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Dye extracted from Bael leaves as a photosensitizer in dye sensitized solar cell

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Abstract

This study has explored a new plant source, Bael tree leaves, as an efficient dye extraction towards green energy harvesting through dye-sensitized solar cells (DSSCs). The photosensitizers, photo-absorption, bandgap, and ionic conductivity characteristics of the extracted dye were determined using thin-layer chromatography (TLC), ultraviolet-visible spectroscopy, Tauc plot, and conductivity meter, respectively. Chlorophyll is the main constituent in the extracted dye confirmed by TLC analysis. An optimum concentration (0.2 g ml⁻¹) with ionic conductivity of 455 μS cm⁻¹ of the dye was used as a photoactive layer in DSSC, demonstrating power densities of 1.345 μW m⁻² and 8.078 μW m⁻² under the illumination of the LED lamp (1555 lx) and tungsten bulb (1926 lx), respectively. Additional parameters, including fill factor (0.26), ideality factor (1.25), characteristic resistance (309 Ω), series resistance (313 Ω), and shunt resistance (662 Ω) of the fabricated DSSC under tungsten illumination reveal that the novel Bael tree leaves-based dye can harvest green energy efficiently through DSSCs.

Introduction

Solar cells are certainly one of the most promising technologies in converting solar energy into electricity. To provide a convenient and equivalent testing environment for solar cells, traditionally tested under one Sun condition (100 mW cm⁻²) that is typically equivalent to 100,000 lx for simulating the outdoor conditions. However, indoor light is considered low or dim due to the low photon flux intensity, ranging from 300 to 2400 lx in offices and reading rooms [1].

Dye-sensitized solar cells (DSSCs) are one of the most promising indoor energy harvesting technologies. These can work effectively in low light such as the cloudy sky, indirect sunlight, or any light source found in the interior [1–4]. However, the low efficiency and stability have prevented them from existing in the bulk electricity power generation for outdoor applications [5]. Research on natural photosensitizers has been attractive for DSSCs due to easy and economical extraction and also being environmentally friendly. In nature, fruit, vegetable, and plant leaves have colorants that can be easily separated and employed in DSSCs [6]. The cells performance mainly depends on light source [4, 7], electrodes [8–10], dye [11, 12], and electrolyte [13].

Poulose & Sreejaya, 2018 [4] showed that the pomegranate juice–based DSSC tested under fluorescent light yielded a higher value of open-circuit voltage (V OCC) than diffused light among the three low light intensity sources, i.e., 35 W tungsten halogen lamp (430 lm), 12 W LED (40–45 lm), and mobile phone flashlight (60–80 lm). The DSSC under halogen lamp considerably provided the highest value of VOC. These VOC values exponentially increased as the distance between the cell and light sources decreased under constant light intensity [4]. Also, the rosella flower extracted dye-based cell tested under a 150 W halogen lamp enhanced the short circuit current (Isc). VOC and efficiency (η) decrease as the light source distance from DSSC decreases [14].
The papaya leaves extract-based DSSC tested under solar illumination (1.5 AM), cool daylight, and warm white LED. In these cases, the best values of $I_{SC}$ and $V_{OC}$ were observed under solar irradiation, and the cool daylight produces more $I_{SC}$ and $V_{OC}$ than warm LED [15]. However, no international standardization is used to characterize the solar cell for indoor applications [16].

The natural extract from plant materials at various concentrations is becoming a new pathway to obtain sensitizing pigments. Increasing dye concentration, increased absorption, exciton generation, and dye adsorption on the TiO$_2$ surface improved the electron injection that initiates the $I_{SC}$ in the circuits [6, 17]. The performance of red cabbage-based DSSC increased by increasing the dye concentrations to the optimum level [18]. An increase in the dye concentration up to the optimum level, increases the number of inactive dye molecules due to aggregation on the surface of TiO$_2$, hence blocking the electron injection process and consequently reducing the efficiency [19]. Interestingly, the variations of concentration of dye solutions derived from papaya leaves did not show a considerable effect on the energy bandgap, HOMOs, LOMOs values, and the IR-functional groups [19]. Moreover, the photosensitizer requires at least one of the following groups: carbonyl (CO), carboxylic (COOH), and hydroxy (OH) groups that are essential for stable adsorption onto the TiO$_2$ thin film [20].

Bael (Aegle marmelos) is a well-known Wood apple belonging to the Rutaceae family and widely used in traditional medicines. The plant extract analysis shows the presence of coumarin, tannins, and flavonoids biomolecules [21]. Further investigations of Bael leave organic extracts reported that aegeline (a type of alkaloid amide) and 1,3-dimethylamylamine are dominant active constituents of these leaves [22].

In this work, photosensitizer was extracted from the leaves of the Bael tree using the solvent extraction method and characterized by TLC, ultraviolet-visible spectroscopy, and ionic conductivity measurement. Here we first establish and report the current–voltage characteristic measurements of the dye under the illumination with the tungsten bulb and LED.

**Material and methods**

**Dye extraction**

Fresh leaves picked from the Bael tree were cleaned with tap water, dried in the open air at room temperature, and then grinding in an electrical grinder. 6 g of leaves powder soaked in 30 ml ethanol for 1 h and grinded with the help of mortar and pestle. Then, dye solution was diluted with ethanol in different ratios [1:4, 1:8, 1:12, 1:16, and 1:20 (V/V)] to observe the effect of dye concentrations on the optical and electrical (ionic) parameters. Insoluble particles were separated from the liquid using filter paper. Then dye solution (dark green with black shades) was stored in an ember-colored bottle to protect the dye from direct light.

**Electrodes**

For working electrode, first titanium dioxide (TiO$_2$) paste prepared by addition of 5 ml mixture of solvent (chloroform, ethanol and deionized water; 6.5:3.5:1.0) to 0.6 g commercially available TiO$_2$ powder dispersed in Agate mortar and pestle and then grinded till obtaining consistency paste. Then this paste was coated on fluorine-doped tin oxide (FTO) conductive glass by the doctor blade technique. Then this TiO$_2$ thin film is heated in the muffle furnace at 460 °C for 15 min. After cooling, this film was submerged into extracted photosensitizer for 24 h.

For a counter electrode, graphite paste in ethanol was bladed on FTO glass using the same technique and then heated in the muffle furnace at 460 °C for 15 min.

**Cell assembly**

A drop of the electrolyte solution [comprising iodide/iodine as a source of (I$^-$/I$_3^-$) and inorganic sodium nitrate salt in acetonitrile/water as solvent] was spotted separately between the working and counter electrodes using capillary to avoid leakage. Then both electrodes were clamped together into a sandwich-type cell using two paper binder clips. The schematic diagram of the DSSC fabrication process is shown in figure 1.

**Characterization techniques**

Thin-layer chromatography was used to identify the presence of photosensitizers through the separation of different pigments in the dye. The extracted dye was characterized by using 60 F$_{254}$ TLC on the aluminum plate as a stationary phase. Initially, three tiny drops of the concentrated dye (0.2 g ml$^{-1}$) solution was put on the TLC plate at baseline using glass capillary and then dried at ambient conditions for 2–3 min. Then this plate was vertically immersed in the glass beaker containing solvent of chloroform, ethanol, and deionized water in the ratios (6.5:3.5:1) as a mobile phase for 12–15 min. After the mobile phase and pigment run, this plate was...
removed from the beaker and dried for 10 min. The active compounds of extracted dye were observed on the plates. The whole process of TLC development (step by step) is shown in figure 2.

Ultraviolet-visible (UV–vis) spectroscopy measurements were performed to investigate the radiation absorption by the extracted dye. The extracted dye solutions [1:4, 1:8, 1:12, 1:16, and 1:20 (V:V)] were characterized by UV–vis spectroscopy (UV-1800, Shimadzu photo-spectrometer) in the wavelength range of 300–700 nm at room temperature.

The ionic conductivity of the extracted dye (0.2 g ml$^{-1}$) and diluted solutions was measured at room temperature using a conductivity meter (Elico CM 180). For this the conductivity cell was cleaned thoroughly with deionized water before use. The conductivity cell was then immersed in a beaker containing the dye solution and moved up and down to remove the bubbles from the conductivity cell. During the measurements, the vent holes were submerged entirely in the dye solution. After then the cell constant was fixed at 1, and the
data read mode was turned on and set to measure conductivity. Finally, the conductivity value is observed directly by the meter. After each measurement, the conductivity cell was cleaned carefully with deionized water.

The current-voltage (I-V) characteristics of DSSC were recorded using Keithley source meter in the presence of LED lamp and tungsten bulb illumination. A specific arrangement of a carton box with dimensions 68 cm × 30 cm × 60 cm was made for I-V measurements. The light intensity was measured using the FLUKE 941 light meter at the cell location point. An active area of 2.565 cm² of the assembled cell was measured using Vernier Caliper.

**Results and discussion**

Thin-layer chromatography of extracted dye is shown in figure 2(c). It is observed that the separated pigments did not show regular circles after migration in the solvent, which indicates a concentrated amount on the TLC plate (figure 2(a)). However, a green/yellow color migration was observed. This color indicates the presence of chlorophyll and its derivatives pigments in the extracted dye [23]. The wide diffusion of color on the plate in different regions indicates the pigments’ activeness, which suggests that ethanol can be considered a suitable solvent for chlorophyll and its derivatives [24]. It is also clear that the three spots on the plate can be moved independently without affecting each other and indicate a single TLC plate can be used for different concentrations of the same or different pigments simultaneously.

UV-vis spectra of dye solutions in the range of 300 to 700 nm are shown in figure 3(a). In the UV region \((\lambda < 400 \text{ nm})\), one prominent absorption band was observed at wavelength 327 nm for all concentrations and indicating the presence of n-π* electronic transition in C=O or C=C functional groups (anchoring molecules) to facilitate their adsorption onto TiO₂ surfaces and enhancing the electron injection into TiO₂. These transitions can initiate the electrical circuit in DSSCs [25, 26]. Two prominent bands were observed in the visible region \((\lambda > 400 \text{ nm})\) at 410 nm (visible blue region) and 663 nm (visible red region) for all concentrations and indicating the presence of chlorophyll pigment in the dye solutions. These observed band positions are agreed and very close to the reported result on chlorophyll pigment extracted from Star Gooseberry leaves in ethanol solvent [12]. An additional three bands were also observed in the blue-red region at 505 nm, 536 nm, and 608 nm for all concentrations, indicating the pheophytin fraction (chlorophyll derivatives and/or degradation products) in the extract [27]. It is also clear from the inset of figure 3(a) that the absorbance is directly proportional to the dye concentration from Bael leaves and following Beer–Lambert Law [23].

The absorption bandgap of the extracted dye is the critical parameter to determine the spectral energy range in which the dye absorbs photons, which is an alternative means of current [6]. The type of optical transitions, the value of optical energy bandgap, and the band theory commonly describe the electronic transitions in organic dye and crystal molecular structure. In which the valence band is represented by the combination of the highest occupied molecular orbitals (HOMOs; \(\pi^*\) orbitals), whereas the conduction band is represented by the lowest unoccupied molecular orbitals (LUMOs; \(\pi^*\) orbitals) [28]. Through these contexts, the value of the optoelectronic energy bandgap \(E_g^{\text{opt}}\) of the organic dye can be obtained using \(E_g^{\text{opt}} \approx 1240/\lambda\) [where \(\lambda = \lambda_{\text{max}}\) is the maximum wavelength and \(\lambda = \lambda_{\text{edge}}\) is the value of the absorption spectra in the direction of longer wavelength] [26], and Tauc assumptions for indirect transitions through \((\alpha h\nu) = C(h\nu - E_g)\) [here \(h\nu\) is the photon energy (in eV), \(C\) is a constant and \(\alpha\) is the absorption coefficient (in cm⁻¹)] [29]. The absorption coefficient \(\alpha\) can be calculated from the well-known formula \(\alpha = 2.303 A w^{-1}\) (where \(A\) is the absorbance, and \(w\) is the UV–vis cuvette width, equal to 1.0 cm) [30]. It is clear from these relations that the energy bandgaps can be obtained from concluding to zero, a linear part of a plot \((\alpha h\nu)^2 \text{versus } h\nu\), as shown in figure 3(b) for all concentrations. The values of \(\lambda_{\text{max}}\), \(\lambda_{\text{edge}}\), \(\alpha\), and \(E_g^{\text{opt}}\) were determined from the UV–vis spectra, Tauc plot method, and derivatives spectroscopy for dye 1:20 concentration is shown in table 1.

The first transition can be found in the low-energy regions (1–2.1 eV), representing the optical bandgap corresponding to the absorption in the blue, red regions or singlet excitation [24, 28]. It has been known that chlorophyll absorbs the photon and transfer their energy to the reaction center as ‘Excitons’ [24]. The second transition can be found in energy regions (2.2–4 eV), which represent the fundamental energy bandgap or the frontiers orbitals (HOMOs-LUMOs) in the chlorophyll pigment [24, 28]. These transitions indicate the presence of chlorophyll-a [31]. The first transition was found at 1.83 eV for all concentrations and agreed with the experimental and calculated bandgap of chlorophyll-a extracted in ethanol by Hedayatifar et al 2016 [24]. The second transition was observed at 2.75 eV, and the value agreed with the calculated bandgap of chlorophyll-a without the phytol group or pheophytin-a [32]. The \(E_g\) is close to the original TiO₂ bandgap (2.8–4 eV) regions [33]. The extracted dye can be absorbed light in the same wavelength range of TiO₂. Therefore, the dye can act as an optimal photosensitizer for DSSCs.
The third transition was observed at 3.36 eV for the lowest dye concentration 1:20 and decreases as the concentration of dye increases (figure 3(b)), indicating the optical behavior of dye solutions. This fundamental absorption at 3.36 eV occurs due to the excitation of electrons in the dye. The conventional Tauc plot method gives the approximate values of $E_g$, as shown in table 1. However, the Tauc equations assume an ideal parabolic band structure and in the case of broadening of the absorption edges, this method may underestimate the values of $E_g$\[34\]. Also, the Tauc method depends on the type of transition, as seen in table 1. Therefore, the corrected values of $E_g$ were determined by an alternative method using derivative spectroscopy of the absorbance (A) as the

![Figure 3](image-url)  

**Figure 3.** (a) UV–vis spectra of Bael leaves dye for various concentrations, and the inset of the figure indicates an absorbance variation with concentrations at 410 nm and 663 nm. (b) Tauc plot of various concentrations with inset of the figure shows the plot of \((\alpha h\nu)^2\) versus \(h\nu\), typically for 1:20 (V:V) concentration.

| Methods -- | Absorption spectrum | Tauc plot | UV–vis derivatives |
|---|---|---|---|
| | $A$ versus $\lambda$ | $1240/\lambda$ | $(\alpha h\nu)^2$ versus $h\nu$ | $dA/dE$ versus $h\nu$ | $d^2A/dE^2$ versus $h\nu$ |
| S. No. | $\lambda_{\text{max}}$ (nm) | $\lambda_{\text{edge}}$ (nm) | $\lambda_{\text{max}}$ | $\lambda_{\text{edge}}$ | $E_g^{\text{opt}}$ (eV) | $E_g$ (eV) | $E_g$ (eV) |
|---|---|---|---|---|---|---|---|
| 1 | 327 | 387 | 3.80 | 3.20 | 3.36 | 3.56 | --- |
| 2 | 410 | 471 | 3.02 | 2.63 | 2.75 | 3.02 | --- |
| 3 | 505 | 546 | 2.46 | 2.27 | --- | 2.35 | 2.45 |
| 4 | 536 | 570 | 2.50 | 2.18 | --- | 2.33 | 2.31 |
| 5 | 608 | 663 | 2.04 | 1.87 | --- | 2.04 | 2.05 |
| 6 | 663 | 681 | 1.87 | 1.82 | 1.83 | 1.88 | 1.87 |

The third transition was observed at 3.36 eV for the lowest dye concentration 1:20 and decreases as the concentration of dye increases (figure 3(b)), indicating the optical behavior of dye solutions. This fundamental absorption at 3.36 eV occurs due to the excitation of electrons in the dye. The conventional Tauc plot method gives the approximate values of $E_g$ as shown in table 1. However, the Tauc equations assume an ideal parabolic band structure and in the case of broadening of the absorption edges, this method may underestimate the values of $E_g$\[34\]. Also, the Tauc method depends on the type of transition, as seen in table 1. Therefore, the corrected values of $E_g$ were determined by an alternative method using derivative spectroscopy of the absorbance (A) as the
function of photon energy \( (E = h\nu) \). The first-order \( \frac{dA}{dE} \), and second-order \( \frac{d^2A}{dE^2} \), for all concentrations as shown in figures 4(a) and (b), respectively, and are given in table 1. It is clearly observed that the \( E_g \) values are the same for all concentrations, and the rate of absorbance, \( \frac{dA}{dE} \), and \( \frac{d^2A}{dE^2} \) increases as the concentration increase and strongly agree with the calculated value from UV–vis spectra at \( \lambda_{\text{max}} \) except the value at 3.36 eV due to the red-shifted toward 350 nm.

Specifically, the bands at 1.83 eV split into two negative and positive maxima’s in the first-order derivatives (figure 4(a)) and one sharp negative maximum with two positive small bands observed in the second-order derivatives (figure 4(b)). These two bands are called ‘satellite valleys’ (satellite bands), as shown in figure 4(b). These valleys can act as high-energy channels for electron transport in the DSSCs [35].

The Bael leaves dye exhibited intermediate transition bands at 2.33 eV (536 nm) and 2.55 eV (505 nm) corresponding to metal to ligand charge transfer (MLCT) states. These ligands were able to enhance the light-harvesting capacity of the dye by increasing their visible light absorption at low energy (MLCT at 2.33 eV). This circumstance causes a large electronic interaction (coupling) between the \( \pi^* \)-orbital of the ligand and the d-orbital of TiO\(_2\), resulting in electron injection from the dye into the conduction band (CB) of TiO\(_2\) [20, 35].

Figure 5 shows a schematic diagram of Beal leaves dye energy levels, electron transfer processes, and photocurrent generation in a DSSC. An interfacial charge transfer, electron transfer kinetics, charge carrier dissociation, and recombination in dye/TiO\(_2\) as described by Klein et al (2016) in DSSC containing N719 or B1 (MLCT at 525 nm). Ultrafast electron transfer from the MLCT photo-excited state of dyes to the conduction band of TiO\(_2\) can arise from a singlet (\(^1\text{MLCT}\)) state as well as from the triplet (\(^3\text{MLCT}\)) state as a result of the dye interacting with metal ions [36].

Ionic conductivity measurements were applied to determine the extracted dye is ionic or molecular compounds through a comparison of dye with ethanol shown in table 2. The higher conductivity values for the extract indicate that the dye is ionic. The ionic compound can easily break down into ions and conduct electricity. Therefore, ionic solutions are suitable to apply as sensitizers in DSSC applications [37].

Figure 4. (a) First derivative (\( \frac{dA}{dE} \)) and (b) second derivative (\( \frac{d^2A}{dE^2} \)) of UV–vis absorbance spectra of Bael leaves dye for various concentrations versus energy (\( E = h\nu \)).
maximum ionic conductivity of 455 μS cm⁻¹ was found for extracted dye (0.2 g ml⁻¹) and decreased from 145 μS cm⁻¹ (1 ml as the extracted dye in 4 ml ethanol) to 141 μS cm⁻¹ (1 ml as the extracted dye in 20 ml ethanol) with increasing concentration of solvent. The high conductivity indicates the presence of a high amount of Mg ions in the dye solutions. Arifin et al (2018) [38] also reported that the chlorophyll pigment contains magnesium ions in the centre of the porphyrin ring, and the high concentration contains more ions in the extracted dye. For the DSSC, short-circuit current and consequently efficiency was found proportional to the concentration of dye sensitizer up to optimum level. So, the more current was related to the more dye adsorption through the TiO₂ photoelectrodes [39]. Therefore, the dye solution with conductance of 455 μS cm⁻¹ was used to fabricate DSSC.

The current-voltage (I-V) and power voltage (P-V) characteristic curves are shown in figure 6. The value of the short-circuit currents (I_SC), open-circuit voltages (V_OC), maximum current (I_MP) and voltage (V_MP) was calculated from these curves. The fill factor (FF) and efficiency (η%) was calculated using the following formulas [40, 41]:

\[
FF = \frac{I_{MP} \times V_{MP}}{I_{SC} \times V_{OC}}
\]

Table 2. Ionic conductivity of solvent and extracted dye solutions for various concentrations.

| Compounds            | Concentration | Ionic conductivity (μS cm⁻¹) |
|----------------------|---------------|-----------------------------|
| Solvent (ethanol)    | 30 ml         | 0.73                        |
| Dye Solution         | 0.2 g ml⁻¹    | 455                         |
| Diluted dye solutions| 1:4 (V:V)     | 145                         |
|                      | 1:8 (V:V)     | 144                         |
|                      | 1:12 (V:V)    | 143                         |
|                      | 1:16 (V:V)    | 142                         |
|                      | 1:20 (V:V)    | 141                         |

Figure 5. The schematic diagram for electron transfer and charge carrier dissociation mechanism of Bael leaves dye/TiO₂ in a DSSC.
and

\[ \eta = \frac{I_{SC} \times V_{OC} \times FF}{I_{IN} \times A} \times 100\% \]

here, \( I_{IN} \) is the incident light intensity (\( W \text{ cm}^{-2} \)), irradiance, and \( A \) is the cell area (\( \text{cm}^2 \)). The illuminance rather than irradiance is the best way to quantify the level of light for an indoor environment but creates conversion problems [42]. There is no standard method for conversion between (lux, illuminance) and (\( W \text{ m}^{-2} \), irradiance) in the light spectrum because there is a different conversion factor for every wavelength that can be determined from the spectral analysis of the light composition [42, 43]. Taking into consideration the fact that the illuminance considers only the visible spectrum where 555 nm is the maximum considering wavelength, the spectral irradiance of the most room light sources show peaks near 550 nm, and the peak of the eye-sensitivity curve is mainly at 555 nm [3, 42]. Therefore, the irradiance can be approximately estimated from the following relation and can be used for efficiency calculations where the efficiency of the cell is not a critical point [42];

\[ I (\frac{W}{m^2}) = 1.464 \times 10^{-3} \times I(\text{lx}) \]

The maximum power is equal to \( I_{SC} \times V_{OC} \times FF \), and thus the efficiency is equal or very close to the photogenerated power density [7]. Therefore, to simplify the comparison, we report only the output power rather than the energy conversion efficiency, then it is easy to infer or confirm the best-suited conditions for device work, where the maximum power densities (\( P_{\text{MAX}} \)) can be calculated as [1];

\[ P_{\text{MAX}} = \frac{I_{MP} \times V_{MP}}{A} \]

The key performance parameters of DSSC under LED lamp and tungsten bulb were presented in table 3. It is clear from figure 6 and table 3 that all the observed values of \( I_{IN}, I_{SC}, V_{OC}, I_{MP}, V_{MP}, \) FF, and \( P_{\text{MAX}} \) for assembled DSSCs increase as light intensity (by the source of light) increase under LED illumination and tungsten bulb irradiation. It is clear also that the maximum photogenerated \( P_{\text{MAX}} \) seems to be proportional to the source of light and/or the light intensity. The key parameters of assembled DSSC are compared with different DSSCs as

![Figure 6. Current and power versus voltage characteristics of DSSC illuminated under (a) LED lamp and (b) tungsten bulb.](image-url)
| Light Source | I$_{IN}$ (lx) | I$_{IN}$ (W/m$^2$) | ISC ($\mu$A) | VOC (mV) | IMP ($\mu$A) | VMP (mV) | FF | P MAX ($\mu$W/m$^2$) | $\eta$% | References |
|-------------|--------------|--------------------|-------------|----------|-------------|---------|----|---------------------|-------|------------|
| LED Lamp    | 1555         | 2.28               | 1.36        | 1.00     | 0.69        | 0.50    | 0.25| 1.345               | 0.058 | Present work |
| Tungsten Bulb | 1926         | 2.82               | 4.92        | 1.65     | 2.59        | 0.80    | 0.26| 8.078               | 0.273 | Present work |
| Tungsten halogen lamp | — | 30,000             | 2.10        | 363      | —           | —       | —  | ~651               | —     | —          |
| White light | 100,000      | 833                | 63.2        | 159      | 37.4        | 96.0    | 0.36| —                  | —     | [43]       |
| LED Lamp    | 30,000       | —                  | 2.10        | 363      | —           | —       | —  | —                  | —     | —          |
| Tungsten halogen lamp | — | 300                | 175         | 360      | —           | —       | —  | —                  | —     | [8]        |
reported in the literature, as shown in table 3. The fabricated DSSC illuminated under tungsten bulb shows
better performance than the jatropha leaves-based DSSC illuminated under (30000 lx) may be due to better
transparency and low resistance of FTO relative to ITO surface for visible light and difference in thickness of the
TiO2 layer [44]. However, the output key parameters for cell may depend on the nature of the light source and
lighting conditions [4, 9], type of sensitizers [11, 12], working electrode thickness [44], and compositions of the
counter electrode [8].

The maximum parameters were obtained under tungsten bulb light illumination. The I-V characteristics
were recorded with varying distances of the cell from the tungsten bulb as shown in figure 7(a) and table 4, where
the light cooperated on the top of the carton wood box as shown in the inset of figure 7(b). The cell moved
vertically toward the light using a wood basement with the illumination of 30–40 s to avoid the dye degradation
and effect of heat generation. Since the DSSC is very sensitive to the temperature generated by light, which may
cause the increase of the VOC predicted theoretically and widely reported experimentally. This behavior
indicates strong temperature dependents of ideality factor (n) that limits the VOC [45, 46]. The effect of
temperature on the stability of natural dye-based cells can also vary under light and temperature based on the

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**Table 4. Key parameters of DSSC at different distance from the tungsten bulb.**

| Distance (cm) | \( I_{SC} \) (μA) | \( V_{OC} \) (mV) | \( IS_{MP} \) (μA) | \( V_{MP} \) (mV) | FF | \( P_{MAX} \) (μW/m²) |
|--------------|------------------|------------------|----------------|----------------|-----|----------------|
| 10           | 11.92            | 4.00             | 5.98           | 2.00           | 0.251 | 46.63         |
| 15           | 9.93             | 3.30             | 5.17           | 1.60           | 0.252 | 32.25         |
| 25           | 7.22             | 2.40             | 3.51           | 1.25           | 0.253 | 17.11         |
| 60           | 4.92             | 1.65             | 2.59           | 0.80           | 0.260 | 8.08          |

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**Figure 7.** (a) Current and power versus voltage characteristics and (b) variation of short circuit current \( (I_{SC}) \) with the distance of DSSC illuminated under a tungsten bulb and inset of the figure indicates carton box for measurements.
The chemical structure of the pigments [47, 48]. It is clear from figure 7 and table 4 that the photogenerated current and power are increased with a decrease in the distance between DSSC and light source, and the result is agreeing or very close to the reported results [4, 14]. Thus, the best suitable distance of the cell is closer to the light source due to the increase of intensity as with reduces the distance between the DSSC and source [49].

The FF is an indicator of power loss, and the most important factors that affect the FF values are series resistance ($R_S$), parallel resistances ($R_{SH}$), recombination current, and the reverse saturation current [49, 50]. The calculated FF for the dye under two different light sources was varied from 0.25 to 0.26, and the distortion in the I-V characteristics from the preferable rectangular shape indicates the presence of series resistance ($R_S$) and shunt resistance ($R_{SH}$) in a solar cell device. Typically, a solar cell is considered as a single diode according to equivalent circuit in ideal cases and with the presence of $R_S$ and $R_{SH}$ in the experimental case as shown in the inset of figure 8(a) [49] and the current-voltage relations of the diode in and light is given below [51]:

$$I = I_{PH} - I_D - I_S = I_{PH} - I_S \left[ \exp \left( \frac{V + IR_S}{nV_T} \right) - 1 \right] - \frac{V + IR_S}{R_{SH}}$$

where $I_{PH}$ is the photogenerated current, $I_S$ is the reverse saturation current, $V_T$ is the thermal voltage equal to $k_B T/q \sim 26 \text{ mV}$ at the room temperature, and $n$ is the ideality factor. The electrical values of $R_S$ and $R_{SH}$ of DSSC were estimated from the inverse slope of the I-V curve near $V_{OC}$ and $I_{SC}$, respectively (inset of figure 8(b)) [49, 50]. Another type of resistance that reduces the FF and efficiency is the characteristic resistance ($R_{CH} = V_{MP}/I_{MP}$) for low fill factor devices [49]. The ideality factor is the indicator of the recombination processes.
inside the cell, and can be calculated under light from I-V curves by using $\ln [I' + I_{SC}] = \frac{q}{n k T} [V - R_s I'] + \ln (I_0)$ \cite{52,53}, here, $I' = I - GV$, and $G = dI/dV$ is the shunt conductance. The plot of $\ln [I' + I_{SC}]$ versus $[V - R_s I']$ is used to calculate $n$, as shown in figure 8. The values of $R_{CH}$, $R_s$, $R_{SH}$, and $n$ for dye under two different light sources are presented in table 5. The $R_s$ values are usually associated with resistance of (1) transparent conductive oxide electrodes, (2) bulk semiconductor material, and (3) metallic contact \cite{54}. The smallest $R_s$ value of the assembled DSSC was observed under tungsten bulb illumination. It resulted in the higher $I_{SC}$ or photogenerated current, and the large current values indicated a low recombination process inside the cell, which reflected with a smaller $n$. However, under LED illuminations, the higher value of $n$ could be contributed by a potential drop at the interfacial layer and the recombination current \cite{51,54}, $R_{SH}$ inside the cell is mainly caused by leakage current, crystal defect and/or impurities in the dye-photoanode interfacing region \cite{51,54}. The resulted $R_{SH}$ values are considerably low and affect the overall performance. However, the best numerical values of $R_s$, $R_{SH}$, and $n$ were observed by using the tungsten bulb, where $R_s$ is small, $R_{SH}$ is roughly large, and lower $n$, thus the overall performance of the cell has been enhanced. $R_{CH}$ is becoming approximately equal to $R_s$, indicating that the DSSC work with its maximum power point under the tungsten bulb.

### Conclusion

Bael tree leaves dye has been successfully extracted in ethanol medium and investigated for the progress of DSSC. The chlorophyll and its derivatives pigments were observed in the extracted dye. A high ionic conductivity value indicates a high amount of Mg ions in the dye solutions. The optoelectronic energy bandgap was measured using UV–vis spectrum, Tauc plot method, and derivatives spectroscopy for various dye solutions. The developed natural dye exhibits a broad absorption spectrum range of 300–700 nm with MLCT states and two satellite valleys from the 2nd derivative spectroscopy analysis. The illumination of a photosensitizer-based DSSC under a tungsten bulb has lowered the recombination process in the cell, thus improving the photogenerated current and showing potential merit. These outcomes are auspicious and could have an advantage in improving low-cost and eco-friendly solar cells.

### Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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