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Research Article

EFFECTS OF NATURAL-PIGMENT DYE-SENSITIZED SOLAR CELLS INCORPORATING AN ELECTROCHEMICALLY SYNTHESIZED TITANIUM-CONTAINING MATERIAL

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Abstract

This study investigated the optical characteristics and photovoltaic performance of dye-sensitized solar cells (DSSCs) incorporating three natural pigment extracts and an electrochemically synthesized titanium-containing material. The material was synthesized from titanium wire in a citric acid/KOH electrolyte at 20 V for 8 h. At a fixed citric acid concentration of 0.5 M, UV–Vis absorption features shifted from approximately 300 to 326 nm as KOH concentration increased from 2 to 6 M, with absorption wavelengths of 300, 308, 316, 324, and 326 nm, respectively. X-ray diffraction (XRD) analysis of products synthesized at 3 and 5 M KOH identified potassium titanate ($K_2Ti_6O_{13}$), brookite TiO_2, and anatase TiO_2. DSSCs were fabricated using reference TiO_2 powder or the synthesized material as photoanodes, sensitized with butterfly pea, bastard teak, or tropical almond extracts. Photovoltaic measurements were conducted under yellow laboratory illumination, with an assumed irradiance of 19 W/m² used for efficiency calculations. Among six experimental combinations, the synthesized-material DSSC sensitized with tropical almond leaf extract exhibited the highest mean electrical output, with Isc = 412.70 μA, Voc = 268.97 mV, Pmax = 5.60 μW, and FF = 6.09%. The calculated power conversion efficiency (η) was 0.098%. These findings demonstrate the influence of natural pigment selection and photoanode composition on DSSC electrical performance and support further development of natural pigment-based photovoltaic devices.

Keywords: electrochemical synthesis, titanium-containing material, natural pigment extracts, dye-sensitized solar cells

Introduction

Energy is essential for economic development and human well-being. However, fossil fuel dependence raises concerns regarding resource depletion, price fluctuations, and environmental impacts. Renewable energy sources, including solar, wind, hydropower, geothermal energy, biomass, and biogas, offer sustainable alternatives for electricity generation. Among these, solar energy is particularly promising due to its availability and environmental benefits (Al-Alwani et al., 2016). Although conventional silicon solar cells achieve high conversion efficiencies, their production requires highly purified materials and complex manufacturing processes, encouraging the development of alternative photovoltaic technologies (Chapin et al., 1954).

Dye-sensitized solar cells (DSSCs) have attracted attention due to their relatively simple fabrication, low material costs, and potential environmental compatibility (Al-Alwani et al., 2016; Prajapat et al., 2024). DSSCs operate through light absorption by photosensitizing dyes, followed by electron injection into a semiconductor photoanode. Titanium dioxide (TiO_2) is commonly used because of its chemical stability and semiconductor properties (O'Regan & Grätzel, 1991). In the present study, electrochemical synthesis was used to prepare a titanium-containing material, and the influence of KOH concentration on its optical absorption characteristics was examined.

Natural pigments containing chlorophylls, anthocyanins, carotenoids, and flavonoids have been investigated as DSSC sensitizers because of their visible-light absorption properties and accessibility (Mejica et al., 2022; Triyanto et al., 2024). Northern Thailand offers locally available natural pigment sources, including bastard teak flowers, butterfly pea flowers, and tropical almond leaves. Although Phubuaduang and Somjit (2021) previously investigated DSSCs incorporating TiO_2 quantum dots and plant-derived pigments, including tropical almond extract, a comparative evaluation of these three pigments with reference TiO_2 powder and an electrochemically synthesized titanium-containing material remains of interest. The present study addresses this comparison through three objectives: (i) to investigate the influence of KOH concentration (2–6 M), at a fixed citric acid concentration of 0.5 M, on the optical absorption characteristics and examine the crystalline composition of the synthesized material; (ii) to compare the UV–Vis absorption characteristics of the three natural pigment extracts; and (iii) to evaluate the photovoltaic characteristics of DSSCs incorporating each pigment with the two photoanode materials. This approach provides a comparative assessment of natural pigment selection, synthesis conditions, and photoanode materials for DSSC applications.

Objectives

1. To examine the effect of KOH concentration (2–6 M at fixed 0.5 M citric acid) on the optical absorption of the electrochemically synthesized titanium-containing material, and to describe the crystalline phases of the two conditions (3 and 5 M KOH) for which archived XRD patterns are available.

2. To compare the UV–Vis absorption characteristics of pigment extracts from bastard teak flowers, butterfly pea flowers, and tropical almond leaves.

3. To compare the photovoltaic performance of DSSCs fabricated with reference TiO_2 powder and the synthesized material using the three natural pigment extracts under the specified laboratory illumination.

Hypothesis

1. Changes in KOH concentration during electrochemical synthesis influence the observed UV–Vis absorption features of the synthesized titanium-containing material, while pigment type and photoanode material influence the measured photovoltaic performance of the fabricated DSSCs under the investigated conditions.

Conceptual Framework

Independent Variables	➡ Research Process	➡ Dependent Variables	➡ Controlled Variables
• KOH concentration (2–6 M) • Type of local plant pigment extract (bastard teak, butterfly pea, tropical almond) • Photoanode material (reference TiO_2 powder or synthesized material)	1. Electrochemical synthesis using two titanium wires at 20 V for 8 h 2. UV–Vis and XRD characterization of the synthesized material 3. Extraction and UV–Vis characterization of plant pigments 4. Fabrication and photovoltaic testing of DSSCs	• Optical absorption of synthesis solutions • Crystalline phases of synthesized material • Optical absorption spectra of pigment extracts • Electrical characteristics and energy-conversion efficiency of DSSCs	• Citric acid (0.5 M) • Titanium-wire dimensions • Solution volume • Applied voltage and synthesis time • Cell-fabrication procedure • Illumination setup and illuminated area during photovoltaic calculations

Figure 1 Conceptual framework of the study

Methodology

The study was divided into three parts: (1) electrochemical synthesis and characterization of a titanium-containing material, (2) extraction and comparison of pigments from local plants, and (3) fabrication and evaluation of dye-sensitized solar cells.

Part 1 Electrochemical Synthesis of Titanium-Containing Material

1) Titanium wire with a diameter of 1.6 mm was polished with abrasive paper and cut into 5-cm lengths.

2) The titanium wires were cleaned with ethanol. Each wire was immersed in ethanol in a test tube, and ultrasonic cleaning was performed for 1 h at 60 °C.

3) The synthesis electrolyte was prepared in 40 mL of distilled water with citric acid fixed at 0.5 M and KOH varied among 2, 3, 4, 5, and 6 M.

4) The cleaned titanium wires were connected to the positive and negative terminals, immersed in the electrolyte, and subjected to a 20-V direct-current potential for 8 h. The five KOH concentrations were compared while citric acid concentration, solution volume, applied voltage, and synthesis time were held constant.

5) The synthesized electrolyte solution was filtered through a 0.45-μm filter and collected in a 25-mL sample bottle.

6) The optical properties of the synthesis solutions were examined using laser-light scattering and UV–Vis spectrophotometry. Absorption spectra for each KOH concentration were plotted and compared.

7) The synthesis solution was transferred to a Petri dish and covered with gauze to reduce contamination while allowing drying. It was dried in a hot-air oven at 60 °C for 3 days until a solid crystalline residue was obtained for structural analysis.

8) The dried material was ground into a fine powder using a mortar and pestle for crystalline-phase characterization. UV–Vis absorption spectra were compared across all five KOH concentrations (2–6 M), while X-ray diffraction (XRD) analysis was conducted on the synthesized materials prepared at 3 and 5 M KOH to identify their crystalline phases.

Part 2 Extraction and Comparison of Pigments from Local Plants

1) Bastard teak flowers, butterfly pea flowers, and tropical almond leaves were washed, dried, cut into small pieces (approximately 10 g of each plant material), and ground thoroughly using a mortar and pestle.

2) Approximately 50 mL of ethanol was added to each ground plant sample. The mixture was heated until the target color intensity used in the original experiment was obtained, filtered to remove plant residues, and stored in an amber bottle protected from light.

3) The optical absorption properties of each filtered plant-pigment extract were measured by UV–Vis spectrophotometry, and the resulting spectra were plotted and analyzed.

Part 3 Fabrication of Dye-Sensitized Solar Cells

1. Fluorine-doped tin oxide (FTO) conductive glass was cut into 2.5 × 2.5 cm pieces, and the conductive surface was identified using a digital multimeter.

2. The FTO substrates were ultrasonically cleaned using soap and ethanol for 10 min at 30 °C, rinsed with distilled water, and dried.

3. Semiconductor paste was prepared by mixing 5 g of the electrochemically synthesized material with 10 mL of 5% acetic acid and 0.5 mL of surfactant. The mixture was magnetically stirred for 1 h. Reference TiO_2 powder was used for comparison.

4. The counter electrode was prepared by coating 2.5 × 2.5 cm foil with a mixture of 5 g of adhesive, 1 g of carbon powder, and 5 mL of ethanol, followed by heating at 300 °C for 1 h.

5. The semiconductor paste was applied to the conductive surface of the FTO glass. The glass edges were covered with adhesive tape to define the central coating area, and a thin glass slide was used to spread the paste uniformly. The coated substrate was subsequently heated at 300 ℃ for 1 h.

6. Natural pigment extract was applied to the semiconductor-coated surface at room temperature using 8–10 drops per application. The application and drying procedure was repeated three times.

7. The electrolyte solution was prepared by mixing 80 mL of acetonitrile, 20 mL of ethylene carbonate, 0.84 g of iodine, and 4.32 g of potassium iodide until a homogeneous solution was obtained.

8. Copper and aluminum strips measuring 0.5 × 7 cm and 0.02 mm in thickness were prepared as electrical contacts. A 2.5 × 2.5 cm polyethylene separator was immersed in the electrolyte. The copper strip was attached to the lateral uncoated area of the FTO glass, and the electrolyte-soaked separator was positioned over the semiconductor-coated surface.

9. The carbon-coated counter electrode was placed over the separator with its coated surface facing the semiconductor layer. The aluminum strip was attached to the opposite lateral uncoated area, and the assembled cell was sealed around the perimeter with plastic.

10. The photovoltaic characteristics of the fabricated DSSCs were measured under yellow laboratory illumination using a digital multimeter and a 10-kΩ variable resistor. The illuminated active area was 3.0 cm², and an assumed irradiance of 19 W/m² was used for efficiency calculations.

11. Three samples were evaluated for each photoanode–pigment combination (n = 3). The photovoltaic parameters, including I_{sc}, V_{oc}, P_{max}, FF, and calculated η, were determined for each sample and summarized using mean values and sample standard deviations.

$$P_{max} = I_{max}V_{max} \quad (1)$$

$$FF(\%) = \frac{P_{max}}{I_{sc}V_{oc}} \times 100 \quad (2)$$

$$\eta(\%) = \frac{P_{max}}{P_{in}} \times 100 \quad (3)$$

P_{in} is the incident optical power, calculated as P_{in} = GA, where G is the assumed irradiance and A is the illuminated active area. Using G = 19 W/m² and A = 3.0 × 10^{-4} m² gives P_{in} = 5.7×10^{-3} W. Consistent units were used in all calculations. P_{max}, FF, and η were calculated for each sample before the mean and sample standard deviation were determined.

Results

The experimental results are presented in three parts corresponding to the three stages of the research procedure.

Part 1 Electrochemical Synthesis and Characterization of the Synthesized Material

The titanium-containing material was synthesized under five electrolyte conditions by varying the KOH concentration from 2 to 6 M in 1-M increments. The citric acid concentration, applied potential, distilled-water volume, and synthesis time were maintained at 0.5 M, 20 V, 40 mL, and 8 h, respectively. UV–Vis absorption spectra were compared across all five KOH concentrations, and crystalline phases were characterized by XRD for the materials synthesized at 3 and 5 M KOH.

The UV–Vis spectra exhibited absorption features at approximately 300, 308, 316, 324, and 326 nm for KOH concentrations of 2, 3, 4, 5, and 6 M, respectively (Figure 2). These features shifted toward longer wavelengths as the KOH concentration increased.

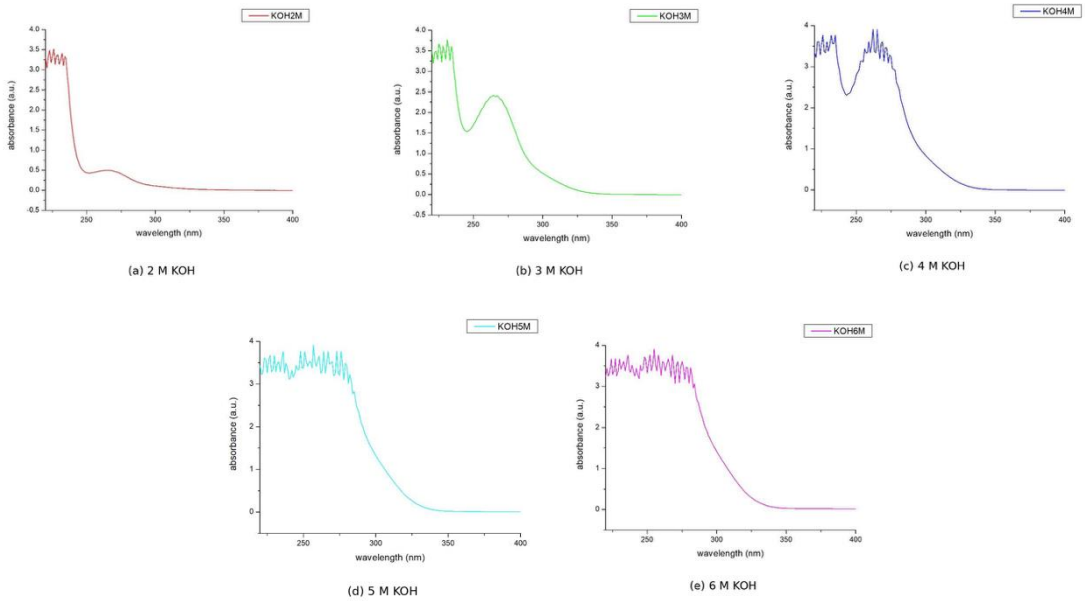
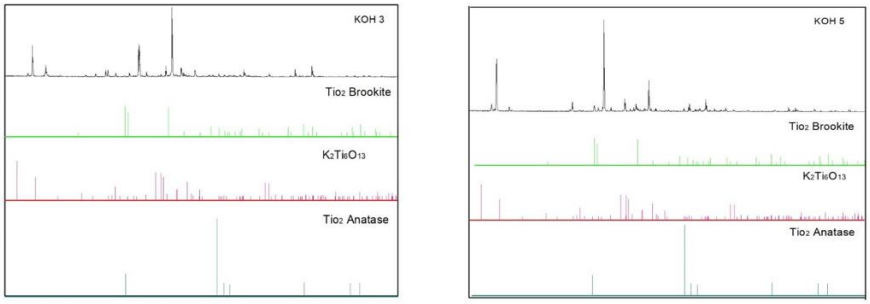


Figure 2 UV–Vis spectra of synthesis solutions prepared with 0.5 M citric acid and (a) 2 M, (b) 3 M, (c) 4 M, (d) 5 M, and (e) 6 M KOH. Spectra reproduced from the archived thesis dataset.

For material synthesized using 0.5 M citric acid with 3 or 5 M KOH in 40 mL distilled water at 20 V for 8 h, XRD patterns showed diffraction features corresponding to $K_2Ti_6O_{13}$ (JCPDS 99-100-9280), anatase TiO_2 (JCPDS 99-101-9414), and brookite TiO_2 (JCPDS 99-101-4505) (Figure 3).



(a) 3 M KOH (b) 5 M KOH

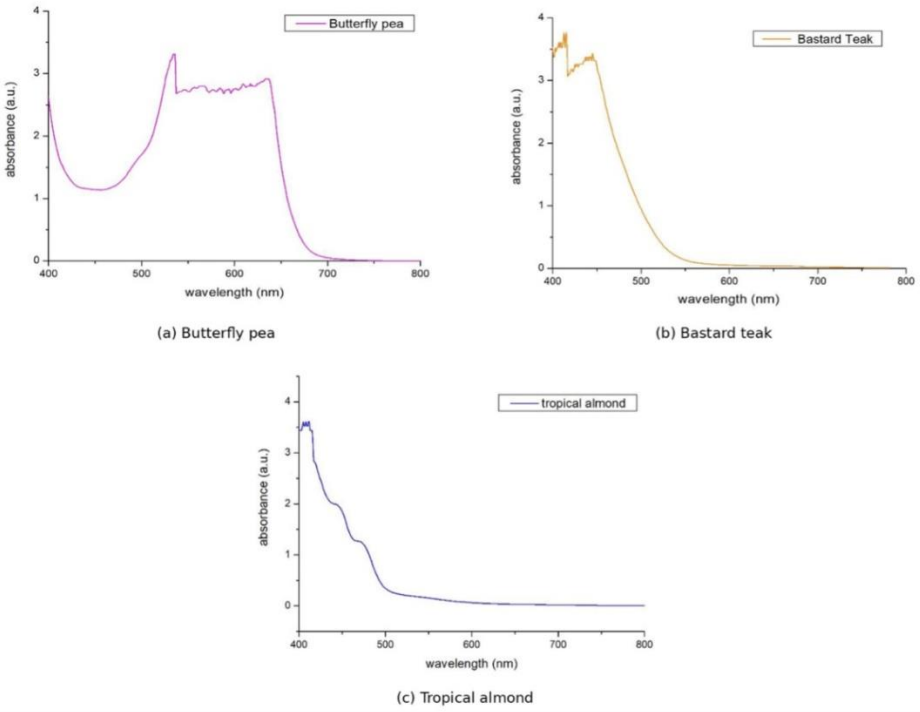
Figure 3 XRD patterns of dried synthesized material prepared with 0.5 M citric acid and (a) 3 M or (b) 5 M KOH, with reference patterns for brookite TiO_2, $K_2Ti_6O_{13}$, and anatase TiO_2.

Part 2 UV–Vis Absorption of Plant-Pigment Extracts

Butterfly pea extract exhibited absorption over approximately 520–650 nm, consistent with the characteristic visible-light absorption range of blue-to-purple anthocyanin pigments.

Bastard teak extract exhibited absorption over approximately 430–480 nm, which falls within the range typically associated with yellow-to-red carotenoid pigments (approximately 400–550 nm).

Tropical almond leaf extract exhibited absorption over approximately 400–500 nm, also within the visible-light range associated with yellow-to-red carotenoid-type pigments (Figure 4).



(a) Butterfly pea (b) Bastard teak

(c) Tropical almond

Figure 4 UV–Vis spectra of (a) butterfly pea flower, (b) bastard teak flower, and (c) tropical almond leaf extracts.

Part 3 Electrical Performance of the Fabricated DSSCs

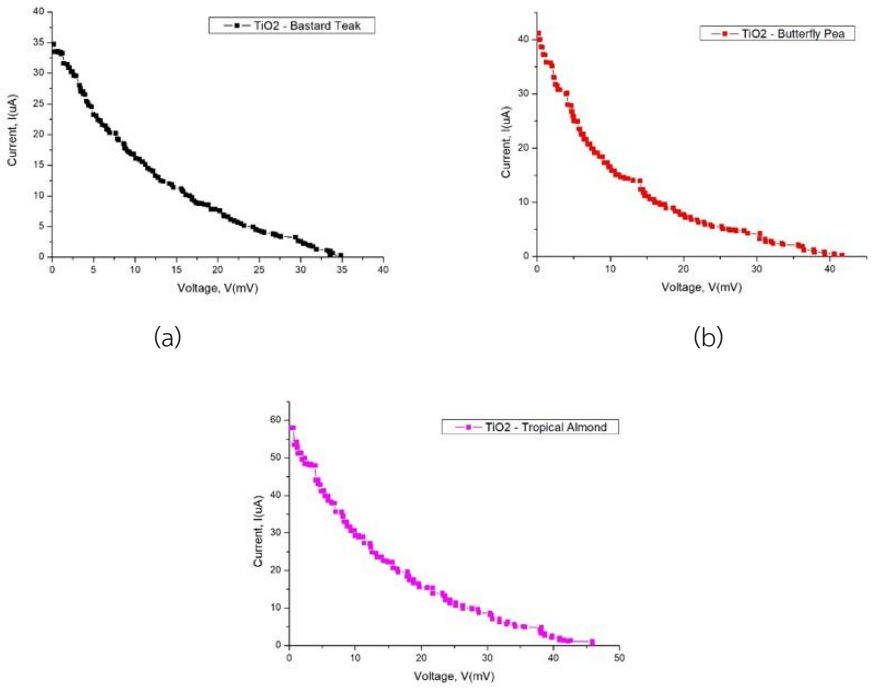
DSSCs were fabricated on FTO glass using either reference TiO_2 powder or the electrochemically synthesized material and were sensitized with extracts from bastard teak, butterfly pea, or tropical almond. Photovoltaic testing was conducted under yellow laboratory illumination over an active area of 3.0 cm², with an assumed irradiance of 19 W/m² used for efficiency calculations. Three samples were available for each condition (n = 3).

Table 1 Electrical characteristics and conversion efficiencies of dye-sensitized solar cells.

DSSC / sensitization condition	I_{sc} (μA)	V_{oc} (mV)	P_{max} (μW)	FF (%)	η (%)
TiO_2 powder + bastard teak	34.50±5.13	34.83±5.05	0.174±0.035	14.94±4.15	0.0031±0.0006
TiO_2 powder + butterfly pea	41.10±12.57	41.60±12.95	0.174±0.084	10.79±4.21	0.0031±0.0015
TiO_2 powder + tropical almond	58.00±14.38	45.87±19.26	0.352±0.162	13.57±1.75	0.0062±0.0028
Synthesized Material + bastard teak	122.70±23.90	124.23±17.45	0.567±0.328	4.39±3.83	0.0099±0.0058
Synthesized Material + butterfly pea	132.00±17.15	109.03±5.95	1.027±0.230	7.44±2.70	0.0180±0.0040
Synthesized Material + tropical almond	412.70±12.30	268.97±154.56	5.599±1.790	6.09±2.64	0.0982±0.0314

Note: Values are presented as mean ± sample standard deviation (n = 3). Conversion efficiencies were calculated using an assumed irradiance of 19 W/m² and an illuminated active area of 3.0 cm².

Table 1 shows the recalculated photovoltaic parameters. The synthesized-material cells produced higher mean I_{sc}, V_{oc}, P_{max}, and η than the reference-TiO_2 cells for the corresponding pigment under the investigated laboratory conditions. The tropical-almond/synthesized-material condition showed the highest mean conversion efficiency, η = 0.0982 ± 0.0314%.

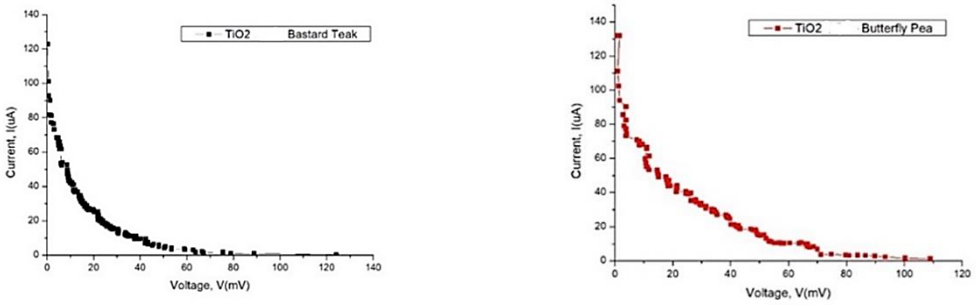


(a) (b)

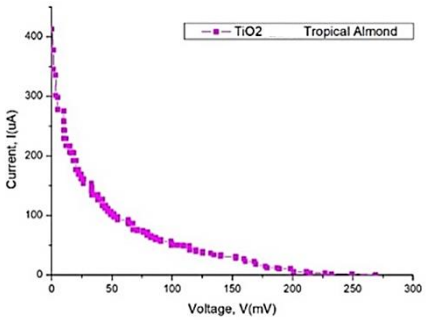
(c)

Figure 5 Available I–V curves of DSSCs using reference TiO_2 powder sensitized with (a) bastard teak flower extract, (b) butterfly pea flower extract, and (c) tropical almond leaf extract.

As shown in Figure 5, the DSSCs fabricated using reference TiO_2 powder exhibited different electrical characteristics depending on the natural pigment extract employed. The mean maximum-power-point current (I_{max}) and voltage (V_{max}) were 11.13 μA and 15.57 mV for bastard teak, 9.60 μA and 17.47 mV for butterfly pea, and 19.67 μA and 17.87 mV for tropical almond, respectively. Among the three pigment extracts, tropical almond exhibited the highest mean maximum-power-point current and voltage, indicating comparatively favorable electrical performance under the investigated laboratory conditions.



(a) (b)



(c)

Figure 6 Available I–V curves of DSSCs using the synthesized material sensitized with (a) bastard teak flower extract, (b) butterfly pea flower extract, and (c) tropical almond leaf extract.

As shown in Figure 6, the mean I_{max} and V_{max} values were approximately 25.37 μA and 21.80 mV for bastard teak, 26.00 μA and 39.20 mV for butterfly pea, and 92.70 μA and 63.87 mV for tropical almond, respectively. The mean conversion efficiencies, calculated) using an assumed irradiance of 19 W/m² over an active area of 3.0 cm², were 0.0099 ± 0.0058%, 0.0180 ± 0.0040%, and 0.0982 ± 0.0314%, respectively.

Discussions

Part 1 Electrochemical Synthesis of Titanium-Containing Material

The UV–Vis absorption analysis revealed a systematic shift toward longer wavelengths as the KOH concentration increased from 2 to 6 M. The absorption wavelengths were approximately 300, 308, 316, 324, and 326 nm at KOH concentrations of 2, 3, 4, 5, and 6 M, respectively. This progressive shift indicates that KOH concentration influences the optical absorption characteristics of the electrochemically synthesized material. The observed trend suggests that changes in the chemical environment during synthesis contribute to variations in the optical properties of the resulting products.

The absorption characteristics observed in this study are broadly consistent with those reported by Suwannapakdee (2016), who investigated electrochemically synthesized TiO_2 quantum dots and reported ultraviolet absorption in a similar wavelength range. Differences in absorption peak positions may be associated with variations in precursor composition and synthesis conditions. These findings highlight the influence of electrochemical synthesis parameters on the optical behavior of titanium-containing materials.

X-ray diffraction (XRD) analysis was conducted to examine the crystalline phases of the synthesized materials prepared using KOH concentrations of 3 and 5 M. The diffraction patterns exhibited features corresponding to potassium titanate ($K_2Ti_6O_{13}$), brookite TiO_2, and anatase TiO_2, demonstrating the formation of multiphase crystalline products under the investigated conditions. A comparison of the XRD patterns obtained at 3 and 5 M KOH confirmed the presence of these crystalline phases in the analyzed products. The identification of potassium titanate is consistent with the potassium-containing synthesis environment, while

the brookite and anatase phases indicate the formation of crystalline TiO_2. The XRD comparison was conducted for the 3 and 5 M KOH conditions, whereas UV–Vis absorption was evaluated across all five KOH concentrations. The UV–Vis and XRD results provide information on the optical absorption and crystalline phases of the synthesized material but do not establish its particle size. Accordingly, the product is referred to as an electrochemically synthesized titanium-containing material.

Overall, the results demonstrate that variations in KOH concentration are associated with changes in the ultraviolet absorption characteristics of the synthesized material, while XRD analysis identifies the formation of potassium titanate and TiO_2 crystalline phases. These findings provide insight into the relationship between electrochemical synthesis conditions, optical absorption behavior, and the crystalline composition of the resulting materials.

Part 2 UV–Vis Absorption of Pigment Extracts

UV–Vis spectroscopic analysis revealed distinct absorption characteristics among the three natural pigment extracts. Butterfly pea flower extract exhibited absorption in the wavelength range of 520–650 nm, corresponding to the visible-light region commonly associated with anthocyanin-containing pigments. This absorption behavior demonstrates the ability of butterfly pea extract to absorb visible light, supporting its potential application as a natural photosensitizer in dye-sensitized solar cells (DSSCs).

The extraction solvent plays an important role in determining the optical properties and photovoltaic performance of natural pigment extracts. Ponnambalam et al. (2023) reported that different extraction solvents influence the conversion efficiency of DSSCs sensitized with natural pigments. In the present study, ethanol was employed to extract pigments from the three plant species, providing a consistent extraction medium for comparing their optical absorption characteristics. The observed differences in absorption behavior therefore highlight the influence of plant species and their respective pigment compositions on light absorption.

Bastard teak flower extract exhibited absorption in the wavelength range of 430–480 nm, whereas tropical almond leaf extract showed absorption over 400–500 nm. These absorption regions overlap with wavelengths commonly associated with carotenoid-type pigments, suggesting the possible contribution of these compounds to the optical characteristics of the extracts. The results demonstrate that both plant extracts possess visible-light absorption properties suitable for investigation as natural sensitizers in DSSCs.

Overall, the UV–Vis results demonstrate that the three natural pigment extracts exhibit distinct optical absorption ranges, reflecting differences in their light-harvesting characteristics. Butterfly pea extract predominantly absorbed at longer visible wavelengths, while bastard teak and tropical almond extracts exhibited absorption in the shorter-wavelength region of the visible spectrum. These findings establish a basis for comparing the electrical performance of DSSCs sensitized with different plant extracts and highlight the potential of locally available natural pigments as photosensitizing materials.

Part 3 Fabricated Dye-Sensitized Solar Cells

The photovoltaic performance of dye-sensitized solar cells (DSSCs) was evaluated using three natural pigment extracts and two photoanode materials: reference TiO_2 powder and an electrochemically synthesized titanium-containing material. Across all three pigments, DSSCs incorporating the synthesized material exhibited higher mean short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), maximum output power (P_{max}), and calculated power conversion efficiency (η) than the corresponding reference-TiO_2 devices. These findings indicate that both pigment selection and photoanode composition influence DSSC electrical performance under the investigated laboratory conditions.

Among the six experimental combinations, the DSSC incorporating tropical almond leaf extract and the synthesized material exhibited the highest mean electrical output, with I_{sc} = 412.70 ± 12.30 μA, V_{oc} = 268.97 ± 154.56 mV, and P_{max} = 5.599 ± 1.790 μW. The corresponding fill factor (FF) was 6.09 ± 2.64%, while the calculated conversion efficiency (η) was 0.0982 ± 0.0314%, based on an assumed irradiance of 19 W/m². These results suggest that tropical almond leaf extract is a promising natural sensitizer when combined with the synthesized photoanode material.

The findings are relevant to Phubuaduang and Somjit (2021), who investigated DSSCs incorporating TiO_2 quantum dots and tropical almond leaf extract. The present study extends this research by comparing three natural pigments—bastard teak, butterfly pea, and tropical almond—with two photoanode materials. However, direct comparisons of conversion efficiencies should be interpreted cautiously because illumination conditions and photovoltaic measurement procedures may differ between studies.

The mean FF values ranged from 4.39% to 14.94%, indicating relatively low fill factors across the investigated conditions. These values suggest that improvements in electrode interfaces, semiconductor-film quality, electrolyte distribution, and cell assembly could enhance photovoltaic performance. Nevertheless, the specific contributions of these factors require further investigation.

Long-term stability is another important consideration for natural dye-based DSSCs. Kabir et al. (2022) emphasized that pigment stability, electrolyte behavior, interfacial contact, and cell sealing can influence device performance and durability. Overall, the results support further investigation of tropical almond extract and the electrochemically synthesized material for DSSC development, particularly through improvements in fabrication conditions, efficiency, and operational stability.

Conclusion

This study demonstrated the influence of synthesis conditions, natural pigment selection, and photoanode materials on the optical and electrical characteristics of dye-sensitized solar cells (DSSCs). Increasing KOH concentration from 2 to 6 M, with citric acid fixed at 0.5 M, shifted the UV–Vis absorption features of the electrochemically synthesized titanium-containing material from approximately 300 to 326 nm. XRD analysis of materials synthesized at 3 and 5 M KOH identified potassium titanate ($K_2Ti_6O_{13}$), brookite TiO_2, and

anatase TiO_2, indicating the formation of multiphase crystalline products. The natural pigment extracts exhibited distinct visible-light absorption ranges: 520–650 nm for butterfly pea, 430–480 nm for bastard teak, and 400–500 nm for tropical almond.

DSSCs incorporating the synthesized material exhibited higher mean electrical outputs than those using reference TiO_2 powder across all three pigment extracts. Among the six investigated conditions, the combination of tropical almond leaf extract and the synthesized material produced the highest mean electrical performance, with Isc = 412.70±12.30 μA, Voc = 268.97±154.56 mV, and Pmax = 5.599±1.790 μW, FF = 6.09±2.64%, and a calculated power conversion efficiency (η) of 0.0982±0.0314%, based on an assumed irradiance of 19 W/m².

These findings highlight the potential of natural pigment extracts and electrochemically synthesized titanium-containing materials for DSSC development and provide a basis for further optimization of photovoltaic devices.

Recommendations

1. Recommendations for Practical Application

1.1 The findings can be used as preliminary information for selecting the synthesized titanium-containing material in combination with locally derived plant extracts for the fabrication of DSSCs.

1.2 Because tropical almond leaf extract combined with the synthesized titanium-containing material produced the highest conversion efficiency among the investigated samples, this combination may serve as a useful basis for selecting natural dyes in further DSSC studies and development.

1.3 The fabricated cells still exhibited relatively low efficiencies compared with silicon solar cells or DSSCs using synthetic dyes. They are therefore more appropriate as prototypes for research, experimentation, and demonstration of light-to-electricity conversion than for direct commercial application.

1.4 Practical application of the findings should consider material-preparation conditions, dye quantity and concentration, cell-assembly procedures, and testing conditions because these factors can affect the electrical characteristics and conversion efficiency of the solar cells.

1.5 The findings may also provide a basis for adding value to local plants by utilizing their pigments as natural sensitizers for DSSCs.

2. Recommendations for Future Research

2.1 Additional citric-acid-to-KOH ratios and concentrations should be investigated to identify synthesis conditions that yield the synthesized titanium-containing material with properties suitable for photovoltaic applications.

2.2 Further characterization of the synthesized titanium-containing material should include particle size, morphology, specific surface area, crystallite size, and band-gap energy to confirm material characteristics and more clearly explain their relationship with DSSC performance.

2.3 The type and properties of semiconductor materials used for the working electrode, together with coating thickness and deposition method on conductive glass, should be investigated to increase dye adsorption and improve electron transfer.

2.4 Other natural dyes that absorb broadly across the visible-light spectrum should be investigated. The co-sensitization or combination of pigments from different plant sources should also be examined because combined pigments may extend the optical absorption range and improve light-harvesting performance (Seithtanabutara et al., 2023).

2.5 The effects of extract concentration, solvent type, extraction time, pH, and electrode-immersion time should be investigated systematically. These factors can influence pigment extraction, dye adsorption, and the photovoltaic performance of natural dye-sensitized solar cells (Ponnambalam et al., 2023).

2.6 The long-term stability of the fabricated cells should be examined under controlled storage and operating conditions. Particular attention should be given to pigment degradation, electrolyte stability, cell sealing, charge recombination, and interfacial deterioration (Kabir et al., 2022).

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