-based dyes which are expensive and known to be highly toxic. Six natural dyes extracted from plant sources, namely: madder, khella, turmeric, alkanet, blood leaf, and lemon leaves have been used in this study. For comparison and evaluation purposes, N3 dye and one of the eco-friendly organic dyes (Pyronin) have also been used.

2. Experimental methods

2.1. Materials:

Ruthenium 535 (N3), purchased from Solaronix Company, Pyronin standard Fluka for microscopy from Sigma-Aldrich, CAS 92-32-0, C.I. 4500. All the plants and herbs were obtained from a local market in Egypt. The conductive glass plates (FTO, 18 Ω/cm2) was received as a gift from Pilkington Kappa Energy, USA. The Pt catalyst was obtained from solaronix in the form of Platisol. Titanium (IV) oxide, anatase nanopowder, < 25
nm particle size, 99.7% trace metals basis obtained from Aldrich, product number 637254. All the solvents and the chemicals employed for the experiments were of laboratory grade chemicals.

2.2. Preparation of dye-sensitizer solutions:

The dyes based on Ruthenium and Pyronin were used as delivered. The concentration of the Ruthenium-based dye used was 0.3 mM in pure ethanol (99.5%) and 0.3 mM of Pyronin in distilled water (Hedbor and Klar, 2005) and (Chena et al., 2007).

The dye solutions of turmeric (Mandal et al., 2007), and alkanet (Tiwari and Vankar, 2001), were extracted from dried powder. 10 g turmeric, 5 g alkanet were separately immersed in 100 ml of acetone (pure). Both turmeric and alkanet solutions were left shaken for 24 hours. Thereafter the powder-acetone-mixtures were filtered successively with sieves to remove powder then by filter paper to remove finest residue.

The dye solution for lemon leaves was prepared by adding 10 g of chopped leaves to 100 ml of extra pure methanol and left over night shaken. The dye solution was then filtered.

The dye solutions for Khella seeds (Ammi visnaga), Madder and Bloodleaf were prepared by refluxing in deionized water, (10g/100ml), (3g/40ml) and (1g/15ml) respectively. Both Khella seeds and Mudder were refluxed for 1 hour and Bloodleaf for only 30 min. Then the dye solutions were filtered.

2.3. Preparation of TiO2 electrode (photoanode) and counter electrode:

The photoanode was prepared by depositing TiO2 film on the conducting glass. Prior to the film deposition the glass substrate was prepared by cleansing with 95% ethanol solution, and left to dry in air (Chena et al., 2007). Then treated with 0.2M TiCl4 solution for half an hour at 70 °C (Halme, 2002) and (Hedbor and Klar, 2005). The edges of the conductive glass were then masked with a scotch tape to give an active area of 0.25 cm2.

The TiO2 paste was prepared by the incremental addition of 3 ml of deionized water and 0.02 ml acetylacetone to 1 g of TiO2 powder and 20 wt% (with respect to TiO2 wt) of PEG (Poly ethylene glycol MW 20,000) was added as a binder, then grinding for 30 min. (Overstraeten and Mertens, 1986) and (Hedbor and Klar, 2005).

The TiO2 paste was spread uniformly on the substrate by doctor blade technique. The TiO2 layer was sintered for 30 min at 450 °C. The TiO2-coated conductive glass is allowed to slowly cool to room temperature, and can be stored for later use (Smestad, 1998) and (Chena et al., 2007).

The counter electrode was prepared by dropping two drops of the Platisol solution on the conductive, and heated at 450 °C for 30 min, then left to cool down to near room temperature before usage, and can be stored for later use (Smestad, 1998).

2.4. Preparation of electrolyte:

The electrolyte was prepared by dissolving I2 (0.05M) and KI (0.5M) in water-free ethylene glycol (Wongchareea et al., 2007).

2.5. The sensitization process:

The TiO2-coated conductive glass at 80 °C was dipped in the dye for 24 hour in a dark place. The substrates were then rinsed with 95% ethanol solution for N3, acetone for turmeric and alkanet, and deionized water flowed by absolute ethanol for the other TiO2 sensitized films. Thereafter they were left to dry and immediately used in mounted cells (Halme, 2002).

2.6. Assembling the solar cell:

The two electrodes, photo and counter electrodes were clipped together facing each other using two clips and one or two drops of the iodide/iodine electrolyte solution can then be placed at the edges of the plates. The two binder clips are alternately opened and closed while in place. The liquid is drawn into the space between the electrodes by capillary action, and can be seen to ‘wet’ the stained TiO2 film (Smestad, 1998) and (Tiwari and Vankar, 2001).

3. Characterization and measurements:

3.1. TiO2 characterization:

**Transmission electron microscopy (TEM);**

For measuring the TiO2 particles diameter, TEM-JEM-1230-JEOL Co.-Japan made was used.
**Scanning electron microscope (SEM):**

Surface characteristics of TiO2 films were observed by scanning electron microscope JEOL Model JXA-840A, Electron Probe Microanalyzer. Films were made by doctor blade (with doctor blade) on microscopic glass slides and sintered at 450°C. Then prepared for the SEM analysis by depositing gold particles on the TiO2 films.

**3.2. Spectral properties measurements:**

- The UV-VIS light Absorbance for dyes solutions were measured using a UNICAM UV 300 spectrophotometer from Thermo Electron Corporation.
- Maximum absorbance wavelength, $\lambda_{\text{max}}$, of TiO$_2$-sensitized films with dyes were measured by reflection measurements using the Hunter Lab UltraScan PRO.

**3.3. Photoelectric characterization of DSSCs (I-V curves):**

- The electrical parameters, currents and voltages of the prepared solar cells for photoelectric characterization their current-voltage, I-V, curves were measured using appropriate current and voltage transducers.
- A multi-range current transducer LA 25-NP is used to measure the load current via converting the DSSC current into a voltage signal (from 0 to 5 V) to be suitable for reading by the AD card.
- For the voltage measurements, a current proportional to the measured voltage must be passed through an external resistor, which is installed in series with the primary circuit of the transducer. The used voltage transducer is a bipolar LV 25-P voltage transducer, with galvanic isolation between the primary circuit (high voltage) and the secondary circuit (low voltage).
- A thermopile pyranometer of type Kipp & Zonen (model CM5-774035) is used to measure the solar radiation intensity. The pyranometer is mounted at the DSSC structure and parallel to it. All measurements were carried out under natural sun light illumination fixing its intensity to 900 W/m$^2$. All measurements were done during the early hours of the day.

Based on I–V curve, the fill factor (FF) of the solar cell is defined as (Ahmad, 1996):

\[
\text{FF} = \frac{V_{\text{mp}} \cdot I_{\text{mp}}}{V_{\text{oc}} \cdot I_{\text{sc}}} = \frac{P_{\text{max}}}{V_{\text{oc}} \cdot I_{\text{sc}}}
\]

where;
- FF: fill factor of the solar cell, is the ratio of the maximum output power from the solar cell to the theoretical maximum power. It determines the shape of the I-V curve for the solar cell. Its value is always less than unity.
- $V_{\text{mp}}$: Solar cell photovoltage at maximum power point, V.
- $I_{\text{mp}}$: Solar cell photocurrent at maximum power point, A.
- $P_{\text{max}}$: Solar cell maximum power, W.
- $V_{\text{oc}}$: Solar cell open-circuit photovoltage, V.
- $I_{\text{sc}}$: Solar cell short-circuit photocurrent, A.

The overall energy conversion efficiency ($\eta$) is defined as:

\[
\eta = \frac{P_{\text{max}}}{A_T \cdot G}
\]

where;
- $A_T$: Solar cell area, m$^2$.


Results and Discussion

4.1. TiO2 characterization

Transmission Electron Microscope (TEM):

Fig. 1 shows the TiO\textsubscript{2} particles by TEM analysis. The diameter of the TiO\textsubscript{2} particles was found in range of less than 25 nm. These data are in complete correlation with the data obtained from a previous study (Halme, 2002), for the TiO\textsubscript{2} powder purchased from Aldrich of product number 637254.

![Fig. 1: TEM analysis of TiO\textsubscript{2} nano particles.](image)

Scanning Electron Microscope (SEM):

The SEM images of TiO\textsubscript{2} films were shown in Fig. 2. The image show that all of TiO\textsubscript{2} particles are in nanometer size. The measured thickness was found about 4\(\mu\)m for the TiO\textsubscript{2} film made with doctor blade.

![Fig. 2: SEM analysis of TiO\textsubscript{2} films; (a) top image, (b) edges of TiO\textsubscript{2} films](image)

4.2. Absorbance Spectra:

Fig. 3 shows the UV/Vis. absorption spectra of the dye solutions applied in DSSCs in this work. From the figures it is clear that the difference in the absorption characteristics is due to the different type of chromophores and colors of the extracts. Fig. 4 shows pictures of the prepared cells.
Table 1 represents the wavelength of the maximum absorbance of the dye-loaded TiO$_2$ film for the dyes used in DSSCs (N3, madder, khella, turmeric, alkanet, bloodleaf, lemon leaves, and pyronin). After immersion of the TiO$_2$-coated electrode (photoanode) in the extracts, observable colors of TiO$_2$ films turned to deep fuchsia for pyronin dye solution, deep maroon for alkanet extract, deep orange for turmeric extract, deep red brick for madder extract, and deep red for blood leaf extract, but light green for lemon leaves extract (Smestad, 1998). Khella is based on coumarone in structure, while lemon leaves is based on Chlorophyll. Meanwhile, chlorophyll absorbs most strongly in the blue and red portions of the absorption spectrum, but poorly in the green, hence the green color of chlorophyll-containing tissues, such as plant leaves. The absorption peaks of the commercial chlorophyll dye and the natural dye are centered at the wavelengths of about 665 and 670 nm, respectively. The chlorophyll molecules tend to aggregate in polar solvents and both exhibit hypochromic shift upon aggregation (Lai et al., 2008).

Spectral shown in Fig. 3 for khella and lemon leaves are similar and having two absorption peaks. They display strong absorption in the visible region. The absorption peaks were 465 and 650 nm for khella, and 475 and 675 nm for lemon leaves. The absorption range for khella on TiO$_2$ film in Table 1 shows blue-shifted vibronic absorptions (from 465 to 410 nm) which attribute to the aggregate formation of dyes and/or the disarraying of dyes on the surface of TiO$_2$ film, although a blue shift is also noticed in case of lemon leaves (from 475 nm to 390 nm) but this may be attributed to the linkage between the ester groups in chlorophyll and TiO$_2$ surface (Liu et al., 2008).
The visible absorption band also shifts to lower energy upon complexation with metal ions. Adsorption of turmeric, madder and alkanet to the semiconductor TiO₂ surface is a quick reaction, forming a very strong complex showing prevalently the quinonodial form (Wongchareea et al., 2007). This chemical reaction is the result of alcoholic bound protons which condense with the hydroxyl groups present at the surface of nanostructured TiO₂ film with the contribution of the chelating effect due to the two nearest hydroxyl groups towards Ti (IV) sites on the semiconductor nanocrystalline layer.

Due to carbonyl group and hydroxyl in curcumin, a chelating bond was produced as the curcumin molecule stays in the enol form as more stable state. Also in alizarin in madder extract chelation occurs due to carbonyl and hydroxyl groups in the anthraquinone structure and the same for alkanin in alkanet extract (Wongchareea et al., 2007), and hence absorbance peak was shifted to a shorter wave length. The data in Fig.3 and Table 1 shows that the wavelength is shifted from 460 nm to 415 nm upon absorption of turmeric dye solution on the TiO₂ film, which confirms this complexation reaction. This phenomenon holds also true in case of madder (λ_{\text{max}} is shifted from 540 to 460 nm), turmeric (λ_{\text{max}} is shifted from 460 to 415 nm), and alkanet (λ_{\text{max}} is shifted from 525 to 405 nm). A stronger chelating bond was produced between TiO₂ and carboxyl groups in iresinin in blood leaf extract (Cai et al., 2005) and (Zhang et al., 2008), however a weaker bond occurred between carbonyl groups in khellin and visnadin of khella extract and TiO₂ film surface due to the absence of the hydroxyl groups in their structure (Wongchareea et al., 2007).

### Table 1: Maximum absorbance wavelength (λ_{\text{max}}) of used natural dyes in solution and on TiO₂ films.

<table>
<thead>
<tr>
<th>Dye/Plant</th>
<th>Dye Structure</th>
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</thead>
<tbody>
<tr>
<td>Madder</td>
<td><img src="image" alt="Madder Structure" /></td>
</tr>
<tr>
<td>Khella</td>
<td><img src="image" alt="Khella Structure" /></td>
</tr>
<tr>
<td>Alkanet</td>
<td><img src="image" alt="Alkanet Structure" /></td>
</tr>
<tr>
<td>Turmeric</td>
<td><img src="image" alt="Turmeric Structure" /></td>
</tr>
<tr>
<td>Bloodleaf</td>
<td><img src="image" alt="Bloodleaf Structure" /></td>
</tr>
<tr>
<td>Lemon leaves</td>
<td><img src="image" alt="Lemon leaves Structure" /></td>
</tr>
<tr>
<td>Pyronin</td>
<td><img src="image" alt="Pyronin Structure" /></td>
</tr>
</tbody>
</table>
The maximum absorption of the TiO$_2$/pyronin is apparently formed of two components contribution and slight wavelength shift with respect to pyronin is observed, 525-535 nm, thus indicating a negligible ground state charge transfer at the interface formed between TiO$_2$ and pyronin, and red shift occurred (Balraju et al., 2009). A requirement for the dye structure is that it should possess several O or –OH groups capable of anchoring to the Ti (IV) sites on the TiO$_2$ surface. The molecular structure of pyronin dye shown in Table 1, exhibits the etheric oxygen group, which is responsible for the transferring of excited electrons into TiO$_2$. However, the bond wasn’t that strong as it occurs between carboxyl groups of N3 dye (Tiwari and Vankar, 2001) and (Wongchareea et al., 2007).

4.3. DSSC Electrical Characteristics:

Current density:

Fig. 5 shows the current densities of the prepared cells. From the figure, it is clear that, the highest value was obtained for the N3 dye (1.168 mA/cm$^2$). Also the current density for pyronin, the synthetic dye, is close to that of madder (0.5 and 0.54 mA/cm$^2$ respectively), knowing that alizarin is the predominant dye in the madder extract (Halme, 2002), then comes khella extract which contains coumarin compounds, then curcumin which is extracted of turmeric (0.288 mA/cm$^2$), and at last comes three dyes close to each other in value, chlorophyll which extracted from lemon leaves, then iresin which is extracted from bloodleaf then alkannin which was extracted from alkanet root (0.272, 0.260, 0.268 mA/cm$^2$).

This difference in the current densities of the cells is due to the difference in the structure of the dyes of each cell, and how fast the charge is injected into the conduction band of the nc-TiO$_2$ film and this is affected by the type of attraction between the sensitizer and its anchoring group with the porous nc-TiO$_2$ film.

![Fig. 5: Current densities, J$_{sc}$, of cells for different dyes used, at a solar radiation 900 W/m$^2$.](image)

Open circuit voltage:

Fig. 6 shows the open circuit voltage, V$_{oc}$, of cells for different dyes used. From the figure, it is clear that cells sensitized with chlorophyll show the highest open circuit voltage (0.529 V) and turmeric was close to this value, then comes N3 dye (0.457 V), then madder (0.389 V) which is close to that of alkanet extract sensitized cell, then at last the bloodleaf extract sensitized cell having the smallest open circuit voltage value of 0.267 V.
Dyes

Fig. 6: Open circuit voltage, $V_{oc}$, of cells for different dyes used, at a solar radiation 900 W/m$^2$.

Maximum output power:

Fig. 7 shows the maximum output power versus dye/plant type at a solar radiation 900 W/m$^2$. It is clear that the maximum power of the natural dyes is less than that for N3. However, it is almost equal to the maximum power for Pyronin dye which is synthetic.

Dyes

Fig. 7: Maximum output power, $P_{max}$, of cells for different dyes used, at a solar radiation 900 W/m$^2$.

The maximum power for bloodleaf and alkanet extracts sensitized cells was equal, 0.03 mW/cm$^2$, for pyronin and madder extracts sensitized cells is equal, 0.09 mW/cm$^2$, for khella extract sensitized cell is 0.049 mW/cm$^2$, for lemon leaves extract sensitized cell was 0.04 mW/cm$^2$, for turmeric extract sensitized cell was the smallest value which is 0.028 mW/cm$^2$.

Fill factor:

The corresponding fill factor, FF, of the cells is shown in Fig. 8. From the figure, we can see that the highest fill factor was obtained for cells sensitized with N3 cell and the values were close to each other, for pyronin and madder, 0.66 and 0.69 respectively, for khella and turmeric, 0.47 and 0.48 respectively, N3 and lemon leaves, 0.76 and 0.74 respectively, alkanet and bloodleaf are equal, 0.46 for each.
**Cell efficiency:**

Fig. 9 shows the efficiency of cells for different dyes used. The figure shows that the N3 dye cell has the highest efficiency, 0.52%, which nearly correlates with previous literature (Tiwari and Vankar, 2001), then pyronin and madder, 0.11 and 0.10% respectively, then khella and lemon leaves cells, 0.05 for each, and the lowest value was for turmeric and alkanet 0.03% for each.

**Current-voltage characteristics:**

Figs. 10 shows the I-V curves for the six natural dyes chosen. The dyes extracted from them promote the sensitization to the nc-TiO2 film but with different photoelectric conversion efficiency even most of them depends basically on the chelation/anchoring with/to the TiO2 nanoparticles through ‘-OH’ and ‘>-C=O’ groups and this is due to the difference in the spectral absorption range, the maximum absorption in solution, and the different direction of their shift on the TiO2 mesoporous layer.

For comparison, Fig. 11 shows the I-V curves for pyronin and rutheinim (N3) dye. Pyronin is a synthetic dye and used here to set a comparison between its behavior as a synthetic organic dye and the natural dyes behavior on the TiO2 and in the cell. Ruthenium (N3) dye is a metal complex dye which effectively delivers electrons injected to the TiO2 mesoporous film. It is used as a reference dye, as found in the literature (Tiwari and Vankar, 2001), (Hedbor and Klar, 2005) and (Hao et al., 2006).

In general, all the cells show a smooth uniform trend for their I-V curves, in correlation with the literature information for other DSSCs and silicon cells and that is as a result of the good fill factor of all cells under study, (Overstraeten and Mertens, 1986).

The performance of the non-purified natural dyes was close in case of madder extract (Fig. 10-e) to the pyronin sensitized cell performance in Fig. 11, this is because madder extract contains the alizarin dye with high percentage giving intense red color to TiO2 film and from the spectral absorption results the madder extract found to have maximum wave length close to that of pyronin (540 and 525 nm for madder and pyronin respectively). Nevertheless they had different shift of their maximum wave length on the TiO2 film (460, 535 nm for madder and pyronin respectively) and this is due to the different way of anchoring/chelation way of the active groups in each dye, as mentioned above in the spectrometry section.

Also the performance for alkanet extract sensitized cell close to that of bloodleaf sensitized cell, Fig. 10-b,d respectively, although both have the less performance among the cell in this study. This closeness is attributed to
the low performance of alkannin in the alkanet due to its shorter absorbance band and the low performance of
the iresinin in the bloodleaf extract even though it has 'COOH' as chelating group which is well known to be the
best chelating group, but the dye also has a shorter absorbance band, as shown in Fig. 3.

![Graphs](a) (b) (c) (d) (e) (f)

**Fig. 10:** Current-voltage, I-V, curves for solar cells sensitized by:
(a) Khella, (b) Alkanet, (c) Turmeric, (d) Bloodleaf,
(e) Madder, (f) Lemon Leaves.

For khella extract sensitized cell and turmeric extract sensitized cell we see a moderate performance, Fig.
10-a and 10-c. The anchoring group of both active components in their extract, ( -O-, =CO, and -OH' for khella
and turmeric respectively), though they have the same shift direction on TiO₂ film, to shorter wave length and
close to each other too ('465, 650' to '415' for khella, and for turmeric extract is '460' to '410', Table 1) and this
attributes to their alike behavior.

N3 dye has the highest performance among all dyes under study, and this is due to the effective injection of
N3 on TiO₂ film through the carboxylic (−COOH) groups of its ligands via metal to ligand charge transfer
(MLCT). Also, N3 dye has a broad band absorption allowing it to sensitize TiO₂ film more effectively than the
other dyes in this study.

Chlorophyll structure, which represents lemon leaves extract, resembles N3 as it has also a central metal
atom complexed with ligands, though its performance was far from the N3 cell behavior for spectral aspects as
was seen in spectral absorption section. This may be due to the absence of the effective chelating group, i.e., −
COOH group, as in case of N3 dye and depending on its ester group in chelation which is far effective to the
carboxyl group. Thus the chlorophyll showed lower photoelectrochemical performance due to its lower affinity
to the surface of TiO$_2$ film (Yamazaki et al., 2007).

Fig. 11: Current-voltage, I-V, curves for solar cells sensitized by (a) Pyronin, (b) N3 dye

Table 2 presents and summarizes the performance of the DSSCs in terms of short-circuit photocurrent densities, \( I_{sc} \), open-circuit voltage, \( V_{oc} \), fill factor, FF, maximum power output, \( P_{max} \) and energy conversion efficiency, \( \eta \).

<table>
<thead>
<tr>
<th>Dye</th>
<th>( J_{sc} ) (mA/cm$^2$)</th>
<th>( V_{oc} ) (V)</th>
<th>FF</th>
<th>( P_{max} ) (mW/cm$^2$)</th>
<th>( \eta ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Madder</td>
<td>0.540</td>
<td>0.389</td>
<td>0.69</td>
<td>0.090</td>
<td>0.10</td>
</tr>
<tr>
<td>Khella</td>
<td>0.384</td>
<td>0.437</td>
<td>0.47</td>
<td>0.049</td>
<td>0.05</td>
</tr>
<tr>
<td>Turmeric</td>
<td>0.288</td>
<td>0.529</td>
<td>0.48</td>
<td>0.028</td>
<td>0.05</td>
</tr>
<tr>
<td>Bloodleaf</td>
<td>0.260</td>
<td>0.267</td>
<td>0.46</td>
<td>0.030</td>
<td>0.04</td>
</tr>
<tr>
<td>Alkanet</td>
<td>0.268</td>
<td>0.372</td>
<td>0.46</td>
<td>0.030</td>
<td>0.03</td>
</tr>
<tr>
<td>Lemon Leaves</td>
<td>0.286</td>
<td>0.539</td>
<td>0.74</td>
<td>0.040</td>
<td>0.05</td>
</tr>
<tr>
<td>Pyronin</td>
<td>0.504</td>
<td>0.310</td>
<td>0.66</td>
<td>0.090</td>
<td>0.11</td>
</tr>
<tr>
<td>N3</td>
<td>1.168</td>
<td>0.457</td>
<td>0.76</td>
<td>0.460</td>
<td>0.52</td>
</tr>
</tbody>
</table>

Obviously, the efficiency of the cell sensitized by the Ru-complex dye is significantly higher than that sensitized by the natural extracts. This is due to a higher intensity and broader range of the light absorption of the N3 on TiO$_2$.

The measured sunlight to electricity conversion efficiencies of the natural dyes used here were quite low compared to the published efficiencies obtained with synthetic dyes, e.g. coumarins and indolines, (Hara et al., 2003) and (Schmidt-Mende et al., 2005). Nevertheless, the efficiencies of the natural extract sensitized cells are quite close to that of the pyronin synthetic dye, and so these extracts can be used as a cheap study tool for DSSC fabrication.

Conclusion:

Six natural dyes extracted from plant sources were used for making six dye-sensitized solar cells. The used dyes are extracted from; madder, khella, turmeric, alkanet, blood leaf, and lemon leaves. For comparison, N3
dye and one of the eco-friendly organic dyes (Pyronin) have also been used. The natural dyes were attached to the TiO$_2$ surface, and hence their maximum absorbance wavelength in solutions were shifted on TiO$_2$ surface accordingly. This shift was a good indication for the reaction of the natural dyes with the TiO$_2$ surface leading to a photoelectrochemical reaction when their cells exposed to light. The natural dyes extracted promote the sensitization to the nc-TiO$_2$ film but with different photoelectric conversion efficiency due to the difference in the spectral absorption range, the maximum absorption in solution, and the different direction of their shift on the TiO$_2$ mesoporous layer. The highest current density was obtained for the N3 dye (1.168 mA/cm$^2$), while the current density for pyronin is close to that of madder (0.5 and 0.54 mA/cm$^2$ respectively). The difference in the current densities of the cells is due to the difference in the structure of the dyes of each cell, and how fast the charge is injected into the conduction band of the nc-TiO$_2$ film and this is affected by the type of attraction between the sensitizer and its anchoring group with the porous nc-TiO$_2$ film. N3 dye cell has the highest efficiency, 0.52%, then pyronin and madder, 0.11 and 0.10% respectively, then khella and lemon leaves cells, 0.05 for each, and the lowest value was for turmeric and alkanet 0.03 % for each.

References