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DESIGN AND FABRICATION OF TIO_2-BASED DYE-SENSITIZED SOLAR CELLS (DSSC) FOR ENHANCED EFFICIENCY

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ABSTRACT

The global pivot toward renewable energy has catalyzed significant interest in photovoltaic technologies capable of emission-free solar-to-electrical energy conversion. While first-generation silicon-based solar cells dominate the market due to high efficiencies, their widespread deployment is often hindered by high module costs and energy-intensive manufacturing processes. Consequently, organic and third-generation solar cells have emerged as compelling alternatives. Among these, Dye-Sensitized Solar Cells (DSSCs) are particularly noteworthy for their low production costs, technical flexibility, and favorable power conversion efficiencies compared to other thin-film technologies.

This study explores the design, fabrication and comparative characterization of DSSCs sensitized with natural dyes extracted from blackberries and pomegranates. These extracts provide a sustainable and cost-effective alternative to rare-metal-based synthetic sensitizers. The optical properties of the dyes were evaluated using UV-Vis spectrophotometry, while the photovoltaic performance was quantified via current-voltage (I-V) response analysis. Key parameters including open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), fill factor (FF), and power conversion efficiency (PCE) were measured to assess the feasibility of these natural extracts for enhancing DSSC performance.

Keywords: Dye-Sensitized Solar Cells (DSSC) , Power Conversion Efficiency (PCE) , UV-Vis Spectrophotometry , Thin-Film Solar Cells , Sustainable Energy , Current–Voltage (I–V) Characteristics .

1. INTRODUCTION

1.1 Overview of Solar Energy

Solar cells, or photovoltaic (PV) cells, are semiconductor devices that convert incident solar radiation directly into electrical energy via the photovoltaic effect. As a clean, low-carbon alternative to fossil fuels, solar technology is critical for mitigating carbon and nitrogen emissions. Current global energy consumption is estimated at 14 TW and is projected to rise by an additional 10 TW over the next four decades. This growing demand necessitates the transition to inexhaustible energy sources like the sun. PV technology offers a decentralized energy solution, enabling on-site electricity generation for applications ranging from residential power to spacecraft.

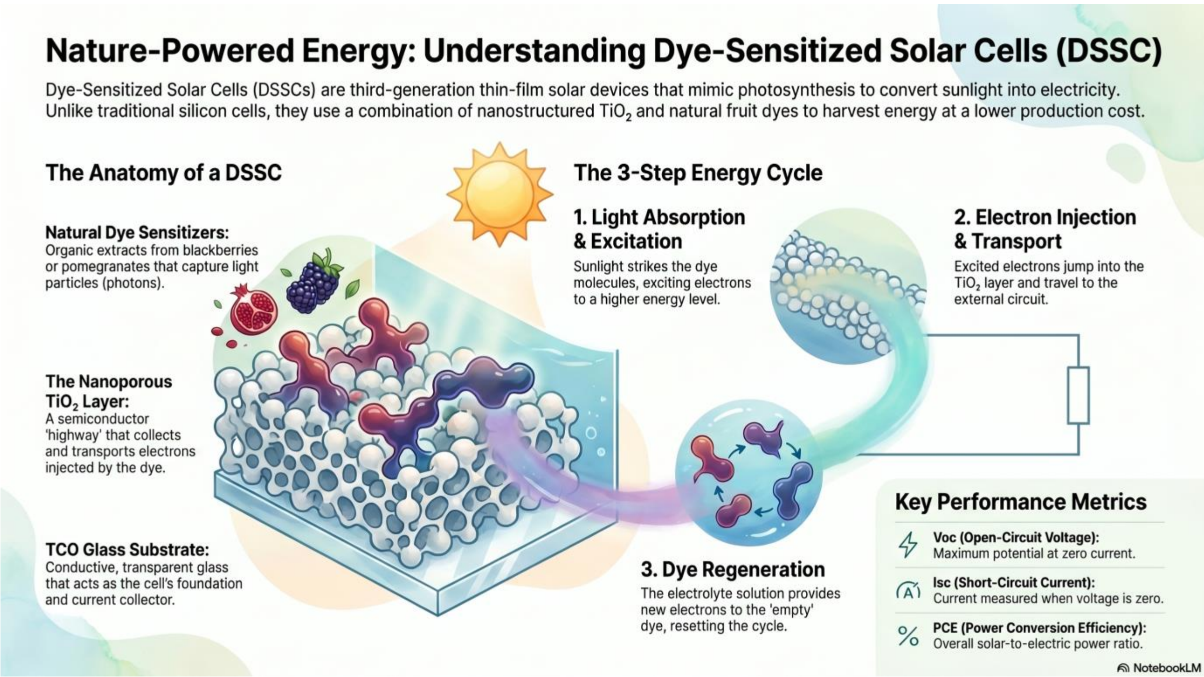

Figure 1: Steps for formation of DSSC

1.2. Evolution of Photovoltaic Technology

Photovoltaic technology is historically categorized into three generations based on materials,

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cost-effectiveness, and market maturity:

1. **First Generation:** Comprised of crystalline silicon (c-Si) cells. They represent the most mature technology with high efficiencies but remain expensive due to the high energy requirements of silicon purification.
2. **Second Generation:** Known as thin-film solar cells, utilizing materials like amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS). These are more cost-effective than the first generation but offer lower conversion efficiencies.
3. **Third Generation:** Emerging technologies that utilize novel materials to achieve high efficiency at a lower cost. This category includes organic photovoltaics (OPV), Perovskite solar cells, Quantum Dot solar cells, and Dye-Sensitized Solar Cells (DSSCs).

2. DYE-SENSITIZED SOLAR CELLS (DSSC) FUNDAMENTALS

2.1. Definition and History

DSSCs are third-generation thin-film devices characterized by a porous semiconductor layer sensitized with a light-absorbing dye. Originally developed in the 1990s by Brian O'Regan and Michael Grätzel at the École Polytechnique Fédérale de Lausanne (EPFL), these cells mimic natural photosynthesis to generate electricity, offering a lightweight and flexible alternative to rigid silicon panels.

2.2. Device Architecture

A standard DSSC is composed of five primary layers. The performance of the cell is intrinsically linked to the material properties of these components, particularly the Transparent Conductive Oxide (TCO) substrates.

Table - 1

Component	Material / Property	Function
TCO Substrate	**ITO:**>80% transmittance, ~18 Ω/cm^2 resistance; **FTO:** ~75% transmittance, ~8.5 Ω/cm^2 resistance	Acts as the current collector and structural foundation.
Semiconductor	Nanoporous Titanium Dioxide (TiO_2)	Wide-bandgap semiconductor that

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Layer		provides high surface area for dye adsorption.
Dye Sensitizer	Natural dyes (e.g., anthocyanins) or synthetic dyes (e.g., Ru-complexes)	Absorbs photons and injects excited electrons into the (TiO_2)conduction band.
Electrolyte	Iodide/Triiodide (I^-/I_3^-) redox couple	Transports ions to regenerate the oxidized dye molecules.
Counter Electrode	Graphite or Platinum-coated FTO	Facilitates the catalytic reduction of the redox mediator to complete the circuit.

2.3. Working Mechanism

The photo electrochemical process within a DSSC follows a cyclical four-step mechanism:

1. **Light Absorption:** Incident photons are absorbed by the dye molecules, promoting electrons from the ground state (S/S^+) to an excited state (S^*/S^+).
2. **Charge Separation (Electron Injection):** The excited electrons are injected into the conduction band of the TiO_2 layer. The dye molecule becomes oxidized in the process.
3. **Charge Collection:** Electrons diffuse through the TiO_2 nanoparticle network to the TCO anode, then flow through the external circuit to the counter electrode.
4. **Dye Regeneration:** The oxidized dye is reduced back to its ground state by accepting an electron from the I^- ions in the electrolyte. The resulting I_3- ions are then reduced back to I^- at the counter electrode, catalyzed by the graphite layer.

3. FABRICATION METHODOLOGY

3.1. Preparation of Materials

- **TiO_2Suspension:** 5.9g of TiO2 powder was placed in a mortar. 9ml of vinegar (acetic acid) was added **slowly** while grinding with a pestle. Careful attention was paid to the titration until the powder transitioned into a smooth, proper paste. One drop of detergent was added to reduce surface tension, and the suspension was allowed to equilibrate for 15 minutes.
- **Iodide Electrolyte Solution:** 0.125g of iodine (I_2) was dissolved in 10ml of Monoethylene Glycol (MEG). While MEG is non-conventional in standard DSSCs, it

was utilized here as a **deep eutectic solvent (DES) approach** to enhance the stability of the redox mediator. This mixture was then added to 40ml of 0.5M potassium iodide (KI).

3.2. TiO_2 Film Deposition (Doctor Blade Method)

The Doctor Blade technique was selected as it represents a "sweet spot" between experimental simplicity and precise control, enabling the production of highly uniform thin films essential for efficient light harvesting.

1. FTO glass slides were cleaned and the conductive side identified.
2. **Scotch tape** was applied to the edges of the slide to define the deposition area and, crucially, to control the **film thickness** by creating a fixed gap between the substrate and the blade.
3. 3–4 drops of TiO2 suspension were applied and spread smoothly using a glass rod.
4. The film was dried for 15 minutes, the tape removed, and the slide was sintered at 450°C for 30 minutes to solidify the nanocrystalline network.

3.3. Dye Extraction and Sensitization

Natural sensitizers were obtained by grinding fresh blackberries and pomegranates and separating the pulp from the juice. The sintered TiO2 films were then immersed in the juices. Based on absorption kinetics, a **staining duration of 72 hours** is recommended to maximize dye loading and photon capture.

3.4. Counter Electrode and Assembly

A second FTO slide was cleaned with ethanol. The conductive side was coated with graphite using a soft pencil. The graphite serves as a **catalyst** for the triiodide reduction reaction. The two electrodes were sandwiched together and the iodide electrolyte was introduced via capillary action to complete the assembly.

4. CHARACTERIZATION TECHNIQUES

4.1. UV-Vis Spectrophotometry

Absorbance measurements were conducted in the 190nm to 1000nm range using a HO-SP-3480 spectrophotometer. This analysis is vital for determining the band gap of the semiconductor and

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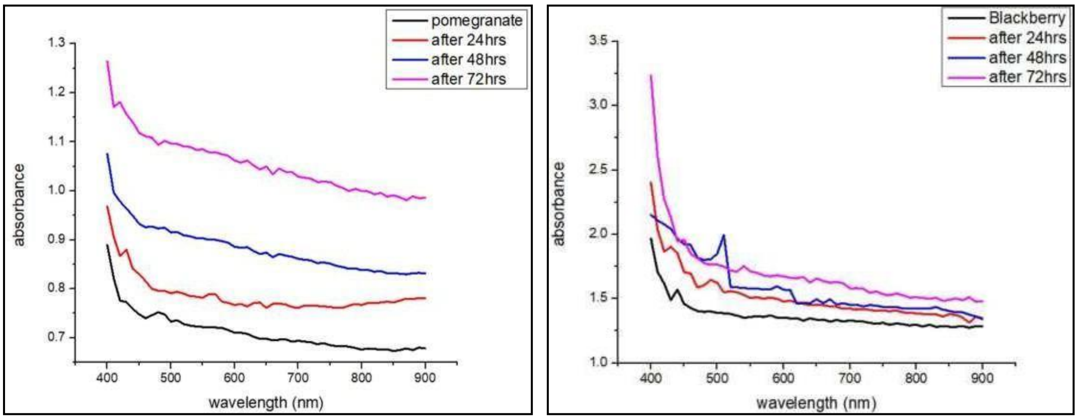
the spectral range over which the dye sensitizers are active.



(a) (b)

Figure: UV-Vis Spectroscopy spectrum of DSSC with Pomgranate Dye (a) and Blackberry Dye (b)

4.2. I-V Response Analysis

The photovoltaic performance was evaluated by measuring the current-voltage response under illumination. The following parameters were derived:

- **Open-Circuit Voltage (V_{oc}):** The maximum voltage available at zero current.
- **Short-Circuit Current (I_{SC}):** The current through the cell at zero voltage, typically expressed as current density (mA/cm^2).
- **Fill Factor (FF):** A ratio reflecting the electrical "squareness" of the I-V curve.
- **Power Conversion Efficiency (PCE):** The ratio of electrical power output to incident solar power.

Parameters	Blackberry Dye	Pomegranate Dye
I_{sc}(A)	**0.2648**	**0.2589**
V_{oc}(V)	**0.1264**	**0.1262**
V_{mpp}(V)	**0.2212**	**0.1982**
I_{mpp}(A)	**0.2658**	**0.2582**
J_{mpp}	**0.0107**	**0.01033**

5. RESULTS AND DISCUSSION

5.1. UV-Vis Absorbance Analysis

The absorbance profile for the pomegranate-sensitized DSSC demonstrated a clear correlation between immersion time and light-harvesting potential. As shown in the experimental data, absorbance significantly increased at the 24h, 48h and 72h marks. Specifically, the **72h pomegranate sample reached a peak absorbance of approximately 1.3 at a wavelength of 400nm**. This corrects the textual error in the source and confirms that longer sensitization periods significantly enhance the dye's ability to capture the visible and near-UV spectrum.

5.2. Advantages and Limitations

The following table summarizes the performance benchmarks and technical trade-offs of DSSCs compared to conventional silicon technology:

Parameter / Feature	Dye-Sensitized Solar Cells (DSSC)	Silicon-Based Solar Cells
Typical Efficiency	11–13%	20–22%
Production Cost	Low (Simple materials/processes)	High (Cleanroom/high-temp requirements)
Physical Properties	Flexible, Lightweight, Semi-transparent	Rigid, Heavy, Opaque
Environmental Impact	Low (Sustainable natural dyes)	Moderate (Energy-intensive manufacturing)
Limitations	Electrolyte volatility and leakage	High module cost and temperature sensitivity

6. CONCLUSION

This research successfully demonstrated the fabrication of TiO_2-based DSSCs utilizing sustainable fruit extracts as sensitizers. The pomegranate extract showed superior spectral absorbance, particularly at the 400nm wavelength after a 72-hour staining period, yielding an absorbance value of ~1.3. The integration of Monoethylene Glycol as a deep eutectic solvent component provided a sophisticated approach to electrolyte formulation. While conversion efficiencies of 11–13% remain below the 20–22% threshold of silicon-based cells, the low-cost

Doctor Blade fabrication and the use of eco-friendly graphite catalysts highlight the potential of DSSCs as a viable solution for sustainable, decentralized renewable energy.

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