FABRICATION OF DYE SENSITIZED SOLAR CELLS USING *Santalum album* FRUIT ETHANOL EXTRACT

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The research explores the development of Dye Sensitized Solar Cells (DSSCs) utilizing natural dye sourced from the fruit of *Santalum album*, also known as White Sandalwood. This study aims to address environmental pollution and energy consumption challenges by investigating sustainable alternatives. Natural dyes, with their eco-friendly properties and effective photon absorption from sunlight, present a promising avenue for renewable energy generation. Specifically, White Sandalwood-derived dye offers an environmentally benign solution for enhancing solar cell technologies. The study successfully constructed a Dye Sensitized Solar Cell (DSSC) using a titanium dioxide (TiO_2) film coated with natural dye extracted from *Santalum album* fruit as the photoanode and platinum-coated glass as the counter electrode. The cell employed a liquid electrolyte of Iodide/Triiodide (I^-/I_3^-). Photovoltaic parameters were evaluated using a Computerized PK-I-V 100 analyzer under LED illumination with an intensity of 100 mW/cm^2. The cell exhibited a short circuit photocurrent density ($J_{(SC)}$) of 1.321 mA/cm^2, an open circuit photovoltage ($V_{(OC)}$) of 599.4 mV, a fill factor (FF) of approximately 0.743, and an efficiency (η) of 0.589%. UV-visible absorption spectra analysis of the *Santalum album* dye in ethanol revealed peaks at 342.3 nm, 283 nm, and 196 nm, primarily comprising flavonoids such as anthocyanin. Incident Photon to Current Efficiency (IPCE) analysis showed the DSSC with *Santalum album* dye achieved the highest efficiency value within the 400 nm to 650 nm wavelength range, with a notable peak at 544.2 nm indicating efficient photon-to-electron conversion. These findings suggest optimal performance of the DSSC with the natural dye coating, particularly at wavelengths corresponding to the observed peaks.

Keywords: *Santalum album* fruit, dye sensitized solar cell, Photovoltaic device

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INTRODUCTION

In this current century, global energy consumption plays a significant role in contributing to pollution, environmental degradation, and the emission of greenhouse gases on a global scale. The escalating levels of energy consumption are primarily fueled by factors such as population expansion and economic progress, both of which typically lead to higher energy usage per individual (oil & gas journal, n.d.).

Researchers are currently focused on identifying and formulating alternative and effective strategies to address these issues. The shift towards renewable energy sources, including solar, wind, and hydroelectric power, offers potential solutions to many existing problems. Utilizing renewable energy provides a cleaner, more sustainable alternative that can greatly reduce dependency on nonrenewable resources, thus alleviating environmental, health, and economic issues, and fostering a more sustainable future (United Nations Climate Action, n.d.) (.nationalgrid/stories/energy-explained, n.d.).

Solar energy is one of the most easily available and eco-friendly renewable energy sources. It can be converted into electrical energy by using solar panel technology such as photovoltaic cells. Solar cell technology has significantly advanced over time, resulting in the development of various generations of solar cells, each distinguished by unique characteristics and efficiency levels.

The first generation, known as crystalline silicon solar cells, represents the conventional form of solar cells. These cells are crafted from crystalline silicon, including both monocrystalline and polycrystalline varieties. Despite their high efficiency and reliability, first-generation solar cells are relatively expensive due to the requirement of high-purity silicon. Second-generation solar cells are categorized as thin-film solar cells. Constructed from layers of semiconductor materials mere micrometers in thickness, these cells are deposited onto substrates such as glass, metal, or plastic. The primary materials utilized in this generation include amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS). The third generation encompasses a diverse array of emerging photovoltaic technologies, many of which are still under development or research. These technologies aim to surpass the efficiency constraints of conventional materials while also reducing production costs. Notable examples of third-generation solar cells include organic photovoltaic cells (OPVs), dye-sensitized solar cells (DSSCs), perovskite solar cells, and quantum dot solar cells. The focus in developing third-generation solar cells lies in utilizing less costly materials and innovative processes that could potentially exceed the efficiency limitations of traditional silicon-based solar cells and mitigate both costs and environmental impacts. (O'Regan B and Gratzel M, 1991) (Wöhrle D.and Meissner D, 1991) (Park, N.G, 2015) (Aroutiounian V, Petrosyan S, Khachatryan A and Touryan K, 2001)

Dye-sensitized solar cells (DSSCs), also known as Grätzel cells, represent a unique class of solar cells that mimics the natural process of photosynthesis. They are known for their relatively low production costs, ease of fabrication, and ability to function under low-light conditions, making them an attractive option for indoor and low-light applications. (Noorasid, 2022).

The fundamental architecture of dye-sensitized solar cells (DSSCs) is composed of four main components: a photoanode, a dye layer, an electrolyte, and a counter electrode. (Gratze, M., 2005). In DSSCs, the process begins when sunlight interacts with the dye molecules, leading to the absorption of photons. This event excites the dye molecules, causing them to release electrons. These electrons are then propelled into the conduction band of the titanium dioxide (TiO_2), from where they move through the TiO_2 to the transparent conductive oxide (TCO) glass, eventually reaching the external circuit. (Carella A, Borboe F, Centore R, 2018).

Upon powering an external device, such as a light bulb or a battery, the electrons are transported to the counter electrode. At this stage, the electrons contribute to the regeneration of iodide ions from triiodide ions in the electrolyte. The regenerated iodide ions then migrate back to the dye molecules, replenishing the electrons that were originally lost during the photon absorption phase. This sequence of events completes the operational cycle of the DSSC, enabling the continuous conversion of solar energy into electrical energy.

DSSCs present multiple advantages, including their low cost, flexibility, lightweight nature, efficient performance under diffuse lighting conditions, various aesthetic options, straightforward manufacturing process, and environmental friendliness. Each of these attributes contributes to the growing interest in DSSCs for diverse applications, ranging from portable electronics to integrated building solutions.

Ongoing research and development are significantly improving the performance and durability of DSSCs, marking them as pivotal in the global move towards sustainable energy solutions. The main goal of this study is to fabricate DSSCs utilizing natural dye extracted from *Santalum album* fruit, (which is commonly known as White Sandalwood) and explore a promising avenue for renewable energy generation (Figure 01).

METHODOLOGY

MATERIALS

P-25 TiO_2 Nano particles, PEG 400, Triton X-100, 0.1M HNO_3, FTO glass plates, Ethanol, *Santalum album* fruit

Dye extraction

Mature fruits of the *Santalum album*, commonly known as White Sandalwood or White Handun, were collected and subjected to extraction. The extraction process involved boiling the fruits in ethanol in a beaker placed on a hot plate. The temperature was maintained between 65°C to 70°C, and the fruits were boiled for 30 minutes until they lost their color. Following the extraction, the resulting natural dyes obtained from the White Sandalwood fruit were filtered and transferred into individual sample bottles. Subsequently, the dyes were wrapped with aluminum foil and stored in a refrigerator at 4°C for future use.

Fabrication of dye-coated film

The cleaning procedure for 2 cm x 1 cm pieces of Fluorine-doped Tin Oxide (FTO) glass plates involved several steps. Initially, the FTO plates underwent a five-minute ultrasonic bath with distilled water and liquid soap, followed by an additional sonication for five minutes using distilled water and concentrated H_2SO_4. Subsequently, the plates were boiled in propyl alcohol at 80°C in a beaker. After boiling, the FTO plates were air-dried using a low-heat hair dryer, and their conductivity was evaluated with a conductivity meter.

For the formulation of the TiO_2 paste, 0.25 g of 20 nm TiO_2 powder was combined with 0.1 ml of 0.1M HNO_3, a drop of Triton-X 100, and a drop of PEG 400. The mixture was stirred until a consistent thick paste was obtained. This paste was then uniformly applied onto the conductive surface of the FTO glass plates using the doctor blade technique. Subsequently, the plates were sintered at 450°C for 30 minutes in a furnace and allowed to cool.

Following the sintering process, the TiO_2-coated glass plates were immersed in test tubes containing dye solutions prepared from Santalum album ethanol extract.

Development of DSSC

An I^-/I_3^- electrolyte in liquid form was employed, prepared by dissolving 0.127 g of iodine (I_2) and 0.83 g of potassium iodide (KI) in a mixture of 10 ml acetonitrile and ethylene carbonate in an 8:2 ratio. The solution was stirred continuously for 5 hours to ensure the complete dissolution of all solid particles (Wickramasinghe G.C, Jayathilaka D.L.N and Perera V.P.S, 2017).

The DSSC was assembled using a dye-coated TiO_2 film on Fluorine-doped Tin Oxide (FTO) glass as the anode and a Platinum (Pt) sputtered glass plate as the counter electrode. These components were connected side by side and secured together using crocodile clips. The liquid electrolyte was then transferred into the capillary gap between the two plates.

Natural Dye and DSSC Characterization

The UV-visible absorption spectra of natural dyes extracted from *Santalum album* fruit in ethanol were analyzed using a CT-2600 Spectrophotometer across the wavelength range of 190 - 700 nm. Additionally, the photovoltaic characteristics of the DSSC were determined. These measurements included the open circuit voltage (V_{OC}), short circuit current (I_{SC}), short circuit current density (J_{SC}), fill factor (FF), efficiency (η), series resistance (R_S), and shunt resistance (R_{Sh}). The analysis was conducted using the computerized PK-I-V 100 I-V analyzer under illumination from an LED light source with an intensity of 100 mW/cm^2. Furthermore, The Incident Photon to Current Conversion Efficiency (IPCE) of the DSSC was examined utilizing a computerized VK-IPCE-10 analyzer.

RESULTS AND DISCUSSION

Natural plant leaves, fruits, and flowers contain several pigments called natural pigments such as chlorophylls, Carotenoids, and Flavonoids (Sousa C, 2022). Because of these natural pigments plants appear with various colors, and these pigments contribute to the photosynthesis process. Natural pigments can absorb the photons from solar radiation and then they convert it into chemical energy in the process of photosynthesis (Webexhibts.org.(n.d), n.d.).

Chlorophyll molecules are responsible for the green pigmentation observed in plants and play a vital role in the process of photosynthesis. They are synthesized within specialized organelles called chloroplasts. Chlorophyll absorbs light energy which is crucial for photosynthesis. Two main types of chlorophyll, namely chlorophyll a and chlorophyll b, exist in green plants, sharing a similar molecular structure with a distinction in a single side chain. The two chlorophyll types absorb light primarily in the blue and red regions of the electromagnetic spectrum, albeit with varying absorption peaks. Chlorophyll b exhibits its highest absorption peak in the blue spectrum, whereas chlorophyll's peak lies in the red spectrum. Remarkably, neither chlorophyll type effectively absorbs light in the green spectrum, which renders plants containing these pigments green to the human eye. Chlorophyll a imparts a darker green hue, while chlorophyll b contributes to a yellowish-green appearance (Webexhibts.org.(n.d), n.d.).

In addition to chlorophyll, carotenoids, a group of pigments, diversify the coloration of plants, fruits, and flowers, by offering hues ranging from yellow to red. Among carotenoids, beta-carotene, a prominent member, is synthesized within chromoplasts, lending vibrant yellow and orange tones to various plant parts. During autumn, as sunlight diminishes, chlorophyll degradation reveals carotenoids, which absorb light predominantly in the blue and green spectra, reflecting yellow, orange, and red hues. Carotenoids comprise two principal categories: carotenes, such as beta-carotene and lycopene, sharing the chemical formula $C_{40}H_{56}$ and terminating in –ene**.** Xanthophylls, like lutein and zeaxanthin, structurally resemble carotenes but incorporate additional oxygen molecules. Analogous to chlorophylls, carotenoids harness solar energy, subsequently transferring it to chlorophyll molecules to bolster photosynthesis.

Flavonoids, another group of plant compounds, contribute to an array of colors including red, yellow, blue, and purple(Figure 02). Predominantly represented by anthocyanin, flavonoids enrich fruits, flowers, and leaves with a red hue. Absorbing light primarily in wavelengths ranging from 250 to 550 nm, flavonoids exhibit heightened absorption in the ultraviolet and blue-green spectra, reflecting light primarily in the blue and violet ranges. This optical property enhances the visibility of insects sensitive to ultraviolet light, potentially attracting them for pollination purposes. Moreover, flavonoids serve as a protective mechanism for plants against various environmental stresses, including ultraviolet radiation, frost, heat, and drought (Encyclopedia of the Environment, n.d.) (Subodro R, 2012).

Figure 01: *Santalum album* fruit, commonly known as White Sandalwood

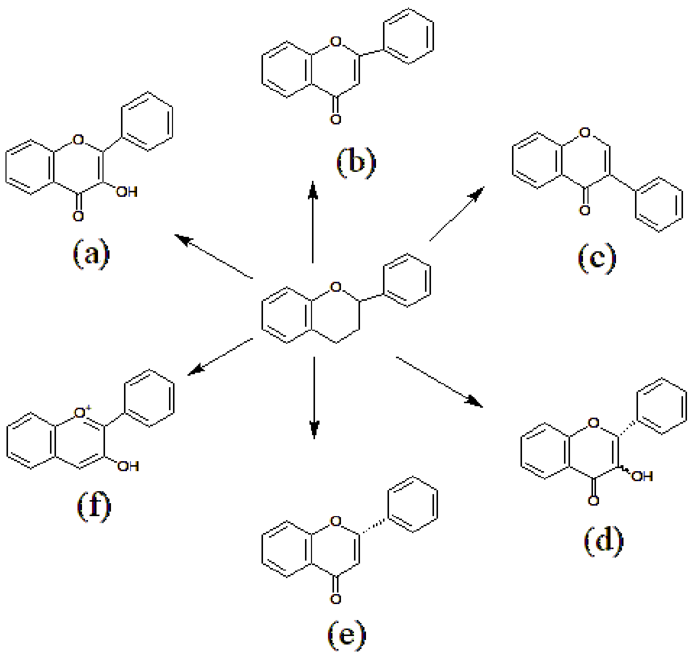

Figure 02: structure of flavonoids a) Flavanol b) Flavone c) Isoflavone d) Flavan-3-ol e) Flavanone f) Anthocyanidin

Photovoltaic characteristics.

Figure 03 depicts the relationship between open circuit voltage and short circuit current density for DSSCs fabricated from the ethanol extract of *Santalum album* fruit.

It is evident from the graph that the J_{SC} is 1.321 mA/cm^2, V_{OC} is 599.4 mV, a fill factor (FF) of approximately 0.743, and an efficiency (η) of 0.589%. Additionally, the series resistance (R_S) is denoted as R1 Ω, and the shunt resistance (R_{Sh}) is denoted as R2 Ω.

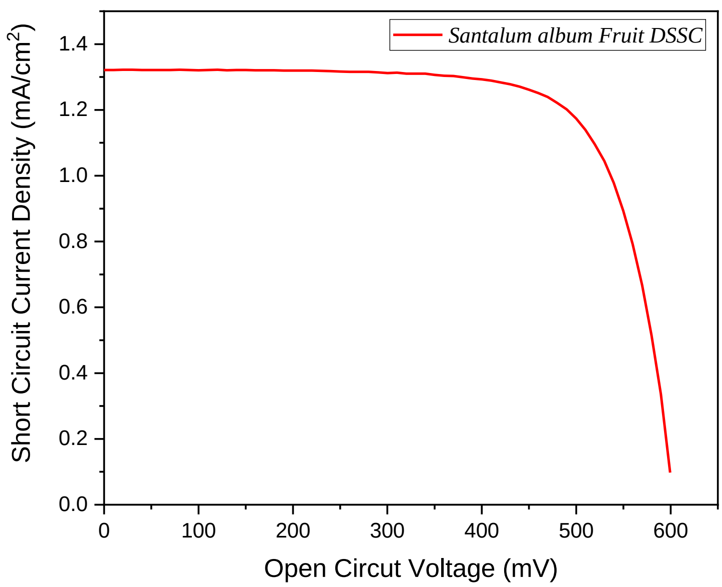

Figure 03: The relationship between open circuit voltage (V_{OC}) and short circuit current density (J) for cells sensitized with dye extracts obtained from *Santalum album* fruit.

UV-Visible characteristics

The absorption spectrum, which represents the unique pattern of wavelengths absorbed by various pigments, serves as a fingerprint revealing their identities. Chlorophyll, for instance, absorbs blue-violet light, while chlorophyll b absorbs red-blue light. Carotenoids absorb blue-green and violet light, reflecting yellow, red, and orange hues.

Many organisms possess combinations of pigments, broadening their absorption spectrum. Spectrophotometry can be used to assess pigment types in photosynthetic plants, which measures transmitted light, thereby unveiling which wavelengths are absorbed. Researchers extract leaf pigments and analyze them in a spectrophotometer to identify the wavelengths of absorbed light. (MAP: RAVEN BIOLOGY).

Figure 04 displays the UV & Visible absorption spectrum of natural dyes extracted from *Santalum album* fruit in ethanol. According to the spectrum analysis graph, the ethanol extracts from *Santalum album* fruit exhibited three major peaks at 342.3 nm, 283 nm, and 196 nm. The primary constituents in the extraction may include Flavonoids such as anthocyanin.

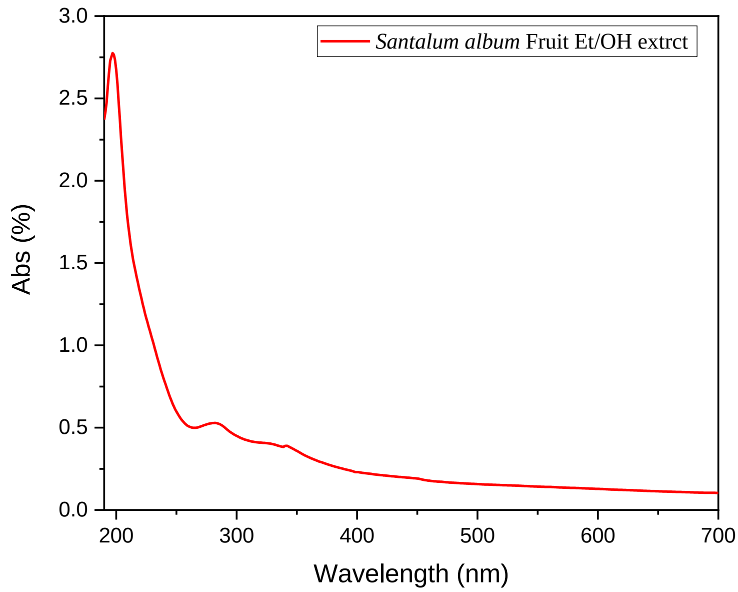

Figure 04: UV & Visible absorption spectrum of natural dyes extracted from *Santalum album* fruit in ethanol

IPCE Characterization

Figure 05 shows The Incident Photon to Current Efficiency (IPCE) of the DSSCs that were measured using a VK-IPCE 10 analyzer. The analysis revealed that the *Santalum album* dye-coated DSSC exhibited the highest Incident Photon-to-Current Efficiency (IPCE) within the wavelength range of 400 nm to 650 nm. Specifically, a high-intensity peak was observed at 544.2 nm, indicating efficient photon-to-electron conversion in this region by anthocyanin.

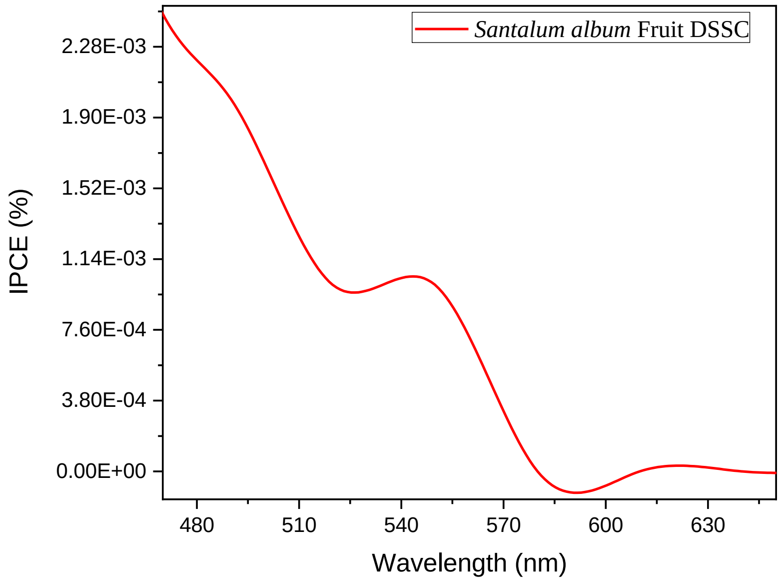

Figure 05: Incident photon to current efficiency graph of the ethanol extract from *Santalum album* fruit

CONCLUSIONS

In conclusion, this research contributes to addressing the pressing need for sustainable energy solutions in the face of environmental pollution and increasing energy demands. By focusing on the fabrication of DSSCs utilizing natural dye extracted from *Santalum album* fruit, commonly known as White Sandalwood, this study explores a promising avenue for renewable energy generation.

The investigation into the photovoltaic characteristics and spectral analysis of DSSCs fabricated with natural dye extracted from *Santalum album* fruit reveals promising insights into the efficacy of this renewable energy technology. The DSSC exhibited notable photovoltaic characteristics, including a short circuit photocurrent density (J_{SC}) of 1.321 mA/cm^2, an open circuit photovoltage (V_{OC}) of 599.4 mV, a fill factor (FF) of approximately 0.743, and an efficiency (η) of 0.589%. These parameters demonstrate the ability of the DSSC to effectively convert incident light into electrical energy.

Analysis of the UV-visible absorption spectra of the *Santalum album* dye extract unveiled peaks at 342.3 nm, 283 nm, and 196 nm, indicative of the presence of Flavonoids such as anthocyanin. These natural pigments contribute to the light absorption capabilities of the dye, enhancing its performance in the DSSC. The IPCE analysis further confirmed the superior performance of the *Santalum album* dye-coated DSSC. The highest efficiency was observed within the wavelength range of 400 nm to 650 nm, with a prominent high-intensity peak at 544.2 nm, indicating efficient photon-to-electron conversion. Additionally, a secondary low-intensity peak at 621 nm suggests supplementary photon absorption and conversion.

Overall, these findings underscore the potential of utilizing natural dye-based DSSCs as a sustainable and efficient means of harnessing solar energy. Further research and development in this area hold promise for advancing renewable energy technologies and mitigating environmental impacts associated with traditional energy sources.

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