

Research Article

Natural Pigments from Plants Used as Sensitizers for TiO₂ Based Dye-Sensitized Solar Cells

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Four natural pigments, extracted from the leaves of teak (*Tectona grandis*), tamarind (*Tamarindus indica*), eucalyptus (*Eucalyptus globulus*), and the flower of crimson bottle brush (*Callistemon citrinus*), were used as sensitizers for TiO₂ based dye-sensitized solar cells (DSSCs). The dyes have shown absorption in broad range of the visible region (400–700 nm) of the solar spectrum and appreciable adsorption onto the semiconductor (TiO₂) surface. The DSSCs made using the extracted dyes have shown that the open circuit voltages (V_{oc}) varied from 0.430 to 0.610 V and the short circuit photocurrent densities (J_{sc}) ranged from 0.11 to 0.29 mA cm⁻². The incident photon-to-current conversion efficiencies (IPCE) varied from 12–37%. Among the four dyes studied, the extract obtained from teak has shown the best photosensitization effects in terms of the cell output.

1. Introduction

Harvesting energy from sunlight using photovoltaic technology is one of the most important research areas because of an ever increasing global energy need. The conventional solid-state silicon based solar cells, though highly efficient, are yet to become popular for mass applications as they are highly expensive. The necessity for developing low cost devices for harvesting solar energy was, therefore, very much desirable. A new hope was generated in this direction when O'Regan and Grätzel reported to have achieved an unprecedented high energy conversion efficiency (η) of 7.1% through a dye-sensitized solar cell (DSSC) developed by using nanocrystalline TiO₂ thin film electrode sensitized by a highly efficient Ru(II) polypyridyl complex [1]. This has proven that significantly high light-to-electricity conversion efficiency can be achieved through DSSCs as well. Once this was established, such cells attracted greater attention of the scientists particularly because of two reasons; first, their production cost was expected to be quite low due to ease of their fabrication, and second, they are more environment friendly as compared to conventional solid-state silicon based

photovoltaic devices [2]. Being optimistic that DSSCs have the potential to become a commercially viable alternative to expensive silicon solar cells, extensive studies have been conducted on such devices during last two decades.

A dye-sensitized solar cell is usually composed of a dye-capped nanocrystalline porous semiconductor electrode, a metal counter electrode, and a redox electrolyte mediating electron transfer processes occurring in the cell. The performance of the cell is primarily dependent on the material and quality of the semiconductor electrode and the sensitizer dye used for the fabrication of the cell. For their application in DSSCs, many wide band-gap metal oxide semiconductors have been studied but most extensively employed semiconductors are TiO₂ and ZnO [3–8]. Titanium dioxide (TiO₂) has several advantages, including long-term thermal and photostability. The essential properties of semiconductor can be changed significantly by using different techniques for their deposition on the substrate [9]. The sensitizer (dye) plays a key role in absorbing light, and in this respect the highest efficiency obtained so far is with Ru (II) polypyridyl complexes [10, 11]. However, the ruthenium complexes are expensive due to the paucity of

the Ru metal and the complexity of preparation procedure limiting the production of low cost DSSC. This has stimulated the search for potential alternative metal complex sensitizers. Simultaneously, organic dyes [12, 13] and natural dyes [14–20] extracted from plants were also studied to explore the possibility of their application as photosensitizer. Organic dyes have been reported to meet the efficiency as high as 9.8% [12]. However, these dyes have been fraught with problems, such as complicated synthetic routes and low yields. On the other hand, the natural dyes found in flowers, leaves, and fruits of plants can be extracted by simple procedures and then employed in DSSCs. The advantages of natural dyes, resembling in functionalities to organic dyes, are their easy availability, nontoxicity, complete biodegradability, and temperature compatibility. Several of natural dyes such as tannin [21], carotene [22], anthocyanin [23], betalain [24], and chlorophyll [25, 26] have been extensively investigated as sensitizers in dye-sensitized solar cells [27].

In this paper, we report the performance of four natural dyes extracted from the leaves of teak (*Tectona grandis*), tamarind (*Tamarindus indica*), eucalyptus (*Eucalyptus globulus*), and the flower of crimson bottle brush (*Callistemon citrinus*). The basic structures of the coloring components found in these extracts are given in Figure 1. Tannin, that is, gallic acid [3,4,5-trihydroxybenzoic acid] and ellagic acid [2,3,7,8-tetrahydroxy(1)benzopyrano(5,4,3-cde)(1)benzopyran-5,10-dione] are the main constituents of these natural dyes along with some minor components [28–30]. Teak extract mainly contains tectoleaquinone, 1,4,5,8-tetrahydroxy-2 isopentadienyl anthraquinone and tannin [28]. To the best of our knowledge, the use of these plant extracts is being reported for the first time as sensitizers for TiO_2 based dye-sensitized solar cells (DSSCs).

2. Experimental

2.1. Materials. Ethanol (A.R. grade, 99.9%, Merck) was used for extracting natural dyes from plants. Titanium paste (HT), platinum catalyst (T/SP), and the sealing tape (SX1170–60, 50 μm thick) were obtained from Solaronix. Propylene carbonate (>99%, Merck) was taken as the medium of cell electrolyte. Anhydrous lithium iodide (99.9%, Aldrich) and iodine (G. R. grade, 99.8%, BDH) were used as redox couple in photoelectrochemical (PEC) experiments without any further purification. FTO-coated (Fluorine-doped tin oxide) conductive glass slides (surface resistivity 15 Ω/\square , thickness 2.2 mm) obtained from Pilkington, USA, were used as substrates for preparing TiO_2 thin film electrode and Platinum counter electrode.

2.2. Apparatus and Instruments. A bipotentiostat (model number AFRDE 4E, Pine Instrument Company, USA) and e-corder (model 201, eDAQ, Australia) were used for current-potential measurements. For photoelectrochemical (PEC) measurements, a 150 W Xenon arc lamp with lamp housing (model number 66057) and power supply (model number 68752), all from Oriel Corporation, USA, was used as the light source. The semiconductor electrode was illuminated after

passing the collimated light beam through a 6-inch long water column (to filter IR part of the light) and condensing it with the help of fused silica lenses (Oriel Corporation, USA). The UV part of this IR-filtered light (referred to as “white light”) was cut off by using a long pass filter (model number 51280, Oriel Corporation, USA) and the light obtained this way is mentioned as “visible light.” The light was monochromatised, when required, by using a grating monochromator (Oriel model 77250 equipped with model 7798 grating). The width of the exit slit of the monochromator was kept at 0.5 mm. To obtain the action spectrum ($J_{\text{photo}}-\lambda$) of the dye-sensitized TiO_2 electrode, monochromatic light-induced photocurrent was measured with the help of a digital multimeter (Philips Model number 2525) in combination with the potentiostat. The intensities of light were measured with a digital photometer (Tektronix model J16 with model J 6502 sensor) in combination with neutral density filters (model number 50490-50570, Oriel, USA). The absorption spectrums were recorded on Shimadzu UV-1700 spectrophotometer. The FT-IR spectra were recorded by Varian 3100 FT-IR spectrometer.

2.3. Preparation of Natural Dye Solutions (Extracts). The natural dyes were extracted with ethanol employing the following procedure: fresh leaves of teak (*Tectona grandis*), tamarind (*Tamarindus indica*), eucalyptus (*Eucalyptus globulus*), and the flower of crimson bottle brush (*Callistemon citrinus*) were washed with water and dried. After crushing them into small pieces in a mortar, these were kept in glass bottles and filled with ethanol; these solutions were kept for one week in the dark at room temperature. Then, the residual (solid) parts were filtered out and the resulting filtrates were used as dye solutions.

2.4. Preparation of TiO_2 Electrode (Photo Anode) and Counter Electrode. TiO_2 thin film electrodes (photoanodes) were prepared by spreading highly transparent paste of TiO_2 (Titanium-HT) on FTO-coated conductive glass plate by the doctor's blade method. On the conducting side of glass substrate, a U-shaped frame of adhesive tape was applied to control the thickness of the film and to provide non-coated area for electrical contact. After spreading TiO_2 paste, the adhesive tapes were carefully removed and films were annealed at 450°C in air for half an hour in a tubular furnace. This resulted in TiO_2 film of $\sim 6 \mu\text{m}$ thickness. The dyes were anchored onto the surface of the TiO_2 thin film electrode by immersing it into ethanol solution of natural dye for overnight. The nonadsorbed dye was washed up with anhydrous ethanol. The dye-coated films were air dried and used as photoelectrode in the cell (Figure 2). The platinum counter electrode was prepared on another FTO-coated glass substrate by depositing platinum catalyst (T/SP, Solaronix) using screen printing method and annealing at 400°C for half an hour in air. The electrolyte consisted of 0.2 M lithium iodide and 0.02 M iodine in propylene carbonate.

2.5. Fabrication of Sandwich Type DSSCs. The photo-electrode (dye-coated TiO_2 film) was put over platinum counter electrode in such a way that the conductive side

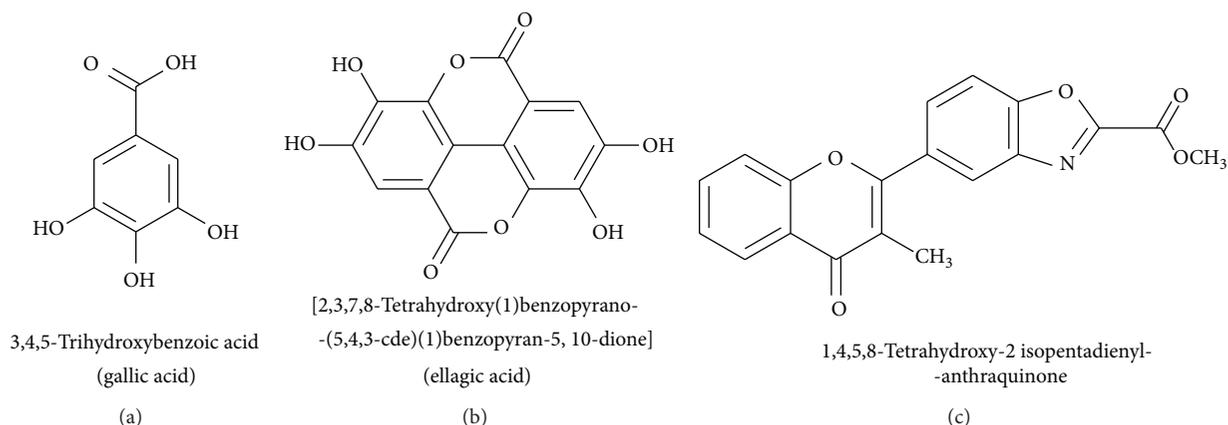
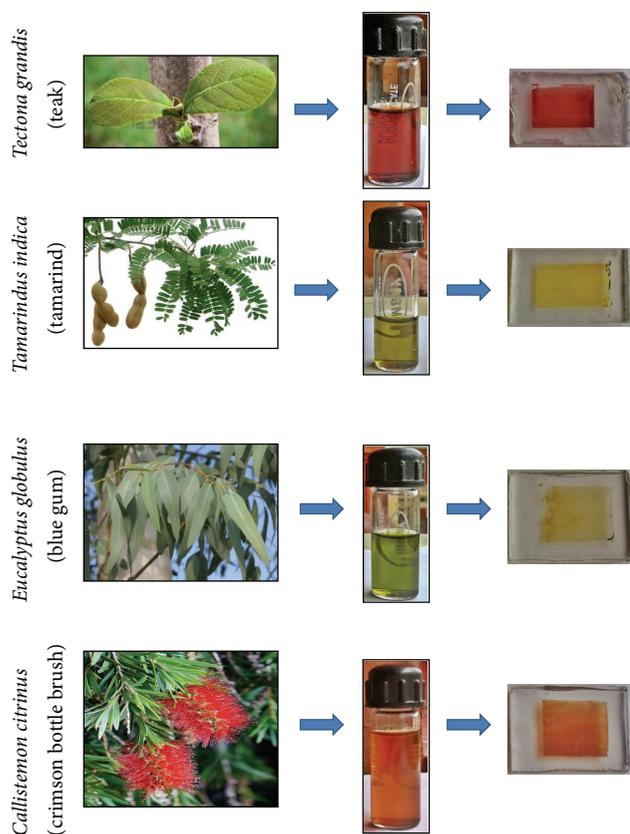


FIGURE 1: Basic molecular structure for the main components of the extracts.

FIGURE 2: Plants, extracted dyes, and the dye-loaded TiO_2 electrode.

of both the electrodes faced each other, and the cell was sealed from three sides using spacer/sealing tape (heating it at $\sim 80^\circ\text{C}$); one side was left open for the injection of electrolyte. The cell electrolyte was injected through open side and was drawn into the space between the electrodes by capillary action. Thereafter, the open side of the cell assembly was sealed properly with Araldite and the contacts were made by copper wires using silver paste (Figure 3).

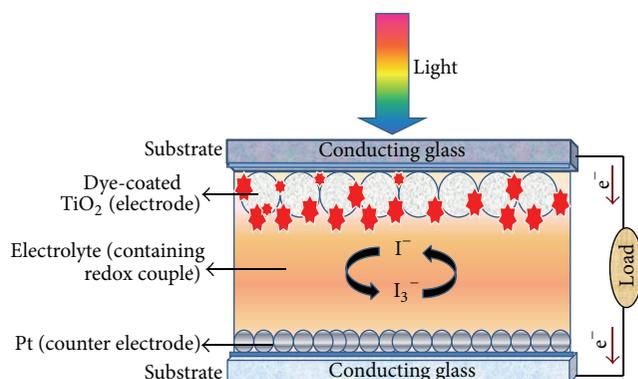


FIGURE 3: Schematic diagram of dye-sensitized solar cell (DSSC) assembly.

3. Results and Discussion

3.1. Absorption Spectra of Natural Dyes. Figure 4 shows the absorption spectra of the ethanol extracts of *Tectona grandis*, *Tamarindus indica*, *Eucalyptus globulus*, and *Callistemon citrinus*. From this figure, it is evident that these natural extracts absorb in the visible region of light spectrum and hence fulfill the primary criterion for their use as sensitizers in DSSCs. To be more specific, *Tectona grandis* exhibited broad absorption band in the range 425–550 nm besides showing a sharp absorption peak at 662 nm. *Tamarindus indica* and *Eucalyptus globulus* have absorption peaks at 410 nm and 472 nm, respectively. Each of them has a common peak at 663 nm which is consistent with the characteristic absorption band of chlorophyll [25, 26]. *Callistemon citrinus* absorbs in the wide range of 410–600 nm with an absorption peak at 450 nm. The differences and variations in the absorption characteristics of dyes can be attributed to the different colors of the extracts due to respective pigments present in them.

3.2. FTIR Spectra. The infrared spectra of these four natural extracts were obtained by pressing them in pellets with KBr.

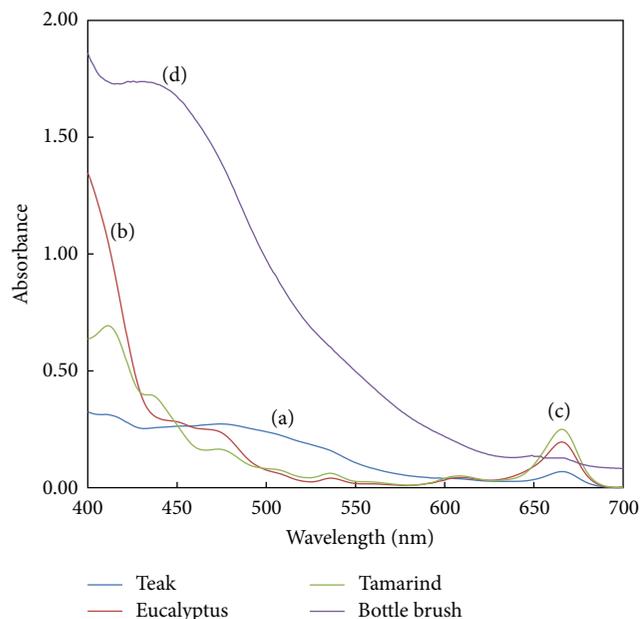


FIGURE 4: Absorption spectra of ethanol solution of natural dyes extracted from (a) teak, (b) eucalyptus, (c) tamarind, and (d) bottle brush, respectively.

The respective FTIR spectra were recorded in the range from 4000 to 400 cm^{-1} and shown in Figure 5. An examination of the spectra reveals that they exhibit broad absorption in the range 3000–3700 cm^{-1} with a wide and strong band at 3407 cm^{-1} which is attributed to the –OH stretching and due to the wide variety of hydrogen bonding between OH. In these spectrums, a sharp peak at around 2927 and a small shoulder at 2855 cm^{-1} associated with the symmetric and antisymmetric –C–H– stretching vibrations of CH_2 and CH_3 groups, respectively, is observed. Also, the signal characteristics bands of C=O (carbonyl) stretching vibration at 1730–1705 cm^{-1} and C–O at 1100–1300 cm^{-1} can be observed due to presence of some aromatic esters. The bands observed in the range 1669–1400 cm^{-1} are due to aromatic ring vibrations, while the ones at 1190 and 1052 cm^{-1} are due to ester linkage. The band at around 751 cm^{-1} is assigned to aromatic C–H bending vibration. Hence, the IR spectra of extracts contain bands that can be assigned to the coloring components found in these extracts as given in Figure 1 Tannin, that is, gallic acid, ellagic acid, and tectoleafquinone, 1,4,5,8-tetrahydroxy-2 isopentadienyl anthraquinone.

3.3. Photoelectrochemical Studies

3.3.1. Current-Potential (J - V) Curves. The photovoltaic performances of DSSCs using natural dyes as photosensitizer (TiO_2 -dye/electrolyte containing I, I_3^-/Pt counter electrode) were determined by recording the current-potential (J - V) curves under visible light illumination and displayed in Figure 6. The similar curve for the cell using bare TiO_2 electrode determined under identical experimental conditions is also shown in the figure (curve (e)). Almost insignificant

current is observed in this case as expected, since visible light is incapable of exciting wide band-gap TiO_2 . The values of photovoltaic parameters derived from these curves are given in Table 1.

With DSSCs using these dyes, open circuit voltage (V_{oc}) from 0.430 to 0.610 V and the short circuit photocurrent densities (J_{sc}) in the range of 0.11–0.29 mA/cm^2 could be achieved. The highest V_{oc} (0.610 V) was obtained with tamarind extract-sensitized DSSC, whereas maximum J_{sc} (0.29 mA/cm^2) was obtained with the DSSC sensitized by teak extract.

3.3.2. Transient Photocurrent-Time ($J_{photo-t}$) Profile. The transient current-time profiles were recorded to know the sustainability of the photocurrent observed initially on illumination of the DSSCs with desired intensity of light. For such an assessment, initially the dark current was monitored for a few seconds; then the semiconductor electrode was illuminated and the short circuit photocurrent was monitored as a function of time. The photocurrent-time ($J_{photo-t}$) profile obtained under visible light (256 mW/cm^2) illumination of natural dye sensitized DSSCs are shown in Figure 7.

Except for the curve (a), in all the other cases, ideal behavior (no decay in photocurrent) was observed. In case of curve (a), initially the photocurrent reached maximum, but the same was not sustained and it decayed to ~93% of its initial value before getting stabilized. This may be the result of slowness of dye regeneration process as compared to rate of charge carriers' injection by the excited dye molecule.

3.3.3. Photocurrent Action Spectrum (IPCE). In order to conclusively ascertain the sensitization of photocurrent by the dyes under investigation, the short-circuit photocurrent (J_{photo}) spectra of dye modified TiO_2 electrodes were determined. From the values of J_{photo} and the intensity of the corresponding monochromatic light (I_{inc}), the incident photon-to-current conversion efficiency (IPCE) was calculated at each excitation wavelength (λ) using the following relation:

$$\text{IPCE (\%)} = \frac{1240 J_{photo} (\text{A}/\text{cm}^2)}{\lambda (\text{nm}) \cdot I_{inc} (\text{W}/\text{cm}^2)} \times 100. \quad (1)$$

The IPCE versus wavelength (λ) curves for different cases (the natural dyes) are shown in Figure 8. It is clearly seen from this figure that there is close resemblance of the nature of IPCE curve with the absorption spectrum of the respective dye providing clear evidence of the sensitization of photocurrent by dye. The IPCE values observed at the characteristic wavelengths of the dyes ranged from 12% to 37%, decreasing in the order *Tectona grandis* > *Callistemon citrinus* > *Tamarindus indica* > *Eucalyptus globules*. The variation in IPCE values for different natural dyes could be due to the varied amount of dye loaded onto the TiO_2 thin film, different degree of charge carrier's recombination, different energy levels of excited dye molecule, and the quenching of excited state.

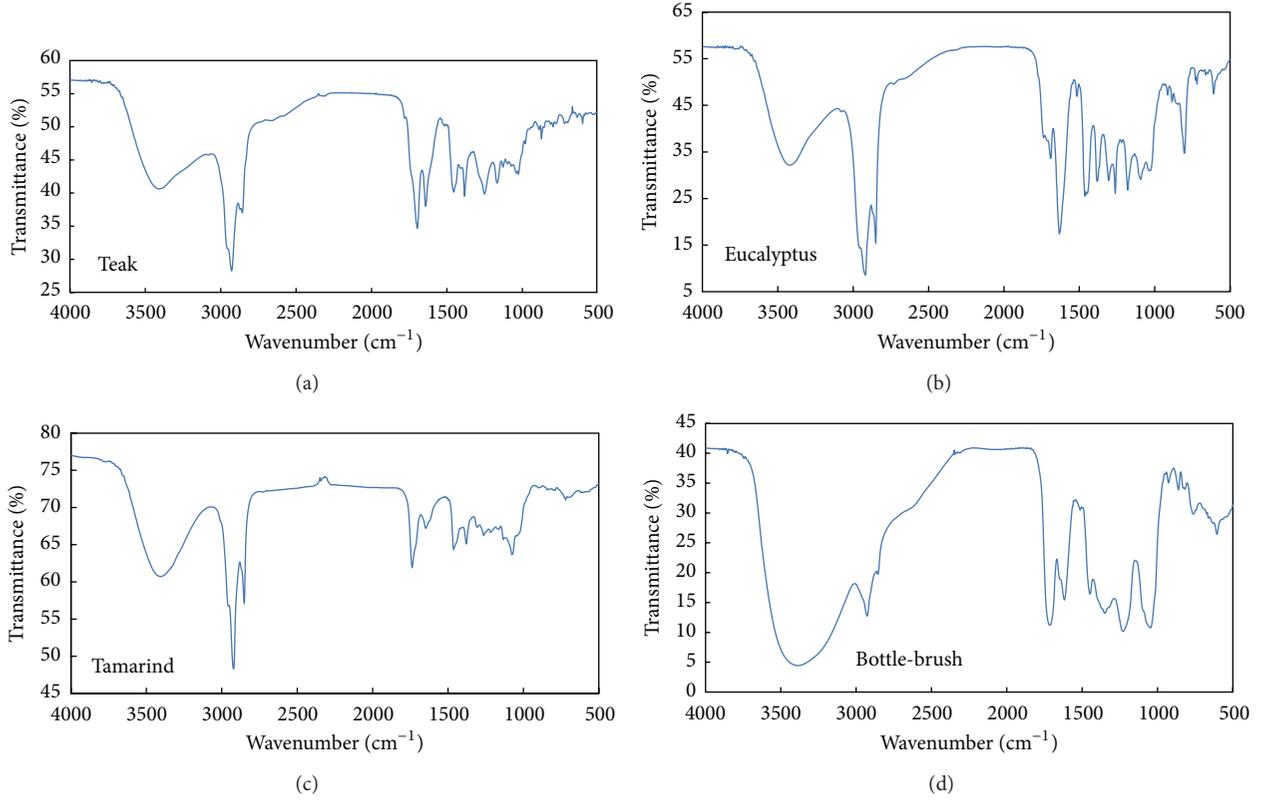


FIGURE 5: Infra-red spectra of extracts obtained from (a) teaks (b) tamarinds (c) eucalyptuss and (d) bottle brush.

TABLE 1: The cell output of DSSCs sensitized by four kinds of natural dyes: (a) teak, (b) tamarind, (c) eucalyptus, and (d) bottle brush under visible light (256 mW/cm²) illumination.

Natural extract	Peak wavelength λ (nm)	J_{sc} (mA/cm ²)	V_{oc} (mV)	IPCE (%)	P_{max} (mW/cm ²)	FF
Teak (<i>Tectona grandis</i>)	470, 662	0.29	460	37	0.105	79
Tamarind (<i>Tamarindus indica</i>)	410, 663	0.18	610	33	0.061	56
Eucalyptus (<i>Eucalyptus globulus</i>)	472, 663	0.15	500	12	0.070	93
Bottle brush (<i>Callistemon citrinus</i>)	450	0.11	430	34	0.030	63

3.3.4. *Power Conversion Efficiency (η) and Fill Factor (FF)*. The power conversion efficiency and the fill factor of dye-sensitized solar cells were determined from the (J - V) curve of the respective cell under illumination by visible light. From the experimentally determined J - V curves (Figure 6), the values of fill factor (FF) and power conversion efficiency (η) were evaluated using the following relations:

$$FF = \frac{P_{max}}{P_{ideal}} = \frac{J_{max} (A/cm^2) \times V_{max} (V)}{J_{sc} (A/cm^2) \times V_{oc} (V)}, \quad (2)$$

$$\eta (\%) = \frac{J_{max} (A/cm^2) \times V_{max} (V)}{I_{inc} (W/cm^2)} \times 100.$$

Here, J_{sc} , V_{oc} , and I_{inc} are short-circuit photocurrent, open-circuit potential, and intensity of incident light, respectively. With the use of these dyes power conversion efficiency follows the order (*Tectona grandis* > *Eucalyptus globulus* > *Tamarindus indica* > *Callistemon citrinus*), while fill factor is obtained as (*Eucalyptus globulus* > *Tectona grandis* > *Callistemon citrinus* > *Tamarindus indica*).

The maximum output power (P_{max}) is obtained by choosing a point on experimentally determined (J - V) curve corresponding to which the product of current (J_{max}) and potential (V_{max}) gives the maximum value. Figure 9 shows the (power versus potential) curves for the natural dye(s)-sensitized solar cells, and the corresponding powers (P_{max}) obtained from various extracts are revealed in Table 1. The maximum photopower was obtained in the case of teak

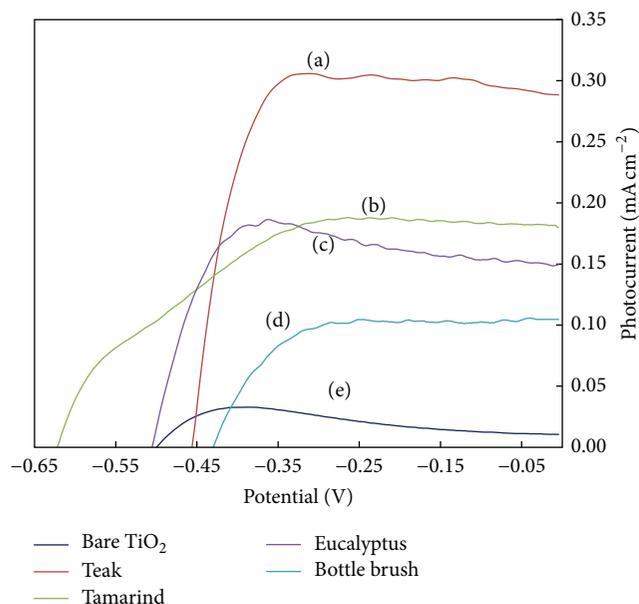


FIGURE 6: Photocurrent-voltage (J - V) curves for the DSSCs sensitized by four kinds of natural dyes: (a) teak, (b) tamarind, (c) eucalyptus, and (d) bottle brush under visible light illumination of intensity 256 mW/cm^2 (electrolyte composition: 0.2 M LiI , 0.02 M I_2 in propylene carbonate). Curve (e) is the same for bare TiO_2 electrode.

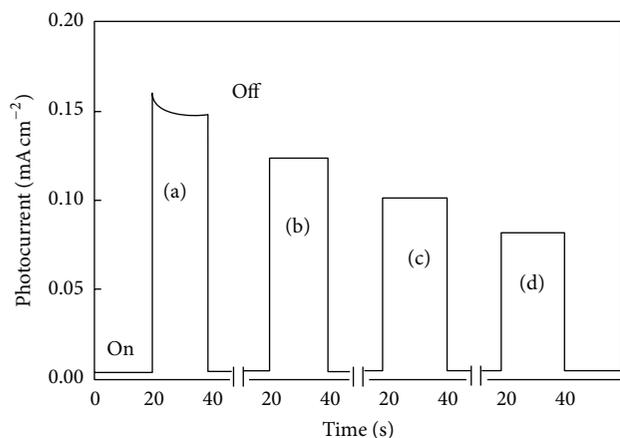


FIGURE 7: Transient current-time ($J_{\text{photo}}-t$) profiles obtained under visible light illumination (intensity 256 mW/cm^2) for the four DSSCs sensitized by (a) teak, (b) tamarind, (c) eucalyptus, and (d) bottle brush, respectively. Electrolyte composition and intensity are the same as in Figure 6.

leaf extract, however low conversion responses may be due to poor interaction of sensitizers with the semiconductor electrode that restricts the transport of electrons from the excited dye molecules to the TiO_2 film.

4. Conclusions

Four natural dyes extracted from the leaves or flowers of the plants were used as sensitizer and their photovoltaic characteristics were studied. The extracted dyes contain tannins as

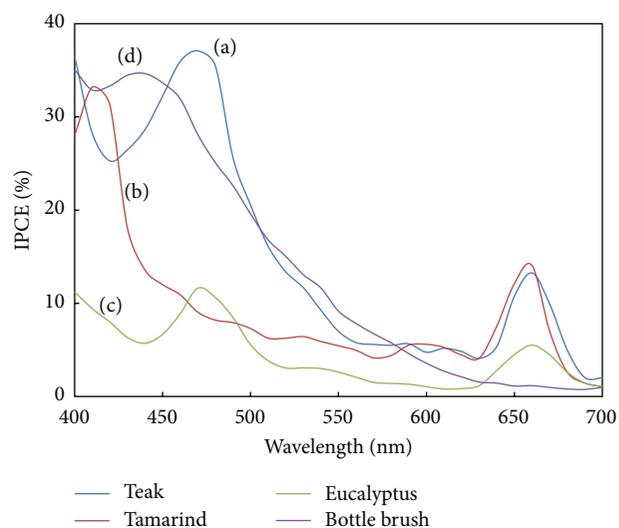


FIGURE 8: Action spectra of solar cell sensitized by the extracts (a) teak, (b) tamarind, (c) eucalyptus, and (d) bottle brush.

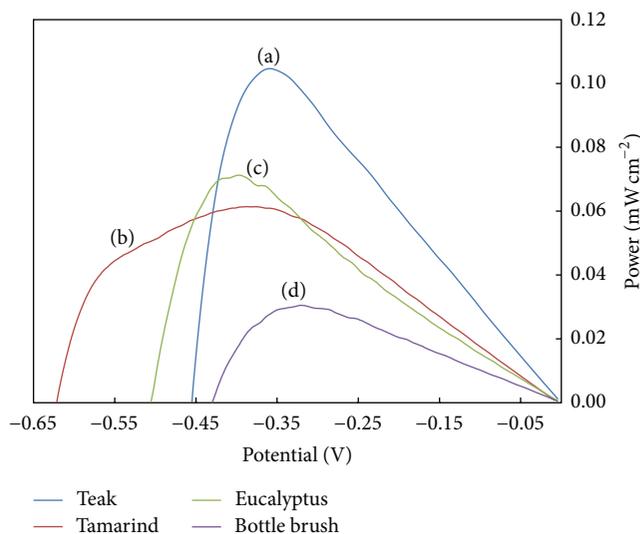


FIGURE 9: Power versus voltage curves of the DSSCs using the natural dyes extracted from the (a) teak, (b) tamarind, (c) eucalyptus, and (d) bottle brush.

the major coloring component along with some other minor components. Chlorophyll is the common component present in all the dyes extracted from the leaves. Tectoleaquinone is the key component present in the teak leaf extract. The chemical adsorption of these dyes becomes possible because of the condensation of hydroxyl and methoxy protons with the hydroxyl groups on the surface of nanostructured TiO_2 . The DSSCs made using the extracted dyes showed the open circuit voltages (V_{oc}) varying between 0.430 and 0.610 V, and the short circuit photocurrent densities (J_{sc}) ranged from 0.11 to 0.29 mA cm^{-2} . The incident photo-to-current conversion efficiencies (IPCEs) varied from 12 to 37%. Among the four dyes studied, the extract obtained from teak has shown the best photosensitization effects in terms of the cell output as

against the expectation arising from the apparent matching profile of the bottle brush extract with the solar spectrum. The natural dye extracts are, generally, a mixture of several pigments. Therefore, the possible reason for the observed differences in sensitization actions of dyes is their varied abilities towards adsorption onto the semiconductor surface. The impact of the different rates of electron transfer from the dye molecule to the conduction band of semiconductor electrode (energy levels alignments) is also reflected. Sometimes, a complication such as dye aggregation on semiconductor film produces absorptivity that results in either the nonelectron injection or the steric hindrance preventing the dye molecules from effectively arraying on the semiconductor film. This leads to the weaker binding and greater resistance, resulting in the low output of cells. Addition of appropriate additives for improving V_{oc} without causing dye degradation might result in further enhancement of the cell performances. Hence, though photocurrent densities, photovoltages, and IPCE obtained with these dyes are somewhat low, they are quite useful for their nontoxicity, greater availability, and very low cost of production opening up a perspective of feasibility for inexpensive and environmentally friendly dye cells.

Acknowledgments

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References

- [1] B. O'Regan and M. Grätzel, "A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO_2 films," *Nature*, vol. 353, pp. 737–740, 1991.
- [2] M. Grätzel, "Dye-sensitized solar cell," *Journal of Photochemistry and Photobiology C*, vol. 4, pp. 145–153, 2003.
- [3] M. Grätzel, "Sol-gel processed TiO_2 films for photovoltaic applications," *Journal of Sol-Gel Science and Technology*, vol. 22, no. 1-2, pp. 7–13, 2001.
- [4] J. Jiu, S. Isoda, M. Adachi, and F. Wang, "Preparation of TiO_2 nanocrystalline with 3–5 nm and application for dye-sensitized solar cell," *Journal of Photochemistry and Photobiology A*, vol. 189, no. 2-3, pp. 314–321, 2007.
- [5] C.-S. Chou, F.-C. Chou, and J.-Y. Kang, "Preparation of ZnO-coated TiO_2 electrodes using dip coating and their applications in dye-sensitized solar cells," *Powder Technology*, vol. 215-216, pp. 38–45, 2012.
- [6] T. S. Senthil, N. Muthukumarasamy, D. Velauthapillai, S. Agilan, M. Thambidurai, and R. Balasundaraprabhu, "Natural dye (cyanidin 3-O-glucoside) sensitized nanocrystalline TiO_2 solar cell fabricated using liquid electrolyte/quasi-solid-state polymer electrolyte," *Renewable Energy*, vol. 36, no. 9, pp. 2484–2488, 2011.
- [7] S. Kushwaha and L. Bahadur, "Characterization of synthetic Ni(II)-xylenol complex as a photosensitizer for wide-band gap ZnO semiconductor electrodes," *International Journal of Photoenergy*, vol. 2011, Article ID 980560, 9 pages, 2011.
- [8] S. S. Kanmani and K. Ramachandran, "Synthesis and characterization of TiO_2/ZnO core/shell nanomaterials for solar cell applications," *Renewable Energy*, vol. 43, pp. 149–156, 2012.
- [9] F. C. Krebs, "Fabrication and processing of polymer solar cells: a review of printing and coating techniques," *Solar Energy Materials and Solar Cells*, vol. 93, no. 4, pp. 394–412, 2009.
- [10] Y. Chiba, A. Islam, Y. Watanabe, R. Komiya, N. Koide, and L. Han, "Dye-sensitized solar cells with conversion efficiency of 11.1%," *Japanese Journal of Applied Physics*, vol. 45, no. 24–28, pp. L638–L640, 2006.
- [11] R. Buscaino, C. Baiocchi, C. Barolo et al., "A mass spectrometric analysis of sensitizer solution used for dye-sensitized solar cell," *Inorganica Chimica Acta*, vol. 361, no. 3, pp. 798–805, 2008.
- [12] G. Zhang, H. Bala, Y. Cheng et al., "High efficiency and stable dye-sensitized solar cells with an organic chromophore featuring a binary π -conjugated spacer," *Chemical Communications*, no. 16, pp. 2198–2200, 2009.
- [13] P. Srivastava and L. Bahadur, "Dye-sensitized solar cell based on nanocrystalline ZnO thin film electrodes combined with a novel light absorbing dye Coomassie Brilliant Blue in acetonitrile solution," *International Journal of Hydrogen Energy*, vol. 37, no. 6, pp. 4863–4870, 2012.
- [14] S. Hao, J. Wu, Y. Huang, and J. Lin, "Natural dyes as photosensitizers for dye-sensitized solar cell," *Solar Energy*, vol. 80, no. 2, pp. 209–216, 2006.
- [15] K. Wongcharee, V. Meeyoo, and S. Chavadej, "Dye-sensitized solar cell using natural dyes extracted from rosella and blue pea flowers," *Solar Energy Materials and Solar Cells*, vol. 91, no. 7, pp. 566–571, 2007.
- [16] G. Calogero and G. D. Marco, "Red Sicilian orange and purple eggplant fruits as natural sensitizers for dye-sensitized solar cells," *Solar Energy Materials and Solar Cells*, vol. 92, no. 11, pp. 1341–1346, 2008.
- [17] K. E. Jasim, S. Al-Dallal, and A. M. Hassan, "Natural dye-sensitized photovoltaic cell based on nanoporous TiO_2 ," *International Journal of Nanoparticles*, vol. 4, no. 4, pp. 359–368, 2011.
- [18] C. Sandquist and J. L. McHale, "Improved efficiency of betanin-based dye-sensitized solar cells," *Journal of Photochemistry and Photobiology A*, vol. 221, no. 1, pp. 90–97, 2011.
- [19] S. Sönmezoglu, C. Akyürek, and S. Akin, "High-efficiency dye-sensitized solar cells using ferrocene-based electrolytes and natural photosensitizers," *Journal of Physics D*, vol. 45, Article ID 425101, 2012.
- [20] L. U. Okoli, J. O. Ozuomba, A. J. Ekpunobi, and P. I. Ekwo, "Anthocyanin-dyed TiO_2 electrode and its performance on dye-sensitized solar cell," *Research Journal of Recent Sciences*, vol. 1, pp. 22–27, 2012.
- [21] R. Espinosa, I. Zumeta, J. L. Santana et al., "Nanocrystalline TiO_2 photosensitized with natural polymers with enhanced efficiency from 400 to 600 nm," *Solar Energy Materials and Solar Cells*, vol. 85, no. 3, pp. 359–369, 2005.
- [22] E. Yamazaki, M. Murayama, N. Nishikawa, N. Hashimoto, M. Shoyama, and O. Kurita, "Utilization of natural carotenoids as photosensitizers for dye-sensitized solar cells," *Solar Energy*, vol. 81, no. 4, pp. 512–516, 2007.
- [23] H. Zhu, H. Zeng, V. Subramanian, C. Masarapu, K.-H. Hung, and B. Wei, "Anthocyanin-sensitized solar cells using carbon nanotube films as counter electrodes," *Nanotechnology*, vol. 19, no. 46, Article ID 465204, 2008.
- [24] D. Zhang, S. M. Lanier, J. A. Downing, J. L. Avent, J. Lum, and J. L. McHale, "Betain pigments for dye-sensitized solar cells,"

- Journal of Photochemistry and Photobiology A*, vol. 195, no. 1, pp. 72–80, 2008.
- [25] W. H. Lai, Y. H. Su, L. G. Teoh, and M. H. Hon, “Commercial and natural dyes as photosensitizers for a water-based dye-sensitized solar cell loaded with gold nanoparticles,” *Journal of Photochemistry and Photobiology A*, vol. 195, no. 2-3, pp. 307–313, 2008.
- [26] A. R. Hernández-Martínez, M. Estevez, S. Vargas, F. Quintanilla, and R. Rodríguez, “Natural pigment based dye sensitized solar cells,” *Journal of Applied Research and Technology*, vol. 10, pp. 38–47, 2012.
- [27] M. R. Narayan, “Review: dye sensitized solar cells based on natural photosensitizers,” *Renewable and Sustainable Energy Reviews*, vol. 16, no. 1, pp. 208–215, 2012.
- [28] R. Aradhana, K. N. V. Rao, D. Banji, and R. K. Chaithanya, “A review on *Tectona grandis.linn*: chemistry and medicinal uses,” *Herbal Tech Industry*, vol. 6, no. 11, 2010.
- [29] R. Mongkholrattanasit, J. Kryštůfek, J. Wiener, and J. Studničková, “Natural dye from Eucalyptus leaves and application for wool fabric dyeing by using padding techniques,” in *Natural Dyes*, E. A. Kumbasar, Ed., chapter 4, 2011.
- [30] E. D. Caluwé, K. Halamová, and P. V. Damme, “*Tamarindus indica* L.: a review of traditional uses, phytochemistry and pharmacology,” *Afrika Focus*, vol. 23, pp. 53–83, 2010.



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