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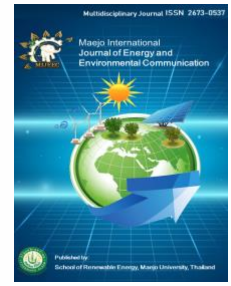

ARTICLE

Evaluating the efficacy and performance of dye-sensitized solar cells using pigments extracted from inthanin leaves

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ABSTRACT

This research study demonstrates the importance of using plants that are grown nearby to extract dyes from pigments. This study involved the production of dye-sensitized solar cells (DSSC) utilizing pigments derived from inthanin leaves to generate electrical energy. The main goal was to evaluate the performance of various DSSCs. The DSSCs were manufactured with dimensions of 3 x 3 cm, and a spectrophotometer examination was performed to investigate the extraction of pigments within the wavelength range of 400-700 nm. The inthanin leaf pigments exhibited the highest level of absorbance in the wavelength intervals of 400-470 nm and 650-680 nm. The analysis of the electrical performance showed the following results for the DSSCs utilizing inthanin leaf pigments: a short-circuit current (I_{sc}) of 0.2970 mA, an open-circuit voltage (V_{OC}) of 0.5907 V, a maximum power (P_{max}) of 0.0013 mW, a maximum voltage (V_{max}) of 0.1191 V, a maximum current (I_{max}) of 0.0106 mA, a fill factor (FF) of 0.720%, and an efficiency (η) of 0.012%. The results indicate that dye-sensitized solar cells made from natural substances, such as inthanin leaves, are feasible for future manufacturing and application.

1. Introduction

Electricity is an essential foundation of contemporary progress, playing a pivotal part in the improvement of nations. To satisfy the increasing need for electricity, it is imperative to produce energy from a range of renewable sources such as solar, wind, hydro, geothermal, and biomass energy (Kongchan et al., 2022). Renewable sources of energy not only meet the increasing need for electricity and help reduce the environmental problems caused by fossil fuels (Manmai et al., 2021). Fossil fuels, despite their status as a primary energy source, make a substantial contribution to environmental degradation, the release of greenhouse gases, and the alteration of the Earth's climate. Minimizing dependence on fossil fuels is crucial for ensuring environmental sustainability and preserving the world's health (Ramaraj et al., 2016; Rathore et al., 2021).

Solar energy is a practical choice for renewable energy, providing a clean, sustainable, and eco-friendly way to generate electricity using solar cells (Ahmad et al., 2021; Trivedi et al., 2023). Solar cells can be classified into three primary categories: silicon-based solar cells (including single-crystal, polycrystalline, and amorphous), compound semiconductor solar cells (such as CIS, CIGS, CdTe, GaAs, GaP, and InP), and third-generation solar cells, which encompass organic solar cells and dye-sensitized solar cells (DSSC). Although silicon-based solar cells now have the most market share, their production process is

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intricate, expensive, and environmentally harmful (Buitrago et al., 2020). The process of extracting and purifying silicon necessitates a considerable amount of energy, resulting in notable carbon emissions. In addition, the disposal of silicon-based solar cells presents environmental difficulties due to the presence of hazardous chemicals used in their manufacturing process (Mejica, et al., 2020).

On the other hand, DSSCs offer a cost-efficient, uncomplicated, and environmentally beneficial option by employing harmless natural dyes that imitate the photosynthesis mechanism found in plants (Khammee et al., 2023). DSSCs employ a photosensitizer, usually a dye, to capture sunlight and produce electrons. Subsequently, these electrons are conveyed to a semiconductor substance, often titanium dioxide (TiO_2), generating an electrical current (Khammee et al., 2022). Utilizing natural dyes in DSSCs presents several benefits, such as decreased production expenses, minimized ecological footprint, and the opportunity to utilize plentiful and renewable plant resources (Mejica, et al., 2022a). This research initiative uses pigments derived from Inthanin leaves to produce DSSCs. The Inthanin tree is a prominent symbol of Maejo University.

The Inthanin tree, scientifically known as *Lagerstroemia macrocarpa* var. *macrocarpa* and part of the Lythraceae family, is commonly called Inthanin bok. Growing 5-12 meters tall, this deciduous tree has brown bark, shallow grooves, and thick leaves. The single, oval leaves are dark green, shiny, and thick, measuring 10-15 cm wide and 20-27 cm long, and serve as food for moth caterpillars. Inthanin flowers bloom in bouquets at the branch ends, featuring round buds about 1 cm in size. It possesses a plentiful supply of green pigments that are frequently not fully exploited. This study examines the viability and effectiveness of DSSCs created using locally accessible plant materials, specifically residual inthanin leaves, as natural pigments.

The extraction procedure entails crushing the leaves, followed by solvent extraction to separate the chlorophyll and other light-sensitive chemicals. The pigments are subsequently deposited onto a substrate coated with TiO_2 to create the photoanode of the DSSC (Mejica et al., 2022b). This research has two main objectives: first, to conduct experiments on fabricating photosensitive dye solar cells utilizing inthanin leaves and second, to assess their effectiveness (Onyemowo et al., 2023). The performance measurements will encompass characteristics such as short-circuit current (I_{sc}), open-circuit voltage (V_{OC}), maximum power output (P_{max}), fill factor (FF), and overall energy conversion efficiency (η).

The anticipated results thoroughly comprehend the efficacy of DSSCs originating from inthanin leaves, which could establish a path for sustainable and environmentally friendly solar energy solutions. This research utilizes natural dyes to advance renewable energy technology and encourage the use of local resources, which aligns with environmental and economic sustainability aims. Furthermore, the practical application of DSSCs with pigments derived from plants should encourage additional investigations into other plant species readily accessible in the area, thereby augmenting the variety and durability of renewable energy sources.

2. Materials and methods

2.1 Preparation of plant material

This study examined the manufacturing and evaluating of photosensitive dye solar cells utilizing Inthanin leaves. Using theoretical and experimental studies, it also investigated the effectiveness of these leaves' photosensitive dye solar cells. The process of preparing Inthanin leaves involved several careful steps. The leaves were collected from Maejo University in Chiang Mai, Thailand (Figure 1A), washed, and dried. They were then crushed into a paste using a mechanical grinder (Figure 1B), which facilitated the release of the dye by breaking down the cell walls. The paste was filtered to separate the liquid dye extract from the solid material (Figure 1C). The liquid dye extract was collected in a flask (Figure 1D) and prepared for integration into the production of photosensitive dye solar cells. This meticulous process ensured the purity and effectiveness of the dye, which is crucial for the performance of the solar cells. It also laid the foundation for comparing dye-sensitized solar cells made from Inthanin leaves.

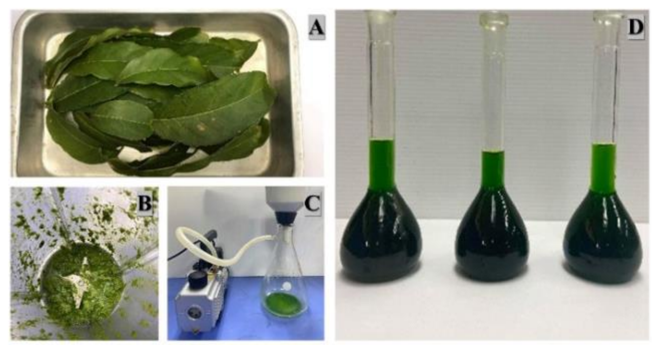

Figure 1. The procedure for preparing Inthanin leaves to extract the photosensitive dye: (A) Gathered unprocessed Inthanin leaves, (B) Leaves being pulverized into a paste, (C) The dye is extracted by a filtration process, and (D) The extracted dye is now in its final form and is prepared for use in solar cells.

2.2 Process for extracting photosensitive dye

The Inthanin leaves were gathered from Maejo University in Chiang Mai, Thailand. Before using photosensitive dye extraction at the Saowarat Building, Nityawarthana, Faculty of Science, Maejo University, Chiang Mai, the objects were cleaned through rinsing and drying, as shown in Figure 1. The Inthanin extraction procedure utilizes methanol as the solvent, with a purity level of 95%. Initially, 30 grams of marigold petals and Inthanin leaves were homogenized with 150 ml of methanol. Subsequently, the concoction underwent filtration using a vacuum apparatus, yielding 150 ml of filtrate. The filtrate was carefully collected in a volumetric flask and preserved at a temperature of 4°C to ensure its stability. Figure 1 illustrates the comprehensive steps of the method.

2.3 Preparing conductive glass

One step in the production of conductive glass was thoroughly cleaning the glass. After washing the glass with soapy water, it was put into an ultrasonicator set to 25 °C for ten minutes. The temperature was maintained throughout the process (Ponnambalam et al., 2023a,b).

2.3 Titanium dioxide paste preparation

To create the TiO_2 paste, 5 grams of titanium dioxide were placed on a magnetic stirrer and stirred for 1 hour. At this juncture, a total of 10 ml of acetic acid with a concentration of 5% and 0.5 ml of surfactant was introduced and adequately blended. Next, the mixture was transferred to a nanoparticle powder mixer and left for 1 hour. Afterward, it was carefully stored in a sealed container to prevent the TiO_2 nanoparticles from evaporating. Subsequently, the scotch tape was detached, and the paste was positioned on a hot plate set at 300°C for 1 hour. Subsequently, a total of 10 droplets of photosensitive dye were administered onto the surface of the TiO_2 at the ambient temperature. The technique was iterated thrice, with intervals for the dye to desiccate between each application, as depicted in Figure 2.

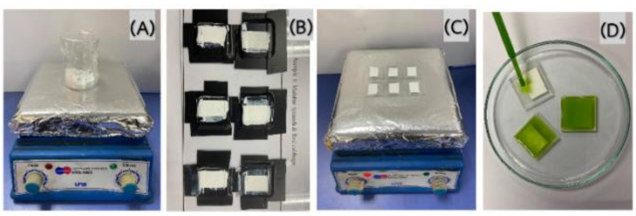

Figure 2. The process of preparing TiO_2 paste and applying a photosensitive dye

2.4 Preparation of the counter-electrode and electrolytes

Get a square-shaped foil measuring 3 × 3 cm. Combine 1 gram of carbon, 5 grams of latex glue, and 5 ml of ethanol, stirring thoroughly to achieve a uniform mixture. Apply the mixture to the foil, then position the foil on a hot plate set at 200°C for 15 minutes to finalize the preparation of the counter-electrode. For electrolytes, combine 80 ml of acrylonitrile, 20 ml of ethylene carbonate, 0.84 g of iodine, and 4.32 g of KI. Stir the mixture thoroughly to achieve homogeneity.

Figure 3. Assembled dye-sensitized solar cells

2.5 Cell assembly and experimental design

Cell assembly refers to grouping cells based on their functional properties or connectivity patterns. Experimental design, on the other hand, involves the planning and organization of scientific experiments to ensure reliable and valid results. The cell assembly commenced by precisely cutting copper and aluminum sheets, each with a thickness of 0.02 mm, into dimensions of 0.5 × 7 cm. A polyethylene separator was precisely trimmed to dimensions of 3 × 3 cm and thereafter affixed to the glass surface in conjunction with a copper plate (Figure 3). The polyethylene separator was saturated with electrolytes and positioned on top of the TiO_2 paste, where carbon paste was subsequently applied and aluminum sheets were utilized. The cells were hermetically sealed using a plastic bag sealer. The investigation employed a completely randomized design (CRD) with three treatment groups: pure titanium dioxide mixed with marigold extract and titanium dioxide with Inthanin leaf extract. The experiment was replicated thrice. The data was obtained by quantifying voltage and current through the utilization of a digital multimeter (UNI-T UT61E) equipped with adjustable resistance (10 kΩ) in the presence of yellow light with an intensity of 24,000 LUX (0.03504 W/cm²).

3. Results and Discussion

This research study conducted an experimental trial on developing photosensitive dye solar cells utilizing inthanin leaves. The procedure involved conducting tests to create photosensitive dye solar cells using inthanin leaves. The acquired data was analyzed to compare the electrical energy production derived from the dyes produced by these plants.

3.1 Spectrophotometric analysis

Spectrophotometry was used to analyze the physical properties of the dye extracts, both qualitatively and quantitatively (Onyemowo et al., 2023). The analysis focused on the wavelength range of 400 – 700 nm. For the Inthanin leaf extract, the light absorption values were notable in the 400 – 470 nm range. Additionally, there was a significant absorbance in the 650 – 680 nm range, corresponding to the chlorophyll color group responsible for producing the green pigment, as shown in Figure 4.

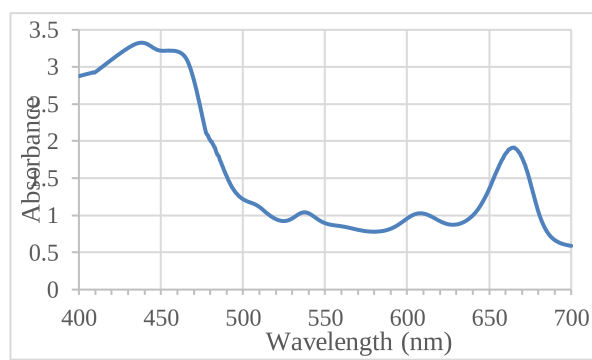

Figure 4. Pigments obtained from Inthanin leaves and their spectrophotometric analysis

The light absorption value derived from the inthanin leaf falls within the 400 – 470 nm range. The absorbance of the chlorophyll color group that creates the green material is represented by values between 650 and 680 nm (Figure 5). The results indicate that inthanin leaf extracts have distinct light absorption properties, potentially impacting their use in photosensitive dye solar cells. The high absorbance in specific wavelength ranges suggests that these natural dyes can effectively harness solar energy, making them viable candidates for further development in dye-sensitized solar cell technology.

3.2 Production of photosensitive dye solar cells

The experiment on fabricating photosensitive dye solar cells encompassed two configurations: one utilizing pure TiO_2 and the other employing titanium dioxide coupled with inthanin leaf extract. The assembling process for these cells was conducted with great care and attention to detail in order to get the best possible performance (Arka et al., 2021). Initially, a copper plate was affixed to a conductive glass sheet that had been previously coated with small amounts of TiO_2 pigment. This configuration enables the assimilation and transformation of light into electrical energy (Lohar et al., 2020). Subsequently, a polyethylene separator sheet infused with electrolyte was meticulously positioned on the glass sheet to uphold the essential ionic conductivity and segregation between the electrodes (Figure 3).

A carbon foil sheet was positioned on the polyethylene separator to improve the cell's performance. This carbon layer serves as a catalyst, enhancing the efficiency of electron transmission within the cell (Mujtahid et al., 2022). Subsequently, an aluminum sheet was included to furnish structural reinforcement and augment the electrical conductivity of the entire assemblage. Subsequently, the complete construction was carefully enclosed with a plastic sheet to prevent contamination and guarantee the cell's stability and durability (Carvalho et al., 2020). The sealing step is essential because it safeguards the delicate interior components from external conditions that may deteriorate performance (Devadiga et al., 2021). The experiment investigates the possible advantages of using Inthanin leaf extract in the titanium dioxide setting to enhance the efficiency of DSSCs. It was anticipated that the natural pigments derived from the Inthanin leaves would enhance light absorption, increasing the overall energy conversion efficiency in the cells. This novel technique exemplifies the increasing fascination with sustainable and environmentally friendly materials in the field of solar cell production.

3.3 Evaluation of titanium dioxide solar cells

The performance of the titanium dioxide solar cells was assessed by measuring different electrical parameters using a digital multimeter (Joseph et al., 2020) with adjustable resistance (10 kΩ) under yellow light with an intensity of 24,000 LUX (0.03504 W/cm²). The measurements yielded the following values: a short circuit current (Isc) of 0.00527 mA, an open circuit voltage (Voc) of 0.094 V, a maximum power (Pmax) of 0.000199 mW, a maximum voltage (Vmax) of 0.048 V, a maximum current (Imax) of 0.00411 mA, an efficiency (η) of 0.019%, and a fill factor (FF) of 40.384%. The findings are succinctly presented in Table 1.

Table 1. Titanium Dioxide Analysis Results

Parameter	Value
Isc (mA)	0.00527
Voc (V)	0.094
Pin (mW/cm²)	3.504
Imax (mA)	0.00411
Vmax (V)	0.048
Pmax (mW)	0.000199
Pmax (mW/cm²)	0.0000664
FF (%)	40.384
η (%)	0.0019

The assessment of TiO_2 solar cells exhibited fundamental performance features commonly observed in DSSCs. The measured Isc of 0.00527 mA and Voc of 0.094 V represent the inherent photoelectric conversion efficiency of TiO_2 without any improvements from natural dyes or other alterations. These numbers demonstrate the energy conversion capacity while emphasizing the constraints of employing pure TiO_2 without other sensitizing agents ().

The cells produced a maximum power (Pmax) of 0.000199 mW, with a matching maximum voltage (Vmax) of 0.048 V and maximum current (Imax) of 0.00411 mA. The cell's overall performance is significantly influenced by its comparatively low efficiency (η) of 0.019% and fill factor (FF) of 40.384%. The efficiency of a solar cell is a measure of the amount of light energy that is successfully converted into electrical energy. On the other hand, the fill factor of a solar cell indicates its electrical quality by comparing the maximum power production to the theoretical power.

These findings indicate that although TiO_2 serves as a basis for solar cell technology, notable enhancements can be achieved by integrating natural colors (Wang et al., 2022). Natural dyes can absorb a broader range of light wavelengths, enhancing the effectiveness of electron injection. Research has demonstrated that plant-derived dyes can improve the photovoltaic characteristics of DSSCs by augmenting their ability to absorb light and generate photocurrent (Armendáriz-Mireles et al., 2023). For example, dyes derived from sources such as Inthanin leaves have shown promise in improving cell efficiency because of their high absorption in the visible light range and their effective electron transfer to the TiO_2.

The first performance of solar cells made solely from TiO_2 highlights the need for additional research and development in incorporating natural colors and other substances. Enhancing the ability to absorb light and facilitate the movement of electrons can increase the efficiency and feasibility of DSSCs, making them more suitable for a broader range of applications in renewable energy. Additional investigation into natural dyes' extraction and application methods is necessary to enhance these solar cells' efficiency and cost-effectiveness.

3.4 Evaluation of inthanin leaf dye cells

The performance metrics were significantly better for the cells using Inthanin leaf dye. The short circuit current (Isc) was 0.2970 mA, and the open circuit voltage (Voc) was 0.5907 V. The maximum power (Pmax) achieved was 0.0013 mW, with a maximum voltage (Vmax) of 0.1191 V and a maximum current (Imax) of 0.0106 mA. The efficiency (η) of the Inthanin leaf cells was 0.012%, and the fill factor (FF) was 0.720%. These results are detailed in Table 2 and illustrated in Figure 5.

The findings demonstrate that the dye derived from inthanin leaves dramatically improves the efficiency of dye-sensitized solar cells compared to pure titanium dioxide. The greater open-circuit voltage (V_{oc}) and overall efficiency (η) indicate that Inthanin leaf dye can absorb light and convert energy. DSSCs have attracted attention because of their potential for reduced manufacturing expenses and their capacity to utilize diverse natural dyes (Yahya et al., 2021). Plant-derived dyes, such as those obtained from inthanin, provide an environmentally friendly substitute for artificial dyes (Najm et al., 2023). Prior research has demonstrated that natural dyes could strongly absorb light within the visible spectrum, a critical factor for the effectiveness of DSSCs (Kaliramna et al., 2022).

Table 2. Inthanin leaf dye cells analysis results

Parameter	Value
Isc (mA)	0.2970
Voc (V)	0.5907
Pin (mW/cm²)	3.504
Imax (mA)	0.0106
Vmax (V)	0.1191
Pmax (mW)	0.0013
Pmax (mW/cm²)	0.0004
FF (%)	0.720
η (%)	0.012

The study found that the Inthanin leaf dye strongly absorbs light in the wavelength regions of 400 – 470 nm and 650 – 680 nm, aligning with chlorophyll's absorption peaks. This is consistent with the results of earlier studies, which suggest that chlorophyll and similar pigments efficiently capture solar energy because they strongly absorb light in these specific locations (Dayan et al., 2020).

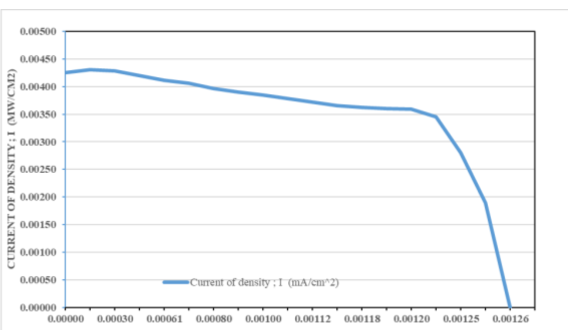

Figure 5. Pigments obtained from Inthanin leaves and their spectrophotometric analysis.

Furthermore, the fill factor (FF) and efficiency (η) detected in the Inthanin leaf cells were remarkable. The dye's FF of 0.720% and efficiency of 0.012% indicate its high capacity to transform absorbed light into electrical energy efficiently. Although the values may be considered small compared to commercial silicon-based solar cells, they demonstrate the potential of Inthanin leaf dye as a practical photosensitizer in DSSCs. The dye's ability to produce a substantial electric potential when exposed to light is highlighted by its comparatively high open-circuit voltage (Voc) of 0.5907 V. This study's findings highlight natural dyes' capacity to improve the performance of DSSCs. Further research might prioritize improving the extraction and application procedures for Inthanin leaf dye and investigating the utilization of alternative plant-derived dyes to enhance the effectiveness and cost-efficiency of dye-sensitized solar cells.

4. Conclusion

This study investigated the viability of using inthanin leaves as a renewable source for manufacturing photosensitive dye solar cells. The study focused on producing photovoltaic dyes from inthanin leaves and methodically assessing their efficacy through rigorous experiments. The findings indicated that the solar cells fabricated from inthanin leaves attained a short circuit current (Isc) of 0.2970 mA, an open-circuit voltage (VOC) of 0.5907 V, and a maximum power (Pmax) of 0.0013 mW. The cells exhibited a peak voltage (Vmax) of 0.1191 V, a peak current (Imax) of 0.0106 mA, and a fill factor (FF) of 0.720%, resulting in an overall efficiency of 0.012%. This result highlights the significance of choosing plant species that can absorb light to advance effective photosensitive dye solar cells. According to the study, augmenting the dimensions and number of solar cells could amplify the electricity generated to fulfill specific requirements of various applications. The findings from this research add to the continuous endeavors in the renewable energy industry to utilize natural materials for sustainable energy solutions.

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