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Photovoltaic Performance of Dye-Sensitized Solar Cells Using Natural Dyes Extracted from Three Acalypha Leaf Species

[1]Teju Philip Olakunle, *[2]Adebowale Clement Adebisi, [3]Gbadebo Taofeek Yusuf, [4]Taiwo Kamorudeen Alasi, [4]Dolapo Eleyele, [5]Sunday Adeoye and [3]Hammidu Ayodeji Rasheed

[1]Department of Biological Sciences, University of Ilesa, Ilesa, Osun State, Nigeria
[2]Department of Physics and Engineering Physics, Obafemi Awolowo University, Ile-Ife Nigeria
[3]Department of Science Laboratory Technology, Osun State Polytechnic Iree, Nigeria
[4]Department of Physics with Electronics, University of Ilesa, Osun State, Nigeria
[5]Department of Industrial Chemistry, University of Ilesa, Ilesa, Osun State, Nigeria.

*Corresponding Author's Email: acadebisi@oauife.edu.ng Phone: +2348104254065

ABSTRACT

Dye-sensitized solar cells (DSSCs) have attracted considerable attention as cost-effective alternatives to conventional solar cells; however, the use of expensive and toxic synthetic dyes remains a major challenge. Natural pigments from plants offer a sustainable and eco-friendly alternative due to their availability, low cost, and broad light absorption properties. In this study, natural pigments were extracted from the leaves of three Acalypha species: Acalypha torta, Acalypha onata, and Acalypha wilkesiana, and used as sensitizers in TiO_2-based dye-sensitized solar cells. These pigments exhibited strong and broad absorption across the visible region (400–700 nm) and showed good attachment to the TiO_2 surface. The fabricated DSSCs produced open-circuit voltages in the range of 0.36–0.62 V and short-circuit current densities between 1.7 and 2.9 mA cm^{-2}. Their incident photon-to-current conversion efficiencies (IPCE) ranged from 11% to 27%. Among the three extracts, Acalypha wilkesiana gave the highest performance, indicating its superior photosensitizing ability and potential as an effective natural sensitizer for DSSC applications.

Keywords:
Acalypha species,
DSSCs,
TiO_2,
Solar Cells,
Growth,
Photosensitization.

INTRODUCTION

Capturing solar energy through photovoltaic technology is a key focus of research due to the growing global demand for energy. Although traditional solid-state silicon-based solar cells offer high efficiency, their widespread use remains limited because of their high cost. The need to create cost-effective devices for solar energy harvesting became increasingly important. A breakthrough in this area emerged when O'Regan and Grätzel (1991) reported achieving a remarkable energy conversion efficiency (η) of 7.1% using a dye-sensitized solar cell (DSSC). This DSSC utilized a nanocrystalline TiO_2 thin film electrode sensitized with a highly efficient Ru(II) polypyridyl complex (O'Regan & Grätzel 1991), offering new promise for affordable solar technologies. This demonstrated that dye-sensitized solar cells (DSSCs) could also achieve very high light-to-electricity conversion efficiencies. Consequently, these cells garnered increased interest from researchers for two main reasons: first, their fabrication process is straightforward, leading to potentially lower production costs; and second, they are more environmentally friendly compared to traditional solid-state silicon-based photovoltaic devices (Gratzel 2003; Yang *et al.,* 2015). The confidence that DSSCs could evolve into a commercially viable and more affordable alternative to costly silicon solar cells led researchers to carry out extensive investigations on these devices over the past twenty years.

A typical dye-sensitized solar cell (DSSC) comprises three main components: a porous nanocrystalline semiconductor photoanode sensitized with a light-absorbing dye, a platinum or carbon-based counter electrode, and a redox electrolyte that completes the internal charge transfer cycle. The overall photovoltaic performance of the device is largely governed by the synergistic interaction between the semiconductor electrode and the photosensitizer. While several wide-bandgap metal oxides such as SnO_2, Nb_2O_5, and $SrTiO_3$ have been investigated, titanium dioxide (TiO_2) and zinc oxide (ZnO) remain the most extensively utilized semiconductors in DSSC research due to their favorable electronic properties and compatibility with various sensitizers (Gong *et al.,* 2012).

Titanium dioxide, in particular, is highly preferred owing to its excellent thermal and photochemical stability, non-toxicity, low cost, and suitable energy band alignment with common redox electrolytes. The morphological and electronic characteristics of these semiconductor films can be significantly tailored through different deposition techniques, including doctor-blading, screen printing, spin coating, and hydrothermal growth, which directly influence parameters such as surface area, porosity, and electron transport efficiency.

The sensitizing dye plays a pivotal role in DSSC operation by harvesting photons and injecting electrons into the conduction band of the semiconductor. To date, the highest power conversion efficiencies have been achieved using ruthenium(II) polypyridyl complexes, which offer broad absorption spectra, excellent electron injection kinetics, and good long-term stability (Fetouh *et al*., 2024; Mahalakshmi *et al*., 2025). However, the practical application of these ruthenium-based dyes is severely constrained by the scarcity and high cost of ruthenium metal, as well as the complicated and expensive synthesis procedures involved. These limitations have prompted intensive efforts to develop alternative sensitizers. In this context, both synthetic organic dyes and natural plant-derived dyes have been actively explored. Certain metal-free organic dyes have demonstrated impressive efficiencies reaching up to 9.8%. Nevertheless, their widespread adoption is often hampered by complex multi-step synthesis routes, relatively low production yields, and occasional toxicity concerns. In contrast, natural dyes extracted from various parts of plants such as leaves, flowers, fruits, and roots can be obtained through simple, low-cost extraction processes. These bio-based sensitizers provide functional similarities to synthetic dyes while offering distinct advantages, including environmental friendliness, biodegradability, non-toxicity, and abundant availability, especially in tropical and subtropical regions.

The genus *Acalypha*, a member of the Euphorbiaceae family, consists of more than 400 species of herbs and shrubs that are widely distributed throughout tropical and subtropical regions, particularly in West Africa. Several species within this genus are distinguished by their striking leaf pigmentation, which is largely associated with the abundance of anthocyanins, flavonoids, and other phenolic constituents (Siraj *et al.,* 2016). These naturally occurring pigments possess strong visible-light absorption properties, making them promising candidates for application as sensitizers in dye-sensitized solar cells (DSSCs). Previous studies have examined the use of extracts from individual species such as *Acalypha wilkesiana* and *Acalypha hispida* in DSSC fabrication, where moderate photovoltaic performances were reported (Ananthi *et al.,* 2020; Mphande & Pogrebnoi 2015; Al-Baitai & Ibrahim 2022). However, despite the growing interest in plant-based sensitizers, there remains a scarcity of comprehensive comparative investigations involving multiple *Acalypha* species. In particular, systematic studies that evaluate and compare their optical characteristics, dye adsorption behavior, and photovoltaic performance under the same fabrication and operating conditions are still limited.

This present study, therefore investigates the photovoltaic performance of dye-sensitized solar cells using natural dyes extracted from three selected *Acalypha* leaf species (*torta*, *onata*, and *wilkesiana*). The research encompasses dye extraction, UV-Vis spectroscopic characterization and the fabrication and testing of DSSCs. By comparing key photovoltaic parameters short-circuit current density (Jsc), open-circuit voltage (Voc), fill factor (FF), and overall power conversion efficiency (η) across the three species, this work aims to identify the most suitable *Acalypha* variant for natural dye sensitization. The findings are expected to contribute valuable insights toward the development of low-cost, eco-friendly solar cells using locally available plant resources in tropical environments.

MATERIALS AND METHODS

Natural dyes were obtained from plant materials using ethanol (A.R. grade, 99.9%, Merck). The titanium paste (HT), platinum catalyst (T/SP), and sealing tape (SX1170–60, 50 µm thick) were purchased from Solaronix. Propylene carbonate (≥99%, Merck) was used as the electrolyte solvent. Anhydrous lithium iodide (99.9%, Aldrich) and iodine (G.R. grade, 99.8%, BDH) were used as the redox couple in the photoelectrochemical (PEC) measurements without any additional purification. The TiO_2 thin-film electrodes and platinum counter electrodes were prepared on FTO-coated glass slides obtained from Pilkington, USA. Current–potential measurements were carried out using a bipotentiostat (AFRDE 4E, Pine Instrument Company, USA) together with an e-corder (Model 201, eDAQ, Australia). The extraction and fabrication processes were carried out at the Central Science Laboratory, University of Ilesa, Ilesa, Nigeria. The photoelectrochemical measurements were conducted at the Department of Physics and Engineering Physics, Obafemi Awolowo University, while the optical characterization was performed at the Central Research Laboratory, Obafemi Awolowo University, Ile-Ife, Nigeria.

For the photoelectrochemical (PEC) measurements, illumination was supplied by a 150 W xenon arc lamp (model 66057) together with its matching power supply (model 68752), both obtained from Oriel Corporation, USA. The semiconductor electrode was irradiated with a collimated light beam that first passed through a 6-inch water filter to remove infrared radiation, after which the beam was focused using fused silica lenses. To ensure that only visible light reached the sample, the infrared-filtered beam was subsequently passed through a long-pass filter (model 51280). When monochromatic light was required, a grating monochromator (Oriel model 77250 fitted with model 7798 grating) was employed, with the exit slit adjusted to 0.5 mm (Adebisi *et al.,* 2025). The action spectrum of the dye-sensitized TiO_2 electrode was obtained by measuring the photocurrent generated under monochromatic illumination using a digital multimeter (Philips model 2525) connected to the potentiostat. Light intensity was monitored with a digital photometer (Tektronix model J16 equipped with a J 6502 sensor), while neutral density filters (model 50490–50570) were used for intensity control. The absorption spectra were recorded using a Shimadzu UV-1700 UV–Vis spectrophotometer.

Preparation of Natural Dye Solutions (Extracts)

The natural dye extracts were prepared using ethanol as the extracting solvent. Fresh leaves from the three *Acalypha* species: *Acalypha torta*, *Acalypha onata*, and *Acalypha wilkesiana* were first washed thoroughly with water to remove any surface impurities and then left to dry. After drying, the leaves were ground into small pieces using a mortar and pestle to increase the surface area for better pigment extraction. The pulverized samples were then transferred into separate glass bottles and soaked in ethanol until fully immersed. The bottles were kept in the dark at room temperature for seven days to allow the pigments to diffuse gradually into the solvent while minimizing possible photodegradation of the dye molecules. At the end of the extraction period, the mixtures were filtered to remove the plant residues, and the clear filtrates obtained were collected and used as the dye solutions. The image of the three *Acalypha* leaf species are presented in Figure 1(a–c).

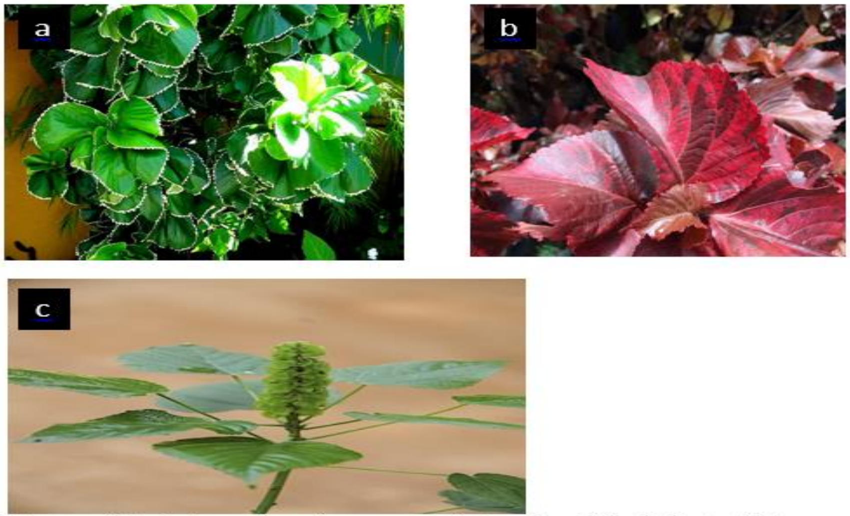

Figure 1: Images of Acalypha Species Used as a Source of Natural Dye (a) Acalypha *Torta* (b) Acalypha *Wilkesiana* (c) Acalypha *Onata*

Preparation of TiO_2 Electrode (Photo Anode) and Counter Electrode

Titanium dioxide-based thin film photoanodes were made by applying a transparent TiO_2 paste (Titanium-HT) onto FTO-coated conductive glass using a doctor's blade method. A U-shaped strip of adhesive tape was placed on the conductive side of the glass to control the film's thickness and leave an exposed area for making electrical contact. After spreading the TiO_2 paste, the tape was peeled away, and the films were sintered at 450 °C in air for 30 minutes in a tubular furnace. This produced a TiO_2 film. The film was then immersed in an ethanol solution of the natural dye for 12 hours to allow the dye molecules to bind to its surface. Afterward, any unbound dye was rinsed off with anhydrous ethanol. Finally, the dye-coated films were air-dried and employed as the photoanode in the cell. A platinum counter electrode was fabricated on a separate FTO-coated glass substrate by applying platinum catalyst (T/SP, Solaronix) via screen printing, followed by annealing in air at 450 °C for 30 minutes. The electrolyte was composed of 0.35 M lithium iodide and 0.22 M iodine dissolved in propylene carbonate.

The dye-coated TiO_2 photoelectrode was placed against the platinum counter electrode so that the conductive surfaces of both electrodes faced each other. The cell was then sealed on three sides with spacer/sealing tape by heating it to about 75 °C, leaving one side open for electrolyte introduction. The electrolyte was injected through the unsealed side and then spread into the gap between the electrodes by capillary action. After that, the remaining opening was sealed tightly with Araldite, and copper wires were attached with silver paste to make the electrical connections.

RESULTS AND DISCUSSION

Optical properties of DSSCs

The optical absorption spectra of the three *Acalypha* species are presented in Figure 2. The spectra reveal that all the extracted natural dyes exhibit significant absorption within the visible region of the electromagnetic spectrum, which is an essential requirement for effective sensitizers in dye-sensitized solar cells (DSSCs). The ability of these pigments to absorb visible light suggests their potential to harvest solar energy efficiently and facilitate photo-induced electron injection into the conduction band of TiO_2. The broad absorption behavior observed for the extracts may be attributed to the presence of naturally occurring pigments such as chlorophylls, anthocyanins, flavonoids, and other phenolic compounds contained in the leaves.

Among the three extracts, *Acalypha wilkesiana* demonstrated the widest absorption range, extending from approximately 475 to 560 nm, together with a pronounced sharp absorption peak centered on 652 nm. This broad absorption profile indicates an enhanced light-harvesting capability across a larger portion of the visible spectrum, which could contribute to improved photovoltaic performance. In contrast, *Acalypha torta* and *Acalypha onata* exhibited their major absorption peaks at about 435 nm and 485 nm, respectively, corresponding to strong absorption in the blue-green region of the visible spectrum. Despite these variations in spectral behavior, all three dye extracts displayed a common absorption peak near 665 nm. This characteristic peak is associated with the typical absorption band of chlorophyll pigments (Zeng et al., 2016; Mongkholrattanasit *et al.,* 2011; Zhan *et al.,* 2024), confirming the presence of chlorophyll-related compounds in the extracts. The occurrence of this absorption feature further supports the suitability of the natural dyes for DSSC applications, since chlorophyll molecules are known for their strong light absorption and efficient photoexcitation properties. The observed differences and variations in their absorption profiles are likely due to the distinct colors of the dye extracts, resulting from the unique pigments present in each plant species (Zhan *et al.,* 2024; Caluwé *et al.,* 2010).

Photo-Electric Performance of DSSCs

The photovoltaic parameters of the three Acalypha species are presented in Table 1. The performance of the DSSCs, which were assembled using TiO_2–dye photoanodes, an iodine-based electrolyte, and platinum counter electrodes, was assessed from their current–voltage (J–V) curves under visible-light illumination. As expected, only a very small current was generated because visible light cannot excite wide band-gap TiO_2 effectively. For the DSSCs sensitized with the natural dyes, the open-circuit voltage (Voc) ranged from 0.36 to 0.62 V, while the short-circuit photocurrent density (Jsc) varied between 1.7 and 2.9 mA/cm². Of the dyes examined, the cell sensitized with Acalypha *torta* extract gave the lowest maximum voltage (Vm) of 0.25 V, whereas the Acalypha *wilkesiana*-based cell recorded the highest Vm of 0.39 V.

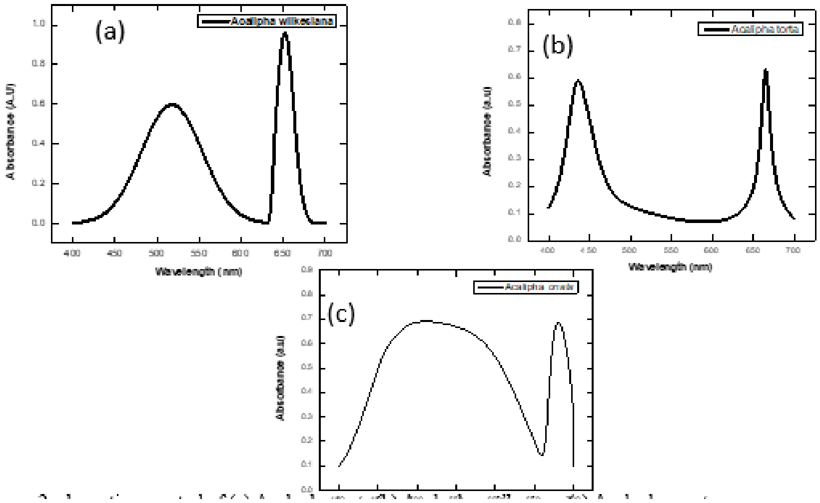

Figure 2: Absorption Spectral of (a) Acalypha *Torta* (b) Acalypha *Wilkesiana* (c) Acalypha *Onata*

To assess the stability and sustainability of the generated photocurrent, transient current-time measurements were first carried out. The dark current was measured for a brief period; then the semiconductor electrode was illuminated, and the short-circuit photocurrent was continuously tracked. This method helped evaluate the performance and consistency of the photocurrent output under simulated solar conditions.

With the exception of the *Acalypha torta* extract, the other *Acalypha*-based dyes showed stable photocurrent behavior, with no noticeable decline during illumination. By contrast, the *Acalypha torta*-sensitized DSSC produced a relatively high photocurrent at the beginning of illumination, but this value gradually decreased to about 91% of its initial level before eventually stabilizing. This early decay in photocurrent suggests that the regeneration of the dye molecules was slower than the rate at which the excited dyes injected electrons into the semiconductor. As a result, the active dye species may have been temporarily depleted faster than they could be replenished, leading to reduced current stability. This behavior is consistent with previous reports in the literature (Jeon *et al.,* 2014; Yu *et al.,* 2017).

Table 1: A Photovoltaic Parameters of Acalipha Leaves Species

Extract	FF %	J_{sc} (mA/cm^2)	V_{oc} (V)	J_m(mA/cm^2)	V_m (V)	IPCE (%)	η %
Acalipha *torta*	40	1.7	0.36	1.10	0.25	11	0.62
Acalypha *onata*	41	1.8	0.61	1.12	0.90	19	0.55
Acalypha *wilkesiana*	47	2.9	0.62	1.85	0.39	27	0.72

To confirm the photoresponse and sensitization effect of the investigated dyes, the short-circuit photocurrent spectra of the dye-sensitized TiO_2 electrodes were recorded under monochromatic illumination. At each excitation wavelength, the corresponding light intensity was measured and used to calculate the incident photon-to-current conversion efficiency (IPCE) according to Equation 1. This parameter provides a direct measure of how effectively incident photons at a given wavelength are converted into electrical current by the sensitized electrode. In other words, IPCE reflects the combined efficiency of light absorption by the dye, electron injection into the TiO_2 conduction band, and charge collection at the device terminals. A higher IPCE value, therefore indicates better utilization of the incident photons and improved photoelectrochemical performance.

$$\text{IPCE}\ (\%) = \frac{1240 \times J_{sc}}{\lambda \times P_{in}} \times 100$$

Where J_{sc} is the short-circuit current density, λ is the wavelength of the incident light, and P_{in} is the incident light power density at that wavelength. The factor 1240 is a constant used to account for the relationship between photon energy and wavelength. Using this expression, the spectral response of each dye-sensitized TiO_2 electrode was evaluated across the chosen wavelength range, allowing comparison of their photon-to-current conversion behavior and overall sensitizing capability.

It was found that the shape of the IPCE curve closely matched the absorption spectra of the corresponding dyes, clearly confirming that the dyes were responsible for photocurrent generation. The IPCE values recorded at the dyes' characteristic wavelengths (Table 1) ranged from 11% to 27%, following the descending order: Acalypha *torta*, Acalypha *onata*, and Acalypha *wilkesiana*. The differences in IPCE values among the various natural dyes may be attributed to factors such as varying amounts of dye adsorbed onto the TiO_2 thin films, differences in charge-carrier recombination rates, variations in the excited-state energy levels of the dye molecules, and possible quenching of the excited states (Chen *et al.,* 2009; Nazeeruddin *et al.,* 1993).

Additionally, the power conversion efficiency and fill factor of the dye-sensitized solar cells were calculated from the current–voltage (J–V) characteristics (Figure 3) of each cell when exposed to visible light. From the experimentally determined J-V curves, the values of fill factor (FF) and power conversion efficiency (η) were evaluated from open-circuit potential, short-circuit photocurrent, and intensity of incident light. Table 1 shows the value of fill factor (FF) to be 40, 41 and 47 in the order of Acalypha *torta,* Acalypha *onata,* and Acalypha *wilkesina*; and the power conversion efficiency to be 0.65%, 0.55% and 0.72% respectively. This is higher than the value reported by Iman *et al.,* (2024) in the process of fabricating high-efficiency natural dye-sensitized solar cells using Mediterranean olive leaf extracts.

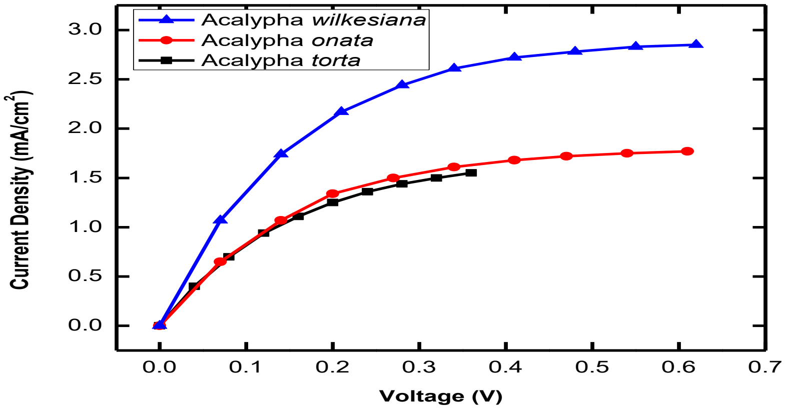

Figure 3: J-V Curves of Acalypha Leaves

The dye extracts obtained from the leaves appear to be composed mainly of tannins as the dominant pigment, along with several other minor phytochemical constituents. Chlorophyll was also detected as a common component in all of the leaf-derived extracts (Roy *et al.,* 2008; Taya *et al.,* 2013). The sensitizing behavior of these natural dyes is strongly influenced by their ability to anchor onto the nanostructured TiO_2 surface, mainly through interactions between the hydroxyl and methoxy protons of the dye molecules and the hydroxyl groups present on the TiO_2 surface. Since natural extracts are typically complex mixtures containing multiple pigments, differences in their photovoltaic performance can reasonably be linked to variations in how effectively each extract adsorbs onto the semiconductor surface (Hao *et al.,* 2006; Zhou *et al.,* 2016). In addition, the observed differences may also arise from variations in electron transfer efficiency from the excited dye molecules to the TiO_2 conduction band, which depends on the relative alignment of their energy levels. In some cases, dye aggregation on the semiconductor film can increase apparent absorbance while at the same time limiting electron injection or creating steric barriers that interfere with proper dye packing on the surface. Such effects weaken dye binding, increase interfacial resistance, and ultimately reduce the overall cell output. Nevertheless, the use of suitable performance-enhancing additives that do not degrade the dye molecules could help improve device efficiency. Therefore, although the photocurrent density, photovoltage, and IPCE values obtained from these dyes remain relatively low, their low toxicity, abundance, and very low production cost make them attractive candidates for the development of inexpensive and environmentally friendly dye-sensitized solar cells.

CONCLUSION

In the present investigation, natural dyes were successfully extracted from the leaves of three *Acalypha* species: *Acalypha torta*, *Acalypha onata*, and *Acalypha wilkesiana* and employed as photosensitizers in dye-sensitized solar cells (DSSCs). The photovoltaic performance of the fabricated devices was systematically evaluated under standard illumination conditions. The assembled DSSCs displayed open-circuit voltages (Voc) ranging from 0.36 to 0.62 V and short-circuit current densities (Jsc) between 1.7 and 2.9 mA/cm². In addition, the incident photon-to-current conversion efficiency (IPCE) spectra revealed notable differences among the dyes, with peak values spanning from 11% to 27%. Remarkably, the dye extract derived from *Acalypha wilkesiana* exhibited the superior overall photovoltaic performance, delivering the highest power conversion efficiency and cell output. This outcome was observed despite the expectation that the dye with the broadest or most optimal spectral overlap with the solar irradiation spectrum would yield the best results. Such findings suggest that factors beyond light-harvesting capability, including molecular anchoring strength on the TiO_2 surface, electron injection efficiency, and dye stability, may play decisive roles in determining device performance. Collectively, these results highlight the promising potential of *Acalypha* leaf extracts as viable, low-cost, and environmentally benign alternatives to conventional synthetic ruthenium-based sensitizers for DSSC applications, particularly in resource-limited tropical regions where these plants are readily available.

REFERENCES

Adebisi, A. C., Omotoso, E., Olorunkosebi, A. A., Eleruja, M. A., & Olofinjana, B. (2025). Photodetection and thermistor applications of Cu-Cd-S thin film. *Journal of Electronic Materials*, *54*(5), 4036-4041.

Al-Baitai, A. Y., & Ibrahim, F. M. (2022). Dye sensitized solar cells based on natural dye-a review. *International Research Journal of Innovations in Engineering and Technology*, *6*(1), 48-53.

Ananthi, N., Subathra, M. S. P., Emmanuel, S. C., & Kumar, N. M. (2020). Preparation and characterization of two dye-sensitized solar cells using Acalypha Godseffia and Epipremnum Aureum dyes as sensitizers. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *42*(13), 1662-1673.

Caluwé, E. D., Halamová, K., & Damme, P. V. (2010). Tamarindus indica L. *A review of traditional uses, phytochemistry and pharmacology. Afrika Focus*, *23*(1), 53-83.

Chen, C. Y., Wang, M., Li, J. Y., Pootrakulchote, N., Alibabaei, L., Ngoc-le, C. H., ... & Gratzel, M. (2009). Highly efficient light-harvesting ruthenium sensitizer for thin-film dye-sensitized solar cells. *ACS nano*, *3*(10), 3103-3109.

Fetouh, H. A., El-Nahass, M. M., & Ashraf, I. M. (2024). Synthesis, characterization and evaluation of new alternative ruthenium complex for dye sensitized solar cells. Scientific Reports, 14, Article 66808. https://doi.org/10.1038/s41598-024-66808-1

Gong, J., Liang, J., & Sumathy, K. (2012). Review on Dye-Sensitized Solar Cells (DSSCs): Fundamental Concepts and Novel Materials. *Renewable and Sustainable Energy Reviews*, 16(8), 5848–5860. https://doi.org/10.1016/j.rser.2012.04.044

Grätzel, M. (2003). Dye-sensitized solar cells. *Journal of photochemistry and photobiology C: Photochemistry Reviews*, *4*(2), 145-153.

Hao, S., Wu, J., Huang, Y., & Lin, J. (2006). Natural dyes as photosensitizers for dye-sensitized solar cell. *Solar energy*, *80*(2), 209-214.

Iman, R. N., Harrabi, K., Younas, M., & Mekki, A. (2024). Fabrication of efficient natural dye-sensitized solar cells using Mediterranean olive leaves as natural dye sensitizer. *Journal of Photochemistry and Photobiology A: Chemistry*, *450*, 115477.

Jeon, J., Park, Y. C., Han, S. S., Goddard III, W. A., Lee, Y. S., & Kim, H. (2014). Rapid dye regeneration mechanism of dye-sensitized solar cells. *The Journal of Physical Chemistry Letters*, *5*(24), 4285-4290.

Mahalakshmi, S., & Savitha Lakshmi, M. (2025). Advancements in ruthenium-based sensitizers for dye-sensitized solar cells: A comprehensive review. Coordination Chemistry Reviews, 521, Article 216472. https://doi.org/10.1016/j.ccr.2025.216472

Mongkholrattanasit, R., Kryštůfek, J., Wiener, J., & Studničková, J. (2011). Natural dye from eucalyptus leaves and application for wool fabric dyeing by using padding techniques. *Natural dyes*, 57-78.

Mphande, B. C., & Pogrebnoi, A. (2015). Outdoor Photoelectrochemical Characterization of Dyes from Acalypha wilkesiana'Haleakala'and Hibiscus sabdariffa as Dye Solar Cells Sensitizers. *British Journal of Applied Science & Technology*, *7*(2), 195.

Mustafa, F. M., Abdel Khalek, A. A., Mahboob, A. A., & Abdel-Latif, M. K. (2023). Designing efficient metal-free dye-sensitized solar cells: A detailed computational study. *Molecules*, *28*(17), 6177.

Nazeeruddin, M. K., Kay, A., Rodicio, I., Humphry-Baker, R., & Müller, E. (1993). P-Liska; Vlachipolous, N.; Grätzel, M. *J. Am. Chem. Soc*, *115*, 6382-6390.

O'regan, B., & Grätzel, M. (1991). A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO2 films.*Nature*, *353*(6346), 737-740.

Roy, M. S., Balraju, P., Kumar, M., & Sharma, G. D. (2008). Dye-sensitized solar cell based on Rose Bengal dye and nanocrystalline TiO2. *Solar Energy Materials and Solar Cells*, *92*(8), 909-913.

Siraj, M. A., Shilpi, J. A., Haque, M. M., Billah, M. M., & Jahan, I. A. (2016). Anti-inflammatory and antioxidant activity of Acalypha hispida leaf and analysis of its major bioactive polyphenols by HPLC. Advanced Pharmaceutical Bulletin, 6(2), 275–283. https://doi.org/10.15171/apb.2016.038

Taya, S. A., El-Agez, T. M., El-Ghamri, H. S., & Abdel-Latif, M. S. (2013). Dye-sensitized solar cells using fresh and dried natural dyes. *International Journal of Materials Science and Applications*, *2*(2), 37-42.

Yu, Y., Click, K. A., Polen, S. M., He, M., Hadad, C. M., & Wu, Y. (2017). Electron transfer kinetics of a series of bilayer triphenylamine–oligothiophene–perylenemonoimide sensitizers for dye-sensitized NiO. *The Journal of Physical Chemistry C*, *121*(38), 20720-20728.

Zeng, L., Wang, Y., & Zhou, J. (2016). Spectral analysis on origination of the bands at 437 nm and 475.5 nm of chlorophyll fluorescence excitation spectrum in Arabidopsis chloroplasts. *Luminescence*, *31*(3), 769-774.

Zhan, C., Mao, H., Fan, R., He, T., Qing, R., Zhang, W., ... & Kang, Z. (2024). Detection of apple sucrose concentration based on fluorescence hyperspectral image system and machine learning. *Foods*, *13*(22), 3547.

Zhou, Z., Song, J., Nie, L., & Chen, X. (2016). Reactive oxygen species generating systems meeting challenges of photodynamic cancer therapy. *Chemical society reviews*, *45*(23), 6597-6626.