

## **Comparison of Optical Properties of Natural Dyes (Coffee, Turmeric, and Beetroot) for Dye - Sensitized Solar Cells (DSSCs)**

**Sakshi Shukla**

Lab Instructor, Career Point School of Pharmacy, Career Point University Kota, Rajasthan

Email # sakshishukla.2405@gmail.com

**Abstract:** Dye-sensitized solar cells (DSSCs) have emerged as a compelling, cost-effective, and sustainable alternative to conventional silicon-based photovoltaics. Natural plant-derived dyes serve as promising sensitizers due to their broad absorption spectra, inherent non-toxicity, and high availability. This research evaluates and compares the optical properties of beetroot, turmeric, and coffee to assess their viability in DSSC applications. UV-Vis spectroscopy revealed distinct absorption peaks across the visible spectrum: beetroot (rich in betalains) exhibited significant absorption between 480–600 nm, turmeric (containing curcumin) peaked in the 400–500 nm blue light range, and coffee extract (comprising quinones and polyphenols) showed broad absorption from 350–550 nm. Beetroot demonstrated superior light-harvesting efficiency based on molar extinction coefficient and bandgap energy analysis. Furthermore, fluorescence analysis elucidated electron recombination tendencies affecting charge transfer. Performance metrics, including open-circuit voltage and short-circuit current, confirmed that beetroot-based DSSCs achieved the highest overall efficiency, followed by coffee and turmeric. This study underscores the critical role of optical characterization in dye selection and suggests that future research focuses on co-sensitization and structural modifications to enhance stability and injection efficiency..

**Keywords:** Coffee, turmeric, beetroot, DSSC, natural dyes, optical characteristics, UV-Vis spectroscopy,

### **I. Introduction**

#### **A. Background on DSSCs**

The architecture of a Dye-Sensitized Solar Cell (DSSC) consists of a photoelectrochemical system where a photosensitive dye is adsorbed onto a mesoporous titanium dioxide ( $\text{TiO}_2$ ) semiconductor. Initially developed in 1991, these devices offer significant advantages, including mechanical flexibility, optical semi-transparency, and cost-effective

manufacturing processes. Unlike traditional silicon photovoltaics, DSSCs decouple the processes of light absorption and charge carrier transport; the dye handles photon capture while the semiconductor/electrolyte interface manages charge movement. This functional separation allows for extensive flexibility in material selection and optimization.( 1, 4)

## **B. Importance of Natural Dyes**

### **Natural Dyes are Superior for Sustainable Goals Like**

**Ecological Footprint:** Unlike synthetic Ruthenium (Ru) complexes—which involve heavy metals and toxic solvents during synthesis—coffee, turmeric, and beetroot extracts are biodegradable and generate zero toxic waste.

**Resource Abundance:** Ruthenium is a rare platinum-group metal, making it expensive and finite. In contrast, the raw materials for natural dyes are agricultural products available globally at a fraction of the cost.

**Simplified Processing:** Natural dyes can be extracted using simple "Green Chemistry" methods, such as aqueous or ethanol extraction at room temperature, whereas synthetic dyes require high-pressure, high-temperature multi-step synthesis.

**Biodegradability:** At the end of a solar cell's lifecycle, natural dyes decompose safely, facilitating easier recycling of the TiO<sub>2</sub> and glass components.( 3,4)

## **C. Overview of Selected Dyes**

The effectiveness of a natural dye in a DSSC depends on its ability to anchor to the TiO<sub>2</sub> surface and absorb a broad range of the solar spectrum.

- **Coffee (Chlorogenic Acids):** Coffee contains polyphenols, primarily chlorogenic acid. It features carboxylic acid groups that act as "anchors," allowing the dye to bind effectively to the TiO<sub>2</sub> semiconductor. It offers a broad but moderate absorption profile.
- **Turmeric (Curcuminoids):** The active component is curcumin. It has a high molar extinction coefficient, meaning it is very efficient at absorbing light at its peak wavelength (~420 nm). However, its narrow absorption band limits its ability to capture red and green light.

- **Beetroot (Betalains):** Beetroot contains betacyanins (red-violet) and betaxanthins (yellow). These pigments are highly effective because they contain carboxylic acid functional groups that facilitate strong electronic coupling with the TiO<sub>2</sub> conduction band, leading to better electron injection. 3-5

## II. Methodology

### A. Dye Extraction Techniques

The goal is to obtain the highest pigment concentration without degrading the sensitive biological molecules.

- **Solvent Extraction (Ethanol/Methanol):** Alcohol is used for turmeric and beetroot because curcumin and betalains are highly soluble in polar organic solvents. Alcohol also helps in faster evaporation during the drying phase.
- **Aqueous Extraction:** Coffee grounds are treated with hot water to extract soluble polyphenols. The temperature must be controlled to prevent the thermal degradation of the antioxidant properties.
- **Purification:** Centrifugation is critical to ensure no solid plant tissue remains, as particles would block the pores of the TiO<sub>2</sub> film and reduce efficiency.

### B. Characterization Methods

**UV-Vis Spectroscopy:** Used to calculate the **Optical Bandgap (E<sub>g</sub>)** of the dye using Tauc plots. A lower bandgap generally allows for the absorption of lower-energy (longer wavelength) photons.

**Fluorescence Spectroscopy:** This measures the "Excited State Lifetime." If a dye has low fluorescence when attached to TiO<sub>2</sub>, it indicates a successful "quenching" process—meaning the electron moved into the semiconductor instead of falling back and emitting light.

**FTIR (Fourier Transform Infrared Spectroscopy):** This confirms the presence of {OH} and {COOH} groups. By comparing the FTIR of the pure dye vs. the dye TiO<sub>2</sub> complex, we can see if chemical bonds actually formed.<sup>3, 4.</sup>

### C. DSSC Fabrication

1. **TiO<sub>2</sub> photoanode:** Mesoporous layer that is sintered and screen-printed.
2. **Adsorption of dye:** Submersion in a dye solution for 12 to 24 hours.
3. **Electrolyte:** redox mediator of iodide and triiodide.
4. **Counter electrode:** conductive glass covered with platinum 1,4

### III. Optical Properties of Coffee-based Dyes

#### A. Absorption Spectrum

- Chlorogenic acids have broad absorption between 300 and 600 nm, with a peak at approximately 450 nm. 3
- Mildly intense in contrast to artificial dyes.

#### B. Fluorescence Characteristics

- Due to the quick injection of electrons into TiO<sub>2</sub>, there is weak fluorescence.

#### C. Light Harvesting Efficiency (LHE)

LHE is a measure of how many photons the dye can potentially capture. It is calculated as:

$LHE = 1 - 10^{-A}$  (where A is Absorbance).

- **Beetroot (65–75%):** Highest due to the synergistic effect of multiple betalain pigments.
- **Coffee (60–70%):** Consistent but limited by the lower concentration of active pigments per gram of extract.
- **Turmeric (50–60%):** Lowest LHE overall because it "misses" most of the visible spectrum beyond 500 nm.
- LHE is between 60 and 70 percent, with a smaller absorption range than black dye 3,4.

### IV. Optical Properties of Turmeric-based Dyes

#### A. Absorption Spectrum

- Curcumin exhibits a sharp peak at approximately 420 nm, with little absorption observed past 500 nm 3.

## B. Fluorescence Characteristics

- Quantum yield of fluorescence is high, suggesting recombination losses( 3).

## C. Light Harvesting Efficiency

- LHE ~50–60% due to limited spectral coverage( 3).

## V. Optical Properties of Beetroot-Based Dyes

### A. Absorption Spectrum

- They encompass green-blue regions and have two peaks at about 480 nm and 535 nm (betalains)( 3).

### B. Fluorescence Characteristics

- The structure of betanin facilitates charge separation, which results in moderate fluorescence( 3).

### C. Light Harvesting Efficiency

- Due to wider absorption, LHE is the highest among natural dyes, ranging from 65 to 75%.

## VI. Comparative Analysis

Property	Coffee	Turmeric	Beetroot
Absorption range	300–600 nm	350–500 nm	400–600 nm
Peak intensity	Moderate	High	High
Photostability	Moderate	Low	Moderate
Conversion	0.5–0.7%	0.3–0.5%	0.8–1.2%

efficiency			
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- **Electron injection efficiency:** Due to betalain's LUMO alignment with TiO<sub>2</sub>, beetroot > coffee > turmeric 3.
- **Photostability:** Turmeric breaks down more quickly than coffee and beetroot when exposed to UV light 4.

## VII. Factors Affecting Optical Properties

### A. pH Dependence

- The betalains in beetroot break down at pH values greater than 6, whereas curcumin remains stable at pH 3.

### B. Solvent Effects

- The yield of curcumin extraction is higher with ethanol than with water (3).

### C. Temperature Sensitivity

- Elevated temperatures (over 60°C) denature betalains, which decreases absorption (3).

### D. Concentration Effects

- LHE is decreased by dye aggregation brought on by oversaturation (>0.5 mM)(3).

## VIII. Challenges and Limitations

- **Stability:** Natural colors break down more quickly than their synthetic counterparts (ruthenium dyes, for example, endure more than 500 hours) 4.
- **Efficiency:** 15.2% for the most advanced DSSCs versus less than 2% 4.
- **Scalability:** Natural sources vary from batch to batch, which impacts consistency 3.

## IX. Future Perspectives

### A. Dye Optimization

- 4. Hybrid systems (such as coffee + beetroot) for panchromatic absorption 3.

- Nanostructured TiO<sub>2</sub> to improve dye loading and electron transport

## **B. Emerging Applications**

- Utilizing the low-light efficiency of DSSCs, indoor light-harvesting for Internet of Things devices 4.

## **X. Conclusion**

### **A. Key Findings**

- Among natural dyes, beetroot has the highest effectiveness (1.2%) because of its wide absorption and advantageous charge injection.
- While turmeric experiences quick photodegradation, coffee strikes a balance between stability and performance.

### **B. Recommendations**

- For high-efficiency applications, give priority to beetroot; for stability, combine with coffee.

### **C. Sustainability Impact**

- Natural dyes lower the cost of producing DSSCs by 30–40% and are consistent with the circular economy 3,4.

This paper summarizes developments in natural dye research and DSSC technology, offering practical advice for the development of sustainable solar energy.

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