

A Study on the Fabrication and Performance Analysis of Natural Dye-Sensitized Solar Cells (DSSCs)

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ABSTRACT: The present study focuses on the fabrication and performance analysis of dye-sensitized solar cells (DSSCs) using plant-based natural dyes as environmentally benign and cost-effective photosensitizers. Natural dyes were extracted from *Beta vulgaris* (beetroot) peels and *Butea monosperma* (Palas/Tesu) flowers using ethanol as the solvent. The results revealed that the DSSC sensitized with *Butea monosperma* dye exhibited significantly enhanced performance, achieving a maximum efficiency of 2.038%, compared to the *Beta vulgaris*-sensitized cell, which showed a lower efficiency of 0.082%.

KEYWORDS: Dye-sensitized solar cells; Natural dyes; *Beta vulgaris*; *Butea monosperma*; TiO₂ photoanode; Photovoltaic performance.

I. INTRODUCTION

The global energy scenario in the twenty-first century is characterized by an unprecedented rise in energy demand driven by rapid population growth, urbanization, industrial expansion, and technological advancement. Modern societies rely heavily on continuous and reliable energy supplies to sustain economic development and improve quality of life. However, the existing energy infrastructure across the world remains largely dependent on fossil fuels such as coal, oil, and natural gas. These conventional energy resources have served as the backbone of industrial progress for more than a century, yet their finite nature and uneven geographical distribution have resulted in serious economic, environmental, and geopolitical challenges. The increasing gap between energy demand and supply, coupled with the depletion of fossil fuel reserves, has intensified the urgency to identify alternative and sustainable energy sources capable of meeting present and future needs. One of the most critical consequences of excessive fossil fuel consumption is environmental pollution. The adverse environmental and health impacts associated with fossil fuels have made it increasingly clear that continued reliance on these resources is neither sustainable nor socially acceptable. As a result, the transition toward cleaner and environmentally friendly energy systems has become a global priority. Among the various renewable energy options, solar energy stands out as the most abundant and universally available resource. The Earth receives an immense amount of solar radiation every day, far exceeding the total energy consumption of humanity. Harnessing even a small fraction of this energy can potentially satisfy global energy requirements in a sustainable manner. Consequently, solar energy technologies have attracted substantial attention from researchers, policymakers, and industry stakeholders worldwide. Conventional PV cells are predominantly based on crystalline silicon, which has demonstrated high efficiency and long-term stability. However, silicon-based solar cells suffer from several limitations, including high material and manufacturing costs, energy-intensive fabrication processes, and rigid device structures. These drawbacks restrict their widespread adoption, particularly in developing regions where cost and accessibility are critical factors. Consequently, extensive research efforts have been directed toward the development of alternative photovoltaic technologies that are cost-effective, environmentally benign, and suitable for large-scale deployment. In this context, DSSCs offer several advantages over traditional silicon-based solar cells, such as low fabrication cost, ease of processing, transparency, flexibility, and the ability to perform efficiently under low-light conditions. The sensitizer dye plays a crucial role in DSSCs, as it is responsible for absorbing sunlight and initiating the charge separation process. Upon light absorption, the excited dye injects electrons into the conduction band of the semiconductor, leading to electricity generation. Plant-based dyes are derived from natural sources such as leaves, flowers, fruits, seeds, and roots, and contain pigments like anthocyanins, chlorophylls, carotenoids, flavonoids,

and betalains. These dyes offer numerous advantages, including abundance, biodegradability, non-toxicity, low cost, and ease of extraction without the need for complex chemical synthesis. Moreover, the use of natural dyes aligns well with the principles of green chemistry and sustainable development. Although natural dyes generally exhibit lower efficiencies compared to synthetic metal-complex dyes, ongoing research has demonstrated that their performance can be enhanced through molecular modification, co-sensitization, metal doping, and optimization of adsorption conditions. Therefore, systematic investigation into the synthesis and application of plant-based dyes as solar cell sensitizers remains an important area of research. In view of this, the present study aims to synthesize plant-based dye materials for solar cell application.

II. MATERIAL AND METHODS

Chemicals and Equipment:

The present study employed chemicals of analytical grade (AR grade), while some reagents of laboratory grade (LR grade) were used based on their ready availability in the laboratory. The chemicals utilized in the investigation are listed in the table 1.

Table 1: List of Chemicals

S. No.	Chemical / Material	Details
1	Titanium Dioxide (Anatase)	Purity: 99.9%
		Dimension: 50 mm × 50 mm × 2.2 mm
2	Fluorine-doped Tin Oxide Glass	Resistivity: 7 Ohms/sq.
3	Beetroot (Chukandar)	-
4	Palas / Tesu Flowers	-
5	Ethanol	-
6	Distilled / Deionized Water	-
7	Hydroiodic Acid	-
8	Hydrochloric Acid	-
9	Iodine	-
10	Diethyl Ether	-
11	Acetone	-
12	2-Propanol (Isopropyl Alcohol)	-
13	RBS 25 Solution	-
14	Graphite (Pencil Lead)	-
15	Polyaniline	-
16	Thiourea	-
17	Ethylene Glycol	-

Table 2 provides the list of equipment and instruments used in the study.

Table 2: List of Equipment and Instruments

S. No.	Equipment and Instruments
1	Ammeter
2	Analytical balance
3	Digital Multimeter
4	Electric furnace
5	Glassware-Borosil
6	Hot Plate
7	Magnetic stirrer
8	Potentiometer (470K)
9	Shimadzu IR AFFINITY-1
10	Voltmeter

Fabrication of DSSC:

In the present study, the fabrication of DSSC is done using the steps given in figure 1.

An electrolyte solution containing 0.05 M iodine (I₂) and 0.5 M potassium iodide (KI) is prepared using an appropriate solvent.

The prepared electrolyte is carefully applied onto the dye-coated TiO₂ semiconductor layer.

A counter electrode is then positioned over the electrolyte-covered TiO₂ layer.

The electrodes are secured using an alligator clip, and any excess electrolyte present at the edges is removed.

Finally, the assembled dye-sensitized solar cell (DSSC) is connected to an external circuit for performance evaluation.

Fig 1: Assembly of DSSC

Electrolyte: In the present study, a potassium iodide–iodine (KI + I₂) solution was employed as the electrolyte, which was prepared following the procedure illustrated in the figure 2.

The iodide/triiodide (I⁻/I₃⁻) redox couple is employed as the electrolyte system for the DSSC.

To enhance electron regeneration and improve electrolyte stability, 0.050 g of cobalt nitrate or terbium chloride is added to the solution.

The primary electrolyte is prepared by dissolving 0.05 M iodine and 0.5 M potassium iodide in 20 ml of ethylene glycol.

The prepared electrolyte solutions are stored in dark containers and subjected to sonication for 30 minutes to achieve complete dissolution.

Finally, the electrolyte is introduced between the photoanode and counter electrode, forming a sandwich-type DSSC assembly.

Fig 2: Preparation of Electrolyte

Dyes: The following materials were used as Dyes in the solar cell fabrication.

Table 3: Preparation of Dyes/ Photosensitizers

S. No.	Material	Procedure
1	Beetroot/ Chukandar (<i>Beta vulgaris</i>)	Approximately 15 g of <i>Beta vulgaris</i> (beetroot) peels were thoroughly washed with distilled water, cut into small pieces, and ground to a fine paste. The ground material was then mixed with ethanol in a 50:50 ratio of dye to solvent. The resulting mixture was stirred continuously and gently heated for about 45 minutes at room temperature. After extraction, the dye solution was stored overnight at 4 °C in dark conditions, followed by filtration and centrifugation to obtain a clear extract.
2	Palas/ Tesu (<i>Butea monosperma</i>)	In the present study, dyes were extracted from the flowers of <i>Butea monosperma</i> . Approximately 10–15 flowers were collected for the extraction process. The petals were carefully separated and thoroughly washed with deionized water. Subsequently, the petals were ground into a fine paste using a mortar and pestle, after which the paste was immersed in ethanol and processed until the desired viscosity was obtained. The resulting solution was then stored in a dark, cold environment for 24 hours to ensure effective dye extraction.

Fabrication of working electrode/ Photoanode: In the present study, a TiO₂ paste was used for photoanode fabrication, and its preparation procedure is illustrated in the accompanying figure 3.

The resistivity of the FTO glass substrate was initially measured, after which the slide was thoroughly cleaned. Following cleaning, the resistivity was rechecked to ensure adequate electrical conductivity.

TiO₂ paste was prepared by adding acetic acid to TiO₂ powder, followed by stirring for 1 hour. Ethanol, Triton X-100, and acid (HCl/HNO₃) were then added to adjust the pH to 3–4. The resulting suspension was sonicated for 1 hour to achieve uniform dispersion.

The paste was heated at 40–50 °C for 30 minutes to evaporate excess solvents and subsequently magnetically stirred for 24 hours to obtain a homogeneous and stable consistency.

The prepared TiO₂ paste was applied onto the FTO glass substrate using the doctor blade technique. The coated slide was then calcined in an electric furnace at 500 °C for 1 hour and allowed to cool naturally to room temperature.

The TiO₂-coated slide was immersed in the dye solution and kept in the dark for 24 hours to facilitate effective dye adsorption. After sensitization, the slide was rinsed to remove unbound dye molecules and air-dried at room temperature.

Finally, two edges of the sensitized slide were covered with adhesive tape, leaving one edge exposed to serve as an electrical contact.

Fig 3: Preparation of Photoanode using TiO₂

Counter Electrode (Graphite): Owing to the high cost of platinum, this study employed graphite as a cost-effective alternative for the counter electrode. The graphite counter electrode was placed adjacent to the photoanode and held in position using clips, and it was fabricated using pencil graphite as the electrode material.

The FTO glass substrate is thoroughly cleaned, and its conductive surface is identified using a multimeter.

In the case of pencil-coated substrates, the slide is annealed at 350 °C for 45 minutes to develop the photocathode layer.

Graphite is deposited onto the conductive side using either a pencil or candle, while one edge is left uncoated to allow electrical connection.

For candle-coated substrates, the carbon layer is stabilized by heating at 100 °C for 30 minutes.

After heat treatment, the prepared slide is allowed to cool naturally to room temperature prior to device assembly.

Fig 4: Preparation of Graphite counter electrode

IR Characterization:

In the present study, FTIR analysis was carried out using a Shimadzu IR AFFINITY-1 spectrophotometer operating in the range of 4000–600 cm^{-1} .

J-V Characterization

The prepared DSSCs were tested under artificial illumination provided by a halogen lamp, and their electrical performance was systematically assessed. Important photovoltaic parameters, namely open-circuit voltage (V_{oc}), short-circuit current density (J_{sc}), maximum power output (P_{max}), fill factor (FF), and overall power conversion efficiency, were obtained from the I–V measurements. The adopted approach highlights the use of mixed dye systems in combination with surfactants and metal salts to enhance light absorption over a wider spectral range, improve charge transfer processes, and optimize overall device performance. Moreover, the use of low-cost materials and simple fabrication procedures provides a practical and scalable pathway for the advancement of DSSC technology. The following parameters were evaluated to calculate the efficiency of the synthesized DSSCs.

1. **V_{oc} (open-circuit voltage):** V_{oc} represents the maximum voltage produced by a dye-sensitized solar cell when there is no external current flow. It corresponds to the voltage at which the net current in the I–V curve becomes zero.
2. **J_{sc} (current density):** J_{sc} is defined as the the maximum photocurrent per unit area generated under short-circuit conditions (zero voltage).
3. **P_{max} (maximum power point):** The maximum power output occurs at a specific operating point characterized by voltage (V_{pp}) and current (I_{pp}), and is expressed as:

$$P_{max.}) = V_{pp} * I_{pp}$$

4. **FF (fill factor):** The fill factor provides a measure of the quality and stability of the solar cell, with higher FF values indicating better performance. The fill factor is given by:

$$FF = V_{pp} * I_{pp} / J_{sc} * V_{oc}$$

5. **Efficiency of the Cell (η):** The power conversion efficiency (η) is a crucial parameter that represents the ability of the DSSC to convert incident light energy into electrical energy and is calculated using the standard efficiency expression:

$$\eta = \frac{FF \times J_{sc} \times V_{oc}}{P_{in}} \times 100$$

III. RESULT AND DISCUSSION

The FTIR spectrum of the *Beta vulgaris* dye extract, as shown in figure 5, provides important information regarding the functional groups present in the dye molecules, which play a crucial role in their performance as sensitizers in dye-sensitized solar cells (DSSCs). The presence of polar functional groups such as –OH, –COOH, and C=O is particularly significant, as these groups are known to enhance dye adsorption on the TiO₂ surface and facilitate efficient charge transfer processes. Such interactions ultimately contribute to improved electrical conductivity and enhanced photovoltaic performance of the solar cell. In the recorded FTIR spectrum, a broad and intense absorption band observed around 3427.1 cm⁻¹ is attributed to the stretching vibrations of hydroxyl (–OH) groups. This broad peak indicates the presence of hydrogen-bonded –OH groups, which are characteristic of phenolic compounds, alcohols, and organic acids commonly found in *Beta vulgaris* pigments such as betalains. The abundance of –OH groups enhances the anchoring ability of the dye molecules onto the TiO₂ surface through hydrogen bonding and coordination interactions, thereby improving dye loading and interfacial contact. A prominent peak observed at 1642.1 cm⁻¹ corresponds to the stretching vibration of C=O groups, which may arise from carboxylic acids, ketones, or amide functionalities present in the dye extract. The presence of C=O and –COOH groups is particularly important for DSSC applications, as these functional groups act as anchoring moieties that bind strongly to the TiO₂ semiconductor surface.

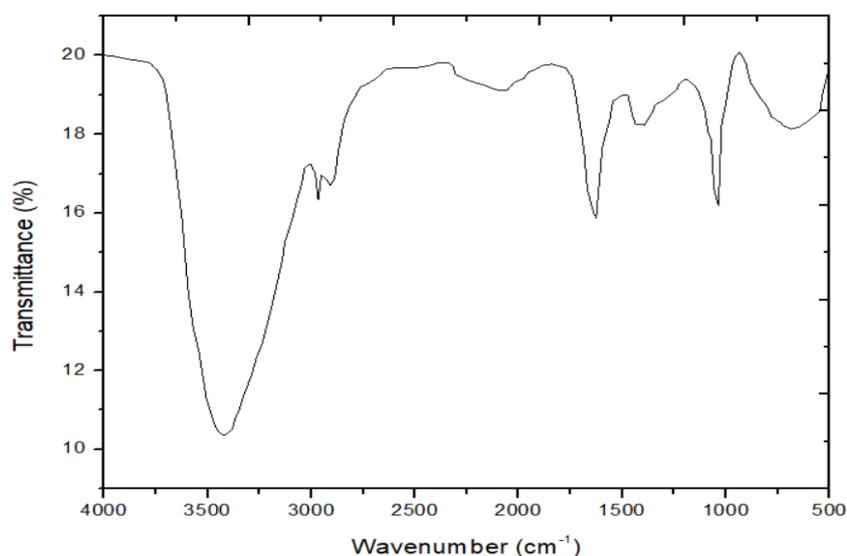


Fig 5: FTIR spectrum of *Beta vulgaris* dye

The FTIR spectrum of the dye extracted from *Butea monosperma* flowers, as presented in figure 6, reveals the presence of several characteristic absorption bands corresponding to important functional groups associated with natural pigments. The FTIR analysis confirms the presence of –C=O and –OH/–HOH functional groups in the *Butea monosperma* dye pigments, which are typical of flavonoids and anthocyanin-based compounds. A broad absorption

band observed in the region of 2975–3600 cm^{-1} , with prominent peaks around 3310 cm^{-1} , corresponds to the stretching vibrations of hydroxyl (–OH) groups. These hydroxyl groups are essential for strong binding of dye molecules to the TiO_2 surface through hydrogen bonding and coordination interactions, thereby enhancing dye adsorption and stability on the semiconductor surface. The presence of a distinct absorption band around 2115 cm^{-1} is attributed to –HOH stretching vibrations, which may arise due to residual ethanol solvent used during the dye extraction process. Additional peaks observed at 1634 cm^{-1} are assigned to the stretching vibrations of carbonyl (C=O) groups, indicating the presence of conjugated ketone or carboxyl functionalities within the pigment structure. These carbonyl groups serve as anchoring sites for effective electron injection from the excited dye molecules into the conduction band of TiO_2 . Furthermore, absorption bands at 1403 cm^{-1} are associated with in-plane bending vibrations of C–H bonds, while peaks appearing at 1083 cm^{-1} , 1040 cm^{-1} , and 880 cm^{-1} correspond to various C=O stretching and C–O vibrational modes. The peak observed near 607 cm^{-1} is attributed to the stretching vibrations of C–O–C aliphatic ester linkages, indicating the presence of esterified functional groups within the pigment molecules. The collective presence of hydroxyl and carbonyl functional groups suggests that the pigments of *Butea monosperma* can bind efficiently to the porous TiO_2 film through monodentate, bidentate, or chelating coordination modes. Consequently, this enhances charge separation and reduces recombination losses in DSSCs.

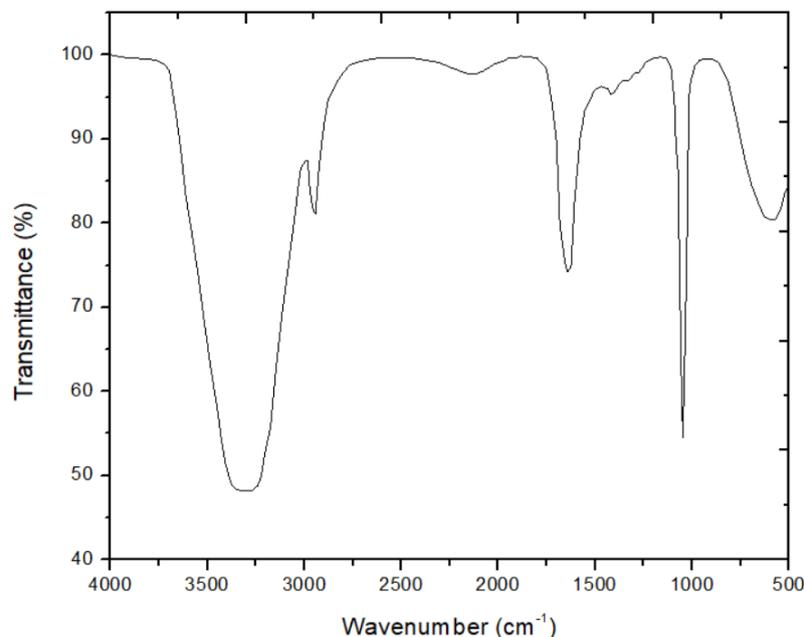


Fig 6: FTIR spectrum of *Butea monosperma* dye

DSSC modules were fabricated and systematically evaluated to determine their photovoltaic performance and efficiency. The electrochemical behavior and overall device performance were analyzed for different systems. I–V measurements were carried out using a digital multimeter, and key performance parameters—including V_{oc} , J_{sc} , FF, and η —were calculated. The fabricated DSSCs were tested for voltage and current output by connecting them to a variable load resistor in an external circuit. Measurements of V_{oc} and J_{sc} were performed under standard illumination conditions of 100 mW/cm^2 (AM 1.5G), and the corresponding current density–voltage (J–V) curves were recorded. These curves were further analyzed to obtain parameters such as V_{pp} and I_{pp} , which were used to evaluate the FF and η . Under illumination, the cell initially exhibits maximum current at zero potential; as the operating conditions change, the voltage gradually increases while the current decreases, until the current reaches zero at the open-circuit condition.

Among the plant-based dyes, *Beta vulgaris* exhibited relatively low photovoltaic performance, with a V_{oc} of 0.521 V, J_{sc} of 0.318 mA, FF of 0.497, and a very low conversion efficiency of 0.082%. The limited current generation and low efficiency can be attributed to insufficient light absorption across the visible spectrum, weaker electronic coupling with the TiO_2 photoanode, and possible recombination losses at the dye–semiconductor interface. Although *Beta vulgaris*

contains functional groups such as –OH and –COOH that facilitate dye adsorption, its overall charge injection and transport capabilities appear to be limited. In contrast, *Butea monosperma* demonstrated a markedly superior performance among the natural dyes. The DSSC sensitized with *Butea monosperma* showed a higher V_{oc} of 0.711 V and a substantially enhanced J_{sc} of 4.649 mA, along with an improved FF of 0.616, resulting in a conversion efficiency of 2.038%. This improved performance can be attributed to the presence of anthocyanin and flavonoid pigments, which exhibit stronger absorption in the visible region and possess suitable functional groups for effective anchoring to the TiO_2 surface. The higher fill factor also indicates reduced internal resistance and improved charge transport within the cell.

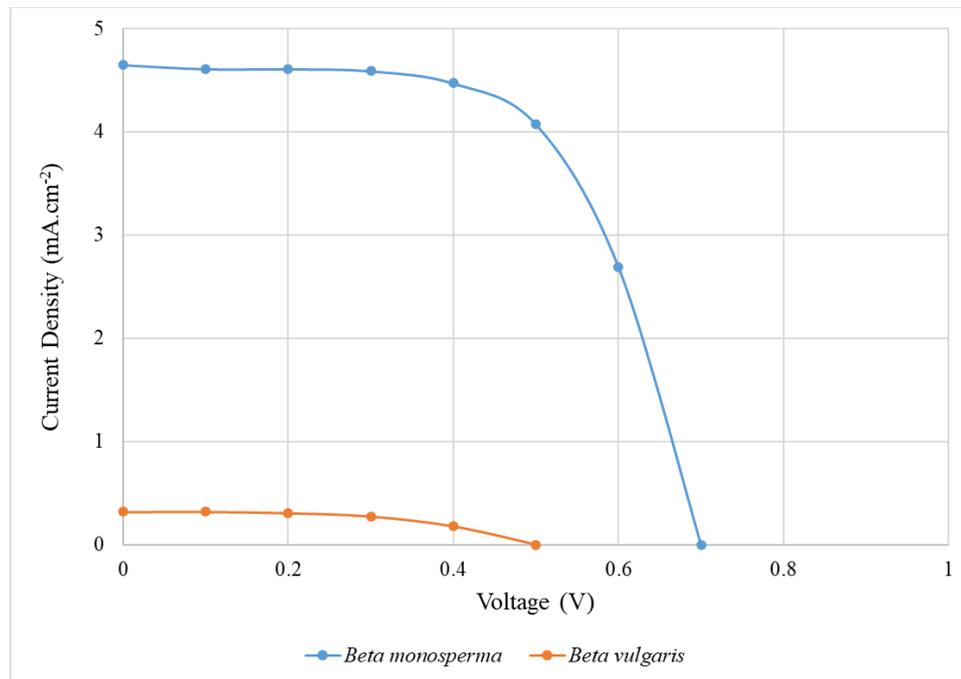


Fig 7: J–V Characteristics of DSSCs using plant-based dyes

Table 4: Photovoltaic parameters of DSSCs sensitized with natural dyes

S. No.	Sample	V_{oc} (V)	J_{sc} (mA)	FF	η (%)
1	<i>Beta vulgaris</i>	0.521	0.318	0.497	0.082
2	<i>Butea monosperma</i>	0.711	4.649	0.616	2.038

The findings of the present study on *Beta vulgaris*-based dye-sensitized solar cells (DSSCs) are largely consistent with trends reported in earlier investigations, while also highlighting certain limitations and contextual differences arising from material choice, extraction conditions, and device architecture. In the present study, FTIR analysis of *Beta vulgaris* dye confirmed the presence of key polar functional groups such as –OH, –COOH, and carbonyl (C=O), with prominent absorption bands around 3427.1 cm^{-1} and 1642.1 cm^{-1} . These observations are in strong agreement with several earlier studies. For instance, Adenam et al. (2020) reported similar FTIR peaks corresponding to O–H, C=O, and C–O–C groups in betalain pigments extracted from beetroot using various solvents. Likewise, Saikia et al. (2025) and Kumar et al. (2021) also confirmed the presence of hydroxyl and carbonyl functional groups in beetroot dyes, emphasizing their role in anchoring dye molecules onto TiO_2 surfaces. These consistent FTIR findings across studies

indicate that *Beta vulgaris* dye inherently possesses functional groups favorable for adsorption on semiconductor surfaces through hydrogen bonding and coordination interactions. Thus, from a chemical compatibility perspective, the results of the present study are in good agreement with previous reports. However, as also suggested by earlier authors, the presence of anchoring groups alone does not guarantee high photovoltaic efficiency, as the electronic structure and excited-state energy alignment of the dye play equally important roles.

The photovoltaic performance obtained in the present study for *Beta vulgaris*-sensitized DSSCs ($\eta = 0.082\%$, $V_{oc} = 0.521$ V, $J_{sc} = 0.318$ mA) falls within the lower-to-moderate range of efficiencies reported in the literature for beetroot-based DSSCs. Almutairi et al. (2022) reported a V_{oc} of 0.38 V and a J_{sc} of 130 $\mu\text{A}/\text{cm}^2$, which is comparable in magnitude to the low current density observed in the present work. Similarly, Patni et al. (2017) reported efficiencies between 0.026% and 0.047% depending on electrolyte composition, values that are slightly lower but broadly consistent with the present findings. On the other hand, some studies have reported higher efficiencies for beetroot-based DSSCs under optimized conditions. For example, Sathyajothi et al. (2017) reported an efficiency of 1.3% using beetroot dye, while Saikia et al. (2025) achieved a maximum efficiency of 0.0155% depending on solvent choice. Kumar et al. (2021) reported an efficiency of 0.11% when beetroot dye was co-sensitized with chlorophyll. These variations highlight the strong dependence of device performance on factors such as dye extraction solvent, co-sensitization strategies, semiconductor morphology, electrolyte composition, and fabrication techniques. The relatively lower efficiency observed in the present study, despite good FTIR-confirmed anchoring functionality, suggests limitations related to weak light absorption over the full visible spectrum, poor overlap between the dye's excited-state energy levels and the TiO_2 conduction band, and increased recombination losses. Similar conclusions were drawn by Adenam et al. (2020), who emphasized that solvent choice significantly affects the optical bandgap and photoabsorber properties of beetroot pigments.

Several recent studies have demonstrated that performance improvements can be achieved through material and structural modifications. Soni et al. (2021) reported a substantial relative increase in efficiency by using C, N, and S co-doped TiO_2 , which enhanced visible-light sensitivity and charge injection from betalain dyes. Shah et al. (2023) showed that co-sensitization strategies involving beetroot and other natural dyes broaden absorption and reduce dye aggregation, leading to improved current density and efficiency. Similarly, Kumari et al. (2020) highlighted that blending beetroot dye with polymer matrices improves film formation and stability, which are critical for organic and hybrid solar cells. In contrast, the present study employed *Beta vulgaris* dye without extensive semiconductor doping, co-sensitization, or polymer modification. This deliberate approach allows a clearer assessment of the intrinsic limitations of the dye itself, thereby reinforcing the conclusion that while *Beta vulgaris* dye is chemically compatible with DSSC architectures, its standalone photovoltaic performance remains modest. In contrast, the FTIR spectrum of *Butea monosperma* dye exhibited intense and diverse absorption features corresponding to hydroxyl ($-\text{OH}$) and carbonyl ($\text{C}=\text{O}$) functional groups, along with additional peaks related to $\text{C}-\text{O}-\text{C}$ ester linkages and $\text{C}-\text{H}$ bending vibrations. The broad $-\text{OH}$ stretching band in the range of 2975–3600 cm^{-1} and the distinct $\text{C}=\text{O}$ stretching band around 1634 cm^{-1} indicate a high density of anchoring groups capable of forming monodentate, bidentate, or chelating bonds with the TiO_2 surface. These observations are fully consistent with earlier studies that have identified *Butea monosperma* pigments as rich in flavonoids, chalcones, and anthocyanin-like compounds.

Agarkar et al. (2011) reported that isobutrin, a chalcone pigment extracted from *Butea monosperma*, forms a strong and stable chelate with TiO_2 through carbonyl and hydroxyl groups, resulting in efficient dye– TiO_2 charge transfer. The strong dye–semiconductor interaction observed in their study directly supports the FTIR-based interpretation of the present work, which suggests improved electronic coupling and efficient electron injection due to the abundance of anchoring functional groups. Similarly, Yadav et al. (2023) emphasized that *Butea monosperma* dye exhibits favorable optical properties and strong binding affinity toward TiO_2 nanorods, leading to enhanced light harvesting and charge transfer. The FTIR results of the present study align well with these conclusions, confirming that the molecular structure of *Butea monosperma* dye is inherently suitable for DSSC applications. The DSSC sensitized with *Butea monosperma* dye in the present study achieved a V_{oc} of 0.711 V, J_{sc} of 4.649 mA, FF of 0.616, and an overall efficiency of 2.038%. This performance represents a substantial improvement over *Beta vulgaris* dye used in the same experimental framework and clearly demonstrates the superior sensitization capability of *Butea monosperma*. When compared with previous studies, the efficiency obtained in the present work is in close agreement with reported values. Yadav et al. (2023) reported a power conversion efficiency of 2.89% for DSSCs fabricated using *Butea monosperma* flower extract, which is slightly higher than the value obtained in the present study. The higher efficiency in their work

can be attributed to the use of vertically aligned TiO₂ nanorod arrays, which provide direct pathways for electron transport, enhanced electrolyte infiltration, and reduced recombination losses.

In contrast, the present study employed a conventional TiO₂-based photoanode, which, while effective, may not offer the same level of charge transport efficiency as nanorod architectures. Qurratulain et al. (2025) also reported an efficiency of 1.34% for TiO₂-based DSSCs sensitized with *Butea monosperma* dye, which is lower than the efficiency achieved in the present study. This comparison highlights that the present device fabrication strategy, dye extraction method, and interfacial compatibility between dye and TiO₂ contributed to improved charge transport and reduced internal resistance, as reflected by the higher fill factor (0.616). Furthermore, Agarkar et al. (2011) demonstrated that chelation of *Butea monosperma* pigment with Ti ions leads to favorable HOMO–LUMO alignment with the TiO₂ conduction band, enabling efficient electron injection. The relatively high Voc and FF observed in the present study are consistent with this mechanism, indicating effective energy level alignment and suppressed recombination losses.

IV. CONCLUSION

In the present study, DSSCs were successfully fabricated using plant-based natural dyes, namely *Beta vulgaris* and *Butea monosperma*, employing a TiO₂ photoanode, graphite counter electrode, and a KI/I₂ electrolyte. FTIR analysis confirmed the presence of hydroxyl and carbonyl functional groups in both dyes, which facilitate effective adsorption of dye molecules onto the TiO₂ surface. The DSSC sensitized with *Beta vulgaris* exhibited low photovoltaic performance ($\eta = 0.082\%$), indicating limited light absorption and charge transfer efficiency despite favorable anchoring functional groups. In contrast, *Butea monosperma* showed significantly improved performance, achieving a higher efficiency of 2.038%, attributed to its strong visible-light absorption and better electronic interaction with the TiO₂ photoanode. Overall, the findings demonstrate that *Butea monosperma* is a more efficient natural sensitizer than *Beta vulgaris* and highlight the potential of plant-based dyes for developing low-cost and eco-friendly DSSCs. Further optimization of materials and device architecture could lead to enhanced performance of natural dye-sensitized solar cells.

REFERENCES

1. Qurratulain, N., Kazmi, S. A., Hameed, S., Pachauri, R. K., Khan, B., & Ali, A. (2025). Study on dye-sensitized solar cell efficiency improvement using methyl orange dye. *Materials for Renewable and Sustainable Energy*, 14(1). <https://doi.org/10.1007/s40243-025-00296-9>
2. Saikia, P. J., Saikia, D., Borah, M. M., Nath, S. D., Gogoi, B., & Kumar, P. (2025). Effect of different solvents on the performance of dye sensitized solar cell (DSSC) fabricated using beetroot dye. *International Journal of Engineering Trends and Technology*, 73(8), 202–213. <https://doi.org/10.14445/22315381/IJETT-V73I8P117>
3. Shah, W., Faraz, S. M., Arshad, S., Haider, S. S., & Sayyad, M. H. (2023). Co-sensitized DSSC with natural dyes extracted from beetroot, pomegranate and cranberry. *Engineering Proceedings*, 32(1), 13. <https://doi.org/10.3390/engproc2023032013>
4. Yadav, S. C., Tiwari, M. K., Kanwade, A., Lee, H., Ogura, A., & Shirage, P. M. (2022). *Butea monosperma*, crown of thorns, red *Lantana camara* and royal poinciana flowers extract as natural dyes for dye sensitized solar cells with improved efficiency. *Electrochimica Acta*, 441, 141793. <https://doi.org/10.1016/j.electacta.2022.141793>
5. Soni, K., Sheikh, A., Jain, V., & Lakshmi, N. (2021). Application of natural betalain dye from beetroot for improved efficiency in dye sensitized solar cell. *IOP Conference Series: Materials Science and Engineering*, 1187, 012005. <https://doi.org/10.1088/1757-899X/1187/1/012005>
6. Almutairi, M. A., Farooq, W., & AlSalhi, M. (2021). Photovoltaic and impedance properties of dye-sensitized solar cell based on natural dye from beetroot. *Current Applied Physics*, 40, 119–125. <https://doi.org/10.1016/j.cap.2021.07.010>
7. Kumar, A., Ramalingam, G., & Vetrivelan, V. (2021). Fabrication of natural dye sensitized solar cell using *Tridax procumbens* leaf and beetroot extract mixer as a sensitizer. *JSM Nanotechnology and Nanomedicine*, 8(1), 1076.
8. Kumari, N. (2020). Polyvinyl alcohol/beetroot dye film as light absorbing material in solar cell. *AIP Conference Proceedings*, 2298, 020023. <https://doi.org/10.1063/5.0029894>
9. Adenam, N., Pirdaus, N., Mat Yunin, M. Y. A., Azmie, K., Wong, K., Adli, H., & Salleh, H. (2020). Study of *Beta vulgaris* (beetroot) extraction in polar solvents as photoabsorber in dye-sensitized solar cells application. *IOP Conference Series: Earth and Environmental Science*, 596, 012014. <https://doi.org/10.1088/1755->

[1315/596/1/012014](#)

10. Patni, N., Sharma, P., Kumari, K., & Pillai, S. G. (2017). Synthesis of dye-sensitized solar cells using polyaniline and natural dye extracted from beetroot. *Research Journal of Recent Sciences*, 6(2), 35–39.
11. Sathyajothi, S., Jayavel, R., & Dhanemozhi, A. C. (2017). The fabrication of natural dye sensitized solar cell (DSSC) based on TiO₂ using henna and beetroot dye extracts. *Materials Today: Proceedings*, 4, 668–676.
12. Agarkar, S., Kulkarni, R., Dhas, V., Chinchansure, A., Hazra, P., Joshi, S., & Ogale, S. (2011). Isobutrin from *Butea monosperma* (flame of the forest): A promising new natural sensitizer belonging to chalcone class. *ACS Applied Materials & Interfaces*, 3(7), 2440–2444. <https://doi.org/10.1021/am200341y>



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