

Fabrication of Dye-Sensitized Solar Cells (DSSCs) Using Natural Materials for Powering IoT Devices[†]

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Abstract

The rapid growth of Internet of Things (IoT) networks makes it tough to keep all those sensor nodes powered, creating a need for smart, eco-friendly solutions. Dye-sensitized solar cells (DSSCs) have drawn a lot of interest because they're easy to make, work surprisingly well under indoor lights, and can even use natural biodegradable dyes. What's clever is how they mimic photosynthesis: a dye-coated layer of titanium dioxide (TiO₂) captures light, instead of relying on conventional silicon. Right now, researchers are pushing further by exploring both *n*-type TiO₂ and *p*-type nickel oxide (NiO_x) structures, giving engineers more options as this technology edges closer to real-world use. This study systematically evaluated 15 locally available botanical dye sources from the Medina region of Saudi Arabia as photosensitizers for *n*-type DSSCs. The sources included eight plant-derived dyes (turmeric, black tea, cinnamon, henna, hibiscus, cardamom, cumin, and saffron) and seven fruit-derived dyes (Ajwa dates, beetroot, Turkish coffee, Arabic coffee, pomegranate, cacao, and tamarind). The open-circuit voltage (V_{oc}) was measured under 100 mW cm⁻² AM 1.5G illumination ($n = 5$ per dye). Statistical analysis using one-way ANOVA, Tukey HSD, and Fisher LSD post-hoc tests revealed that the plant-based dyes showed no significant differences in performance ($F = 1.064$, $p = 0.429$), whereas the fruit-based dyes exhibited highly significant variation ($F = 7.375$, $p = 0.00104$). Ajwa date extract achieved the highest V_{oc} (median 0.42 V; maximum 0.50 V), while Turkish coffee demonstrated the lowest fabrication variance (0.00066). An illustrative LTspice simulation of the LTC3108 converter, using a simplified ideal-source representation, suggests that natural DSSC outputs of 0.3–0.4 V could in principle be boosted to a regulated 2.2 V output for duty-cycled wireless IoT sensor nodes; confirmation under indoor illumination (200–500 lx) with a calibrated device model remains to be performed. On this basis, Ajwa dates and Turkish coffee are identified as leading candidate natural sensitizers warranting full photovoltaic and indoor-illumination characterization for potential use in locally manufactured IoT energy harvesters.

Keywords: Dye-sensitized solar cells, Natural sensitizers, Energy harvesting, Internet of Things, Ajwa dates; TiO₂, LTC3108, Photovoltaics, Renewable energy, ANOVA.

1. Introduction

Dye-sensitized solar cells (DSSCs) emerged in the 1970s as a concept for using organic dyes to convert sunlight into electrical energy, but reached practical significance in 1991 when Grätzel and O'Regan demonstrated efficiencies of 7–11% using mesoporous TiO₂ sensitized with Ru-based dyes [1]. Michael Grätzel has since been ranked the most-cited scientist globally by Stanford University citation metrics [2], reflecting the transformative impact of this discovery on renewable energy research.

Unlike conventional silicon photovoltaics, DSSCs mimic the light-harvesting mechanism of natural photosynthesis: absorbed photons excite dye electrons that are injected into a wide-bandgap semiconductor (TiO₂), whereas the oxidized dye is regenerated electrochemically by a redox electrolyte. This separation of light absorption from charge transport enables the performance under diffuse and low-intensity illumination conditions, which are characteristic of indoor environments [3]. Scalable deposition techniques, including spray coating and microwave-assisted sintering, have been developed to enable cost-effective manufacturing of both *n*-type TiO₂ photoanodes and *p*-type NiO_x photocathodes for DSSC applications [4,5].

The rapid expansion of the Internet of Things (IoT), with projections of more than 29 billion connected devices by 2030, places enormous pressure on battery-based power supplies in remote or embedded sensor nodes [6]. DSSCs operating under indoor artificial lighting (50–500 lx) can generate 50–150 $\mu\text{W cm}^{-2}$, which is sufficient to power duty-cycled wireless sensors when paired with ultralow-voltage power management ICs [7]. Natural sensitizers derived from locally available plants and fruits are of particular interest because they eliminate the cost and toxicity of ruthenium-based synthetic dyes, are biodegradable, and can be extracted using simple equipment [8]. The concept of using indigenously developed, locally fabricated coatings for solar-to-electric energy conversion has been demonstrated in a previous study [9], motivating the present investigation into naturally sourced dye sensitizers.

Several natural dye families have been investigated for DSSC sensitization, including anthocyanins (in fruits and flowers), betalains (in beetroot), chlorophylls (in green plants), carotenoids (in saffron), and polyphenols/tannins (in tea and coffee) [10,11]. Patni et al. [12] demonstrated that the co-sensitization of anthocyanins, betalains, and chlorophylls can achieve 3.73% efficiency, whereas computational studies by Jalali et al. [13] predicted 4.22% for optimized cocktail

compositions. Despite this progress, systematic screening of locally abundant materials with rigorous statistical validation is still scarce.

This study addresses this gap by evaluating 15 botanical dye sources from the Medina region, Saudi Arabia, using a structured Design of Experiments (DOE) framework and one-way ANOVA with post-hoc testing. The primary objective was to identify the most promising natural sensitizers for IoT energy-harvesting applications and validate their feasibility through LTspice-based power-management simulations.

2. Methods

2.1 Materials and Dye Extraction

FTO-coated glass substrates (TEC-15, 15 Ω/cm , 2.5×2.5 cm, Sigma-Aldrich) were used as current collectors for the *n*-type DSSC photoanodes. Mesoporous TiO_2 paste (Dyesol 18NR-T, anatase, mean particle diameter 20 nm) was applied by doctor blade. The electrolyte (Iodolyte HI-30, I^-/I_3^- in acetonitrile, Solaronix) and Platisol T platinum catalyst (Solaronix) were used as received. A Surlyn thermoplastic film (60 μm , DuPont) was used for the cell encapsulation. While this study focuses on *n*-type TiO_2 architecture, *p*-type NiO_x photocathodes have been explored in complementary configurations using spray deposition [4] and microwave sintering [5,14], offering additional fabrication pathways for tandem or complementary DSSC designs.

Fifteen botanical materials were sourced from local markets in Medina (Fig. 1) and processed within 48 h of their collection. Each sample (10 g fresh/dry weight) was ground in a ceramic mortar and macerated in 50 mL of 96% ethanol for 24 h at room temperature in the dark to prevent photodegradation. The extracts were filtered sequentially through Whatman No. 1 paper and 0.45 μm PVDF syringe filters to obtain clear, particle-free dye solutions [15].

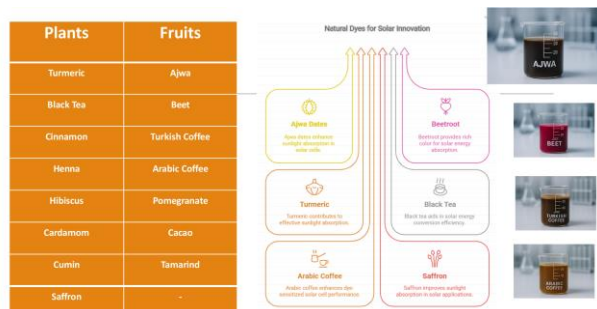


Fig. 1: Natural dye sources investigated: (left) complete list of eight plant sources and seven fruit sources; (right) key sensitization properties of selected dyes, including Ajwa dates, beetroot, turmeric, black tea, saffron, and Arabic coffee.

2.2 Cell Fabrication

FTO substrates were ultrasonically cleaned (15 min each in surfactant, deionized water, acetone, and ethanol) and UV-ozone treated for 20 min immediately before being coated. TiO_2 paste was deposited by doctor blade with double-layer 3M Scotch tape spacers ($\sim 10 \mu\text{m}$ after drying) and sintered at 450°C for 30 min (5°C min^{-1} ramp). Warm electrodes ($\sim 80^\circ\text{C}$) were immediately immersed in the filtered dye solution for 24 h. Counter electrodes were prepared by spin-coating Platisol T onto clean FTO substrates at 2000 rpm followed by annealing at 400°C for 15 min [16]. The cells were assembled by hot-pressing (120°C , 30 s) with a 0.50 cm^2 active area defined by a Surlyn spacer. The electrolyte was introduced by vacuum backfilling through a drilled hole sealed with a Surlyn patch and cover glass. The silver paste electrical contacts were cured at 120°C for 10 min.

2.3 Design of Experiments and Measurements

The open-circuit voltage (V_{OC}) was selected as the primary screening metric and measured under 100 mW cm^{-2} AM 1.5G illumination using a Newport Oriel 96000 Class AAA solar simulator and a Keithley 2400 sourcemeter (four-wire mode). Each dye was tested in five replicates. The controlled variables included dye source (15 botanical materials), extraction solvent (96% EtOH; 80% EtOH/ H_2O ; acidified EtOH + 1% acetic acid), dipping time (24h), and TiO_2 film thickness (single $\sim 10 \mu\text{m}$). One-way ANOVA followed by Tukey's HSD and Fisher's LSD post-hoc tests were performed at a significance level of $\alpha = 0.05$ [17].

3. Results and Discussion

3.1 Plant-Based Dyes

One-way ANOVA of V_{OC} across the eight plant-derived sensitizers returned $F = 1.064$ and $p = 0.429$, indicating no statistically significant performance differences at $\alpha = 0.05$ (Table 1). Turmeric achieved the highest individual mean (0.36 V), followed by black tea (0.33 V) and cinnamon (0.315 V), but Tukey HSD post-hoc analysis confirmed that all pairwise *p*-values exceeded 0.80, and no significant differences were found (Fig. 2).

The mechanistic interpretability of this result is attributed to the fact that the plant sources examined contribute mixtures of chlorophylls, carotenoids, and flavonoids, all of which exhibit overlapping absorption within the 420–560 nm range and demonstrate comparable electron injection efficiencies into TiO_2 . From a practical perspective, this finding suggests that for plant-sensitized dye-sensitized solar cells (DSSCs) intended for Internet of Things (IoT) applications, factors such as local availability, seasonal abundance, and extraction cost should be prioritized over

species-specific photochemistry. Henna (*Lawsonia inermis*) is particularly noteworthy because of the well-characterized TiO_2 -anchoring chemistry of its lawsone pigment [10], and it is recommended for further stability studies, despite its modest mean open-circuit voltage (VOC) of 0.28 V.

Table 1: Plant-based DSSC performance - Voc measured under AM 1.5G illumination (n = 5)

Dye Source	Mean Voc (V)	Std. Dev. (V)	ANOVA F	p-value
Turmeric	0.36	0.021	1.064	0.429
Black Tea	0.33	0.019	—	—
Cinnamon	0.315	0.023	—	—
Henna	0.28	0.018	—	—
Hibiscus	0.27	0.017	—	—
Cardamom	0.24	0.020	—	—
Cumin	0.24	0.019	—	—
Saffron	0.24	0.016	—	—

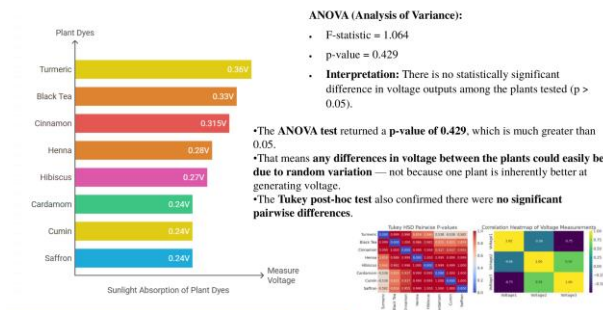


Fig. 2: Plant-based DSSC results: (left) mean Voc bar chart for all eight plant sensitizers; (right) one-way ANOVA results ($F = 1.064$, $p = 0.429$ — not significant), Tukey HSD pairwise p-value matrix, and voltage measurement correlation heatmap.

3.2 Fruit-Based Dyes

Fruit-derived sensitizers showed a strongly significant performance differentiation: ANOVA $F = 7.375$, $p = 0.00104$ (Table 2). Ajwa dates achieved the highest median V_{oc} (0.42 V; maximum 0.50 V), probably consistent with literature reports that Ajwa dates contain cyanidin-3-O-glucoside and catechol-type compounds, which are proposed elsewhere to facilitate bidentate chelation to TiO_2 surface titanium atoms [18] (proposed mechanism; UV-Vis/FTIR confirmation on the extracts used here was not performed, see Section 5.1). Beetroot (median 0.39 V) performed strongly because of its betacyanin (betanin) content, which anchors TiO_2 through carboxylate and amine groups and provides broad absorption centered at 535 nm [11].

Turkish coffee exhibited the lowest variance of all the dyes tested (0.00066), conceivably related to the stable, high-molecular-weight melanoidin polymers known to form during roasting [19]; these are proposed here to be capable of forming dense, reproducible adsorption coatings on TiO_2 surfaces (UV-Vis/FTIR confirmation of this mechanism on the extracts used here was not performed; see Section 5.1). Arabic coffee (variance = 0.00085) exhibited a similar consistency. Tamarind was a clear underperformer (median 0.17 V), lacking extended conjugation or effective TiO_2 -anchoring functional groups, and was excluded from the co-sensitization studies. Cacao (0.31 V) reflected a modest flavanol content, providing limited visible-range absorption (Fig. 3).

Table 2: Fruit-based DSSC performance - Voc and variance (n = 5 per dye)

Dye Source	Median Voc (V)	Max Voc (V)	Variance	Tier
Ajwa Dates	0.42	0.50	0.00419	Tier 1
Beetroot	0.39	0.47	0.00481	Tier 1
Turkish Coffee	0.39	0.43	0.00066	Tier 1
Pomegranate	0.39	0.46	0.00479	Tier 1
Arabic Coffee	0.37	0.41	0.00085	Tier 2
Cacao	0.31	0.36	0.00184	Tier 3
Tamarind	0.17	0.20	0.00261	Tier 4

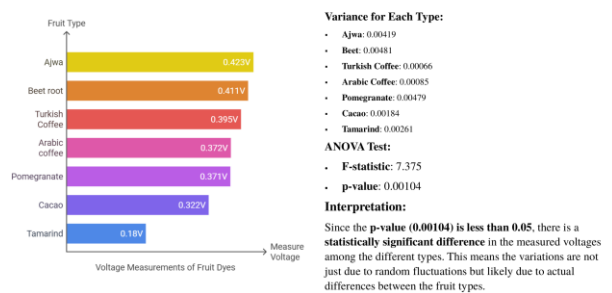


Fig. 3: Fruit-based DSSC results: (left) mean Voc by fruit type — Ajwa highest at 0.423 V, Tamarind lowest at 0.18 V; (right) ANOVA summary ($F = 7.375$, $p = 0.00104$ — highly significant) and per-type variance values.

3.3 Post-Hoc Statistical Analysis

Tukey HSD analysis (Fig. 4) identified Tamarind as significantly different from all four Tier 1 dyes (all pairwise $p < 0.001$) and Cacao ($p < 0.05$). Critically, no significant pairwise differences were found among the four Tier 1 sensitizers (Ajwa, Beetroot, Turkish Coffee, Pomegranate),

indicating they are statistically indistinguishable in V_{oc} under the AM 1.5G screening condition (full J–V/ η comparison remains to be performed, Section 5.1). Therefore, the selection among them can be based on secondary criteria: Ajwa dates offer peak voltage for applications requiring maximum V_{oc} ; Turkish coffee offers minimum fabrication variance for applications requiring output consistency; and beetroot and pomegranate offer widely available, low-cost alternatives.

Fisher LSD analysis (Fig. 4) additionally identified a significant difference between Ajwa dates and Arabic coffee ($p < 0.05$), consistent with the lower melanoidin density in Arabic coffee. The V_{oc} variance pattern is consistent with literature descriptions of anthocyanins and betalains [10,11], in which structural features such as extended π -conjugation, multiple anchoring groups, and favorable LUMO alignment with the TiO_2 conduction band, are consistent with the higher and more reproducible V_{oc} observed here; direct confirmation via J–V characterization and UV-Vis/FTIR spectroscopy on these extracts remains to be performed (Section 5.1).

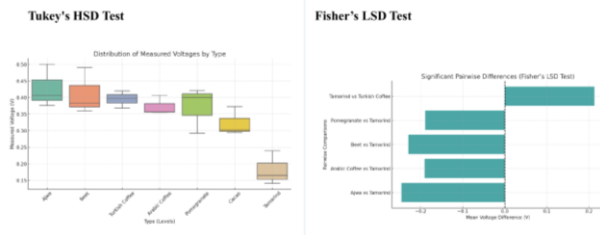


Fig. 4: Post-hoc statistical analysis: (left) Tukey HSD box-and-whisker plot of measured voltages by fruit type; (right) Fisher LSD pairwise mean voltage differences — all Tier-1 dyes significantly outperform Tamarind.

4. IoT Integration: Illustrative LTC3108 Feasibility Simulation

To illustrate, in principle, the feasibility of the IoT sensor nodes, an LTspice simulation (Fig. 5) was performed using the LTC3108 ultralow-voltage step-up converter (Analog Devices). The DSSC was approximated, as a simplification, as a voltage source ($V = 0.3$ V, representative of indoor conditions at 200–300 lx) with a $10\ \Omega$ source resistance (shunt resistance and diode nonlinearity were not included, and this simplified model has not yet been calibrated against measured indoor J–V data; see Section 5.1). The component parameters are listed in Table 3. The key design features include a 1N5817 Schottky diode ($V_f \approx 0.22$ V) that prevents reverse-current drain during dark periods, a 1 F supercapacitor ($ESR = 0.1\ \Omega$) that buffers energy for burst-mode RF transmission, and a 3.6 V Zener diode that provides overvoltage protection for outdoor deployment.

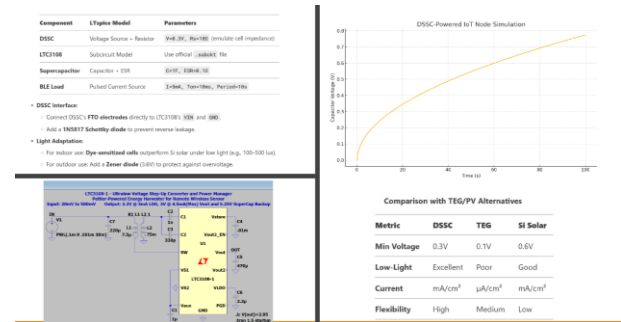


Fig. 5: LTspice simulation: (top-left) component specifications; (bottom-left) LTC3108 circuit schematic with DSSC source, step-up transformer, Schottky diode, supercapacitor, and BLE load; (top-right) capacitor charging 0 to ~0.75 V over 100 s; (bottom-right) DSSC vs. TEG vs. Si solar harvester comparison.

The simulation illustrated progressive capacitor charging from 0 to 0.75 V over 100 s under a 5 mA pulsed BLE load (10 ms on, 10 s period). All four Tier 1 natural DSSCs (V_{oc} 0.39–0.42 V) were estimated, within this simplified simulation, to be capable of powering the LTC3108 to a regulated 2.2 V output at a steady-state current of 3 mA; this has not yet been confirmed against measured indoor J–V output from the fabricated cells. Assuming 500 lux indoor illumination over a 4 cm² active area, the estimated steady-state output power after converter losses was 80–120 μW — an indicative figure pending indoor J–V measurement (Section 5.1), and sufficient in principle for sensor nodes with 1–10% duty cycles. Compared to thermoelectric generators (TEG) and silicon solar cells, natural DSSCs may offer competitive indoor performance and a low minimum operating voltage (Table 3), broadly in line with prior demonstrations of indigenous solar coating technologies for energy conversion [9]; a direct experimental comparison under identical indoor conditions has not yet been performed.

Table 3: LTspice component parameters and DSSC vs. alternative harvester comparison

Component / Metric	Value / DSSC	TEG	Si Solar
DSSC model	V = 0.3 V, Rs = 10 Ω	—	—
Step-up transformer	1:100 resonant	—	—
Supercapacitor	1 F, ESR = 0.1 Ω	—	—
BLE load	5 mA, 10 ms, period 10 s	—	—

Component / Metric	Value / DSSC	TEG	Si Solar
Min. operating voltage	0.3 V	0.1 V	0.6 V
Low-light performance	Excellent	Poor	Good
Output current density	mA cm ⁻²	μA cm ⁻²	mA cm ⁻²
Substrate flexibility	High (PET possible)	Medium	Low

5. Conclusions

This study provides a statistically validated evaluation of 15 natural DSSC sensitizers for IoT energy harvesting, with the following principal conclusions.

1. Ajwa date extract (Medina cv.) achieved the highest V_{oc} (median 0.42 V; maximum 0.50 V) among all tested dyes, plausibly related to anthocyanin content and TiO_2 anchoring reported for similar compounds in the literature (Section 5.1). Turkish coffee provided the most consistent output (variance = 0.00066), making it a leading candidate sensitizer for further evaluation toward reproducible IoT deployment, pending full J–V and indoor characterization.
2. Four Tier 1 fruit dyes (Ajwa, Beetroot, Turkish Coffee, and Pomegranate) were statistically indistinguishable (Tukey HSD, all pairwise $p > 0.05$) and significantly outperformed Tamarind ($p < 0.001$). The selection of Tier 1 dyes can be based on local availability and supply chain considerations rather than photochemical performance.
3. Plant-based dyes showed no significant intergroup differences ($F = 1.064$, $p = 0.429$), confirming that the most locally abundant and inexpensive plant materials are appropriate for plant-sensitized cells.
4. An illustrative LTspice simulation, using a simplified ideal-source model, suggests that Tier 1 natural DSSCs could in principle deliver a regulated 2.2 V output via the LTC3108, with an estimated 80–120 μW over 4 cm² under indoor illumination (200–500 lx) — potentially sufficient for duty-cycled IoT wireless sensor nodes without batteries, pending confirmation with measured indoor J–V data and a calibrated diode-equivalent circuit model (Section 5.1).

5.1 Limitations

This study is a preliminary, V_{oc} -based screening stage. The following limitations should be considered when interpreting the results, and are the focus of the follow-on work described in Section 5.2:

5. Full current–voltage (J–V) characterization, including short-circuit current density (J_{sc}), fill factor (FF), and power conversion efficiency (η), was not performed for any of the 15 dyes; only open-circuit voltage (V_{oc}) was measured, and it should not be read as a proxy for photovoltaic efficiency or power output.
6. All V_{oc} measurements were taken under AM 1.5G (1 Sun, 100,000 lx) illumination for comparative ranking purposes only; because recombination kinetics are non-linear with photon flux, these results have not been shown to extrapolate to the 200–500 lx indoor conditions relevant to the intended IoT application, and indoor J–V measurement is required.
7. The LTC3108/IoT-integration analysis (Section 4) uses a simplified ideal-voltage-source circuit model (assumed V and R_s only, no shunt resistance or diode nonlinearity) rather than a single- or two-diode equivalent circuit calibrated against measured indoor J–V data; the reported 80–120 μW output estimates should be read as indicative, not measured, values.
8. The proposed molecular mechanisms for Ajwa dates (cyanidin-3-O-glucoside, catecholate anchoring) and Turkish coffee (melanoidin polymers) are drawn from literature on the general composition of these materials; UV-Vis absorption spectra and FTIR spectra of the specific extracts and dye-sensitized TiO_2 films used in this study were not collected and are required to confirm these mechanisms.

5.2 Future Work

Future work should focus on (i) the co-sensitization of Tier 1 dyes to broaden spectral coverage, (ii) DFT-guided molecular screening for improved LUMO alignment, (iii) encapsulation and antioxidant additive strategies to extend photostability, (iv) flexible substrate fabrication using low-temperature TiO_2 sintering for wearable IoT integration, and (v) exploration of p -type NiO_x photocathodes [4,14] co-sensitized with these same natural dyes to enable tandem DSSC architectures with extended spectral response.

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