Journal of Technomaterial Physics
Journal homepage: https://talenta.usu.ac.id/JoTP

Optical, Electrochemical, and Photovoltaic Evaluation of Suji Leaf (*Dracaena angustifolia*) Extract as a Natural Sensitizer for Dye-Sensitized Solar Cells

Asti Sawitri[1]*, Hasniah Aliah[2], Siti Nur Jaoharoh Muthmainnah[3], and Ryan Nur Iman[4]

[1]*Department of Physics, Universitas Halim Sanusi, Bandung, 40116, Indonesia*
[2]*Department of Physics, Faculty of Science and Technology, UIN Sunan Gunung Djati, Bandung, 40614, Indonesia*
[3]*Darul Muqarabbin, Bandung, 40215, Indonesia*
[4]*Department of Electrical Engineering, Faculty of Engineering and Agriculture, Universitas Islam Nusantara, Bandung, 40286, Indonesia*
*Corresponding Author: astisawitri@uhs.ac.id

ARTICLE INFO

Article history:
Received 15 June 2026
Revised 18 August 2026
Accepted 24 August 2026
Available online 25 August 2026

E-ISSN: 2656-0755
P-ISSN: 2656-0747

How to cite:
A. Sawitri, H. Aliah, S. N. J. Muthmainnah, and R. N. Iman, "Optical, Electrochemical, and Photovoltaic Evaluation of Suji Leaf (*Dracaena angustifolia*) Extract as a Natural Sensitizer for Dye-Sensitized Solar Cells," Journal of Technomaterial Physics, vol. 08, no. 02, pp. 147-158, Aug. 2026, doi: 10.32734/jotp.v8i2.26017.

ABSTRACT

A dye-sensitized solar cell (DSSC) is a third-generation solar cell technology that uses a dye as a sensitizer to convert light energy into electrical energy. This study aims to evaluate the potential of suji leaf extract (*Dracaena angustifolia*) as a natural dye for TiO_2-based DSSC using acetone and ethanol as solvents. Characterization was performed using UV-Vis, cyclic voltammetry (CV), and current–voltage (I–V) measurements. The UV-Vis results showed a maximum absorption peak at around 655 nm, indicating the dominance of chlorophyll pigments. The acetone extract produced higher absorbance and chlorophyll-a content than the ethanol extract. The CV results showed that the HOMO and LUMO energy levels of the acetone extract were −4.86 eV and −4.29 eV, respectively, whereas those of the ethanol extract were −4.90 eV and −4.44 eV. DSSC testing revealed that the acetone extract yielded a higher V_{oc} value (0.0194 V) compared to the ethanol extract (0.0175 V), while both exhibited a J_{sc} value of 0.0667 mA·cm^{-2}. The ethanol extract achieved a higher FF (57.9%) than the acetone extract (53.2%). The power conversion efficiencies obtained were 0.050% for the acetone solvent and 0.049% for the ethanol solvent. The results indicate that suji leaf has potential as a natural sensitizer in DSSC, with performance influenced by the choice of extraction solvent.

Keywords: Chlorophyll, DSSC, Natural Dye, Photovoltaic, Suji Leaf, TiO_2

ABSTRAK

Dye-Sensitized Solar Cell (DSSC) merupakan teknologi sel surya generasi ketiga yang memanfaatkan pewarna sebagai sensitizer untuk mengonversi energi cahaya menjadi energi listrik. Penelitian ini bertujuan mengevaluasi potensi ekstrak daun suji (*Dracaena angustifolia*) sebagai pewarna alami pada DSSC berbasis TiO_2 dengan menggunakan pelarut aseton dan etanol. Karakterisasi dilakukan menggunakan UV-Vis, *cyclic voltammetry* (CV), dan pengujian arus–tegangan (I–V). Hasil UV-Vis menunjukkan puncak serapan maksimum pada sekitar 655 nm yang mengindikasikan dominasi pigmen klorofil. Ekstrak aseton menghasilkan absorbansi dan kandungan klorofil-a yang lebih tinggi dibandingkan ekstrak etanol. Hasil CV menunjukkan tingkat energi HOMO dan LUMO ekstrak aseton masing-masing sebesar −4,86 eV dan −4,29 eV, sedangkan ekstrak etanol sebesar −4,90 eV dan −4,44 eV. Pengujian DSSC memperlihatkan bahwa ekstrak aseton menghasilkan nilai V_{oc} (0,0194 V) yang lebih tinggi dibandingkan ekstrak etanol (0,0175 V), sementara keduanya menunjukkan nilai J_{sc} sebesar 0,0667 mA·cm^{-2}. Ekstrak etanol mencapai FF yang lebih tinggi (57,9%) dibandingkan ekstrak aseton (53,2%). Efisiensi konversi daya yang diperoleh adalah 0,050% untuk pelarut aseton dan 0,049% untuk pelarut etanol. Hasil penelitian menunjukkan bahwa daun

http://doi.org/10.32734/jotp.v8i2.26017

suji berpotensi digunakan sebagai sensitizer alami pada DSSC, dengan performa yang dipengaruhi oleh jenis pelarut ekstraksi.

Kata kunci: Daun Suji, DSSC, Fotovoltaik, Klorofil, Pewarna Alami, TiO_2

1. Introduction

Currently, energy has become an essential human need to support various activities, including basic, industrial, and commercial activities. Along with population growth and economic development, global energy demand continues to increase from year to year [1]. This condition raises concerns about global energy security, particularly due to the heavy dependence on fossil energy sources, whose availability is becoming increasingly limited [1], [2]. The decrease of fossil energy reserves has encouraged the development of various renewable energy sources as more sustainable alternatives. In addition to meeting long-term energy demands, renewable energy also has a lower environmental impact than conventional fossil fuel-based energy sources [1]. Therefore, numerous studies continue to be conducted to develop renewable energy technologies that are not only efficient in energy production but also environmentally friendly.

Solar energy is one of the renewable energy sources with potential for development in Indonesia. Indonesia has enormous solar energy potential because it is located in the tropics and is crossed by the equator, so it receives relatively high solar radiation throughout the year [2]. The average intensity of solar radiation in most parts of Indonesia reaches around 4–5 kWh/m^2/day, making solar energy one of the most prospective renewable energy sources to be developed [1], [2]. This abundant solar energy can be converted into electrical energy using solar cells. Solar cells work based on the photovoltaic effect, which is the process when photons from sunlight are absorbed by semiconductor materials, resulting in electron-hole pairs that are then separated to produce an electric current. The solar cell technology that is currently developing rapidly is the DSSC [3], [4]. This technology is attracting attention because it offers relatively low fabrication costs, a simple manufacturing process, and the ability to utilize dyes as sensitizers to absorb solar light energy [4]–[6]. DSSC was first introduced by O'Regan and Grätzel in 1991 through the use of nanocrystalline semiconductor materials that can increase the efficiency of converting light energy into electrical energy [7]. DSSC generally consist of several main components, including semiconductor layers, dye sensitizers, electrolytes, and transparent conductive electrodes. DSSC performance is greatly influenced by the interaction between these components, especially the ability of semiconductors to transfer electrons and the ability of dyes to absorb light and inject electrons into semiconductors [8].

In the early stages of its development, DSSC widely used synthetic dyes based on ruthenium complexes because they have a broad absorption spectrum and high energy conversion efficiency [9]. However, the use of synthetic dyes faces several obstacles, including a complex synthesis process, relatively high production costs, limited material availability, and potential environmental impacts due to the use of heavy metals [9]–[11]. These limitations have encouraged various studies to develop natural dyes as alternative sensitizers that are cheaper, environmentally friendly, easily obtained, and sustainable [12]. Various sources of natural dyes have been explored, especially those derived from plants containing photosynthetic pigments such as chlorophyll, anthocyanin, and carotenoids [13]. These pigments have chromophore groups that are able to absorb light in the visible spectrum region, making them potentially useful as sensitizers in DSSC. Among the various natural pigments that have been studied, chlorophyll is a promising candidate because it has strong absorption bands in the blue and red regions of the visible spectrum. These characteristics allow chlorophyll to play an effective role in the process of photon absorption and electron transfer in the DSSC system [14]. Therefore, various plants that have high chlorophyll content are starting to be evaluated as a source of natural dyes to improve DSSC performance while supporting the development of more sustainable energy technology. One plant that has the potential to be developed as a natural source of chlorophyll is suji leaf (*Dracaena angustifolia*). This plant has long been used as a natural green coloring in various food products because of its high chlorophyll content and ability to produce a stable green color [15]. Apart from that, *Dracaena angustifolia* is a tropical plant that is widely found and cultivated in Southeast Asia, including Indonesia, so the availability of raw materials is relatively abundant and easy to obtain [15]. The high chlorophyll content in suji leaf makes it a potential source of natural dye that can absorb visible light [16] for DSSC applications.

Several studies have explored the potential of *Dracaena angustifolia* as a source of sensitizersfor DSSC. Ahliha et al. reported that suji leaf chlorophyll extracted using acetone had absorption peaks at around 665.5 nm and 412 nm with a power conversion efficiency of 0.058% [17]. The study focused on the interaction of chlorophyll functional groups with TiO_2 photoanodes through FTIR characterization, but did not evaluate the electronic properties of the dye, such as the HOMO–LUMO energy levels, which play an important role in the electron injection process. Subsequently, Sova and Setiarso developed the characterization of suji leaf chlorophyll through electrochemical, optical, and photovoltaic analysis using ethanol extracts. They reported HOMO and LUMO energy levels of around −5.68 eV and −3.17 eV, respectively, then complemented it with UV–Vis spectroscopy, band gap estimation, cyclic voltammetry, and photovoltaic testing to evaluate the feasibility of chlorophyll as a DSSC sensitizer [18].

However, all previous studies have used a single solvent in the *Dracaena angustifolia* extraction process. Therefore, the effect of solvent type on chlorophyll composition, optical characteristics, electrochemical properties, and photovoltaic performance of DSSC has not been systematically evaluated. Solvent polarity determines pigment extraction efficiency, the resulting molecular composition, dye adsorption on the TiO_2 surface, and the electron injection process, which directly impacts energy conversion efficiency. Therefore, the relationship between extraction solvent, chlorophyll composition, optical properties, electronic energy levels, and DSSC performance remains incompletely understood.

In this study, suji leaf chlorophyll extracts obtained using two solvents of different polarities, acetone and ethanol, were systematically compared to evaluate the effect of solvents on chlorophyll composition, optical characteristics, HOMO–LUMO energy levels, and DSSC photovoltaic performance. Unlike previous studies, this study integrates the relationship between pigment composition, optical properties, electronic properties, and photovoltaic performance, providing a more comprehensive understanding of the role of extraction solvents in determining the performance of chlorophyll-based natural sensitizers.

Based on this, this study aims to evaluate the potential of suji leaf extract (*Dracaena angustifolia*) as a DSSC sensitizer through characterization of chlorophyll composition, optical properties, electrochemical properties, and photovoltaic performance. DSSC were fabricated using a sandwich configuration with a TiO_2 photoanode made through a screen printing method. The results of this study are expected to provide a scientific basis in selecting optimal extraction solvents to improve the performance of natural sensitizers while supporting the development of environmentally friendly and low-cost DSSC.

2. Research Methods

2.1. Materials

The materials used in this study include suji leaf (*Dracaena angustifolia*) from traditional markets in Bandung, West Java, Indonesia, as a source of natural dye. Suji leaf pigment was extracted using acetone and ethanol solvents (for analysis, EMSURE® ACS, ISO, Reag. Ph Eur) from Merck. Anatase phase titanium dioxide (TiO_2) from Brataco served as the semiconductor material. The conductive substrate was fluorine-doped tin oxide (FTO) glass. The carbon counter electrode was prepared using graphite obtained from a commercial graphite pencil (Faber-Castell, 2B). The electrolyte consisted of polyethylene glycol (PEG-400), iodine (I_2), and potassium iodide (KI), all purchased from Merck.

2.2. Suji Leaf Extract

The suji leaf extraction process used a 1:10 ratio of suji leaf to solvent. The cleaned suji leaves were oven-dried for 20 minutes at 70 °C to reduce water content. The dried leaves were then ground and soaked in different acetone and ethanol solvents. Sensitization occurred without direct exposure to sunlight. Filtration with luminar paper provided the suji leaf extract.

2.3. Construction of DSSC

The DSSC was assembled in a sandwich configuration consisting of a TiO_2-coated FTO working electrode, a carbon-coated FTO counter electrode, and an iodide/triiodide electrolyte. The working electrode was prepared by dispersing 2 g of TiO_2 in 6 mL of ethanol under continuous stirring until a homogeneous paste was obtained. The TiO_2 paste was deposited onto fluorine-doped tin oxide (FTO) glass by screen printing using an M180 mesh with an active area of 1.0×1.5 cm^2, followed by heat treatment at 250 °C for 60 min. After cooling, the TiO_2-coated electrode was immersed in the suji (*Dracaena angustifolia*) leaf dye solution to allow dye adsorption. The counter electrode was prepared by coating the conductive side of FTO glass with a thin layer of graphite obtained from a commercial graphite pencil, followed by exposure to the candle flame to improve the adhesion of the graphite layer. The resulting counter electrode had an active area of approximately 1.0×1.5 cm^2. The electrolyte was prepared by dissolving 0.2 g of iodine (I_2) and 0.8 g of potassium iodide (KI) in 10 mL of polyethylene glycol (PEG-400) under magnetic stirring at 100 rpm for approximately 1 h until a homogeneous solution was obtained. The dye-sensitized TiO_2 working electrode and the graphite-coated counter electrode were then assembled in a sandwich configuration. A adhesive was applied between the two electrodes to prevent direct contact and to confine the electrolyte within the cell while avoiding leakage into the active semiconductor area.

2.4. Characterization of dye

The dye absorption of suji extract was characterized using an Edinburgh DS5 UV-Vis Spectrophotometer in the wavelength range of 300 nm to 800 nm. Electrochemical characterization was carried out using a conventional three-electrode electrochemical cell. A carbon paste electrode served as the working electrode (WE), while a platinum (Pt) wire and an Ag/AgCl electrode were used as the counter electrode (CE) and reference electrode (RE), respectively. The electrochemical measurements were performed in an iodide/triiodide (I^-/I_3^-) electrolyte prepared by dissolving iodine (I_2) and potassium iodide (KI) in polyethylene glycol 400 (PEG 400) as the solvent. The cyclic voltammetry (CV) measurement setup is illustrated in Figure 1.

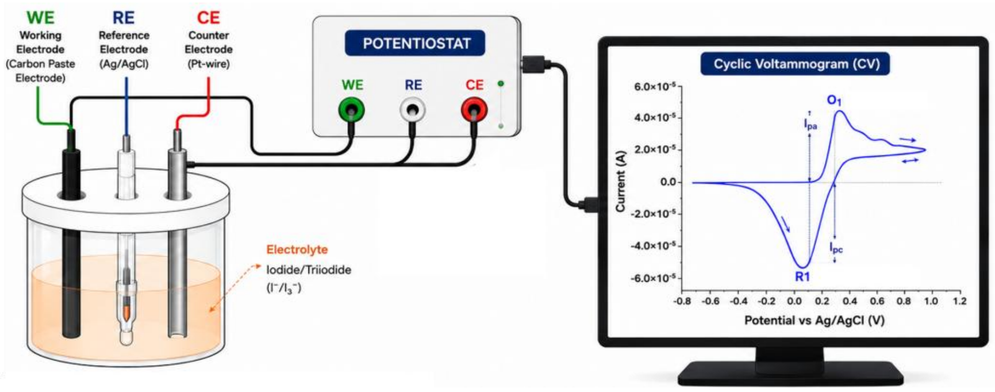

Figure 1. Schematic CV measurements.

2.5. The photovoltaic performance

The photovoltaic characteristics of the DSSC were evaluated by measuring the output voltage and current under a lamp with a radiation intensity of 13.8 W m^{-2} using the test circuit measured in Figure 2. The DSSC was connected to a potentiometer as a variable load, while the voltage and current were measured simultaneously using two digital multimeters controlled as a voltmeter and ammeter. The current value obtained was then normalized to the active area of the cell to produce the current density (J), thus obtaining the J–V curve.

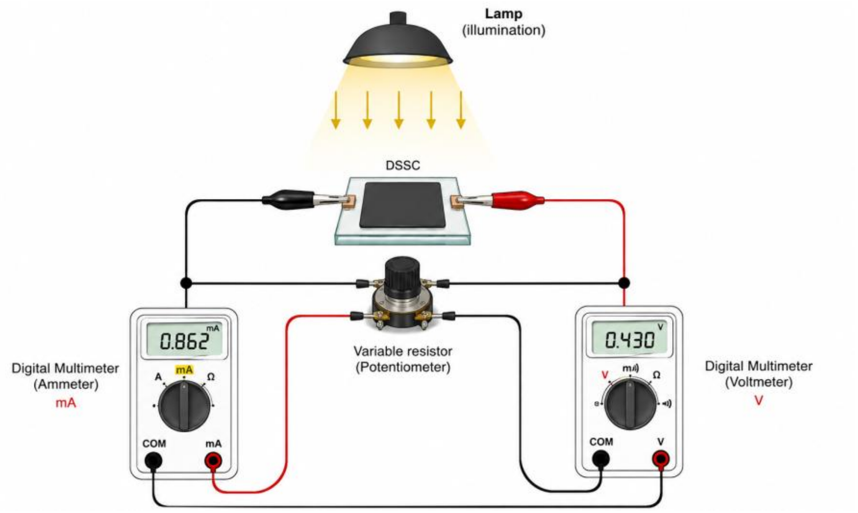

Figure 2. Schematic I-V measurements.

3. Results and Discussion

3.1. Optical Properties of Suji Leaf Dye

Extraction of *Dracaena angustifolia* using acetone and ethanol produced dark green dye solutions, indicating the successful extraction of chlorophyll-containing pigments (Figure 3). However, the visual appearance of the extract alone cannot be used to determine its optical absorption characteristics. Therefore, the light-harvesting capability of the extracted dyes was quantitatively evaluated using UV–Vis spectroscopy, and the corresponding spectra are presented in Figure 4.

Figure 3. Photographs of suji leaf extracts prepared using (a) acetone and (b) ethanol under identical visible-light illumination.

The UV–Vis spectra show that both extracts exhibit a strong absorption band with a maximum absorption wavelength (λ_{max}) at approximately 655 nm, which is characteristic of chlorophyll pigments. The optical characteristics obtained in this study are consistent with previous studies using *Dracaena angustifolia* as a natural sensitizer for DSSC. Ahliha et al. reported a maximum absorption wavelength of approximately 665.5 nm for suji leaf chlorophyll extracted with acetone [17], while Sova and Setiarso reported a λ_{max} of approximately 663 nm for chlorophyll extracted with ethanol [18]. Although the maximum absorbance obtained in this study slightly shifted towards a lower wavelength (655 nm), the absorption band remained within the characteristic Q-band region of chlorophyll pigments [19], [20]. Such wavelength shifts are frequently reported for chlorophyll extracts and are generally attributed to differences in extraction conditions, solvent composition, pigment concentration, molecular aggregation, and the microenvironment around the chlorophyll molecules, all of which affect the electronic transitions of the porphyrin macrocycle [13], [21].

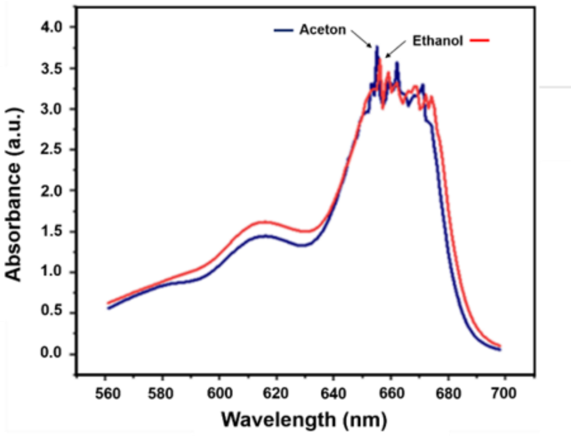

Figure 4. Absorbance graphs of suji leaf extracts using acetone and ethanol solvents.

In this study, the suji leaf extract obtained using acetone solvent showed a slightly higher maximum absorbance value (3.68) compared to the extract using ethanol solvent (3.61). The difference in absorbance characteristics is related to the composition of chlorophyll pigments successfully extracted by each solvent. Based on the calculation of chlorophyll content using the Arnon (1949) equation [22]. The ethanol extract contained 33.74 mg/L chlorophyll-*a*, 39.20 mg/L chlorophyll-*b*, and 72.94 mg/L total chlorophyll, whereas the acetone extract contained 35.23 mg/L chlorophyll-*a*, 34.92 mg/L chlorophyll-*b*, and 70.15 mg/L total chlorophyll. Although ethanol extracted a slightly higher total chlorophyll concentration, the acetone extract exhibited a slightly higher chlorophyll-*a* concentration.

The observed differences are attributed to the polarity of the extraction solvents and the molecular structures of chlorophyll pigments [23], [24]. Chlorophyll-*a* contains a methyl (–CH_3) substituent, making it relatively less polar than chlorophyll-*b*, which contains a formyl (–CHO) group that increases its polarity [23], [24]. Consequently, ethanol, as a more polar solvent, preferentially extracted chlorophyll-*b*, whereas acetone more effectively extracted chlorophyll-*a* [23]–[25]. Chlorophyll-a is the primary photosynthetic pigment that functions as the reaction-center pigment responsible for photon absorption and primary charge separation, whereas chlorophyll-b mainly acts as an accessory pigment by broadening the absorption spectrum and transferring excitation energy to chlorophyll-a. Therefore, a relatively higher proportion of chlorophyll-a can enhance the efficiency of photon harvesting and increase the probability of photoexcitation under visible-light irradiation [21], [25]. The porphyrin macrocycle of chlorophyll provides an extended π-conjugated electronic system that enables efficient absorption of visible light and facilitates electron excitation [25]. Consequently, the stronger absorbance observed for the acetone extract suggests a greater population of photoexcited electrons generated under illumination, which is expected to improve the subsequent electron-transfer process in DSSC [4], [26], [27]. However, efficient light absorption alone is insufficient to achieve high photovoltaic performance. The excited electrons must also possess suitable molecular energy levels to enable spontaneous electron injection into the TiO_2 conduction band and efficient dye regeneration by the electrolyte [4] [28]. Therefore, the electrochemical properties of the extracted dyes, particularly the HOMO and LUMO energy levels, are essential for understanding the relationship between optical characteristics and photovoltaic performance and are discussed in the following section.

3.2. Electrochemical Properties of Suji Leaf Dye

Cyclic voltammetry (CV) characterization was carried out to evaluate the electrochemical properties of suji leaf extract obtained using acetone and ethanol solvents. Electrochemical characteristics are one of the important parameters in determining the suitability of a dye as a sensitizer in DSSC because they are directly related to the electron transfer mechanism and photovoltaic energy conversion efficiency [11], [26]. Through CV analysis, the oxidation potential (E_{ox}) and reduction potential (E_{red}) can be determined, which are then used to estimate the energy levels of the Highest Occupied Molecular Orbital (HOMO) and Lowest Unoccupied Molecular Orbital (LUMO) of the dye. These parameters play an important role in determining the suitability of the dye as a sensitizer in TiO_2-based DSSC because they affect the electron injection and regeneration processes during the conversion of light energy into electrical energy. The results of cyclic voltammetry characterization are shown in Figure 5.

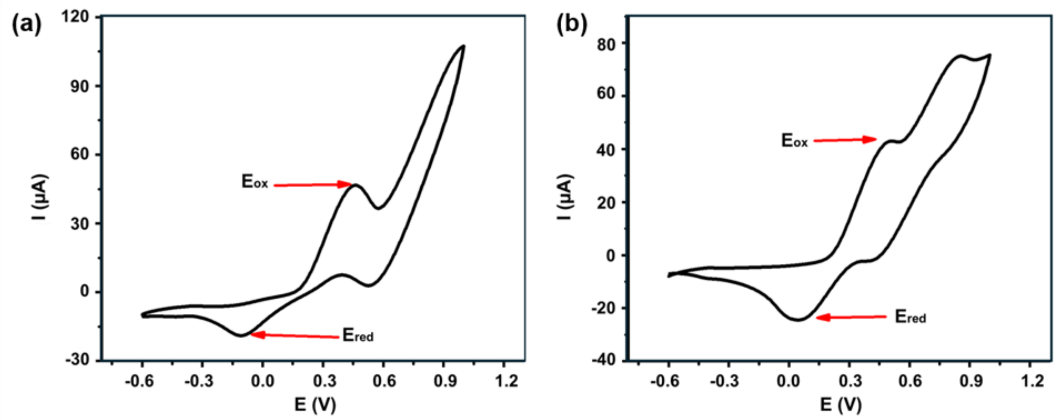

Figure 5. Cyclic voltammetry (CV) graphs of dye with solution ekstrak (a) Aceton dan (b) Ethanol.

The cyclic voltammetry (CV) curves presented in Figure 5 exhibit distinct oxidation and reduction peaks for the suji leaf extracts, confirming the electrochemical activity of the chlorophyll-based pigments. These reversible redox characteristics are essential for DSSC as the photoelectrochemical conversion process relies on continuous electron transfer between the photoexcited dye, the TiO_2 semiconductor, and the electrolyte [11], [29]. The HOMO and LUMO energy levels were estimated from the oxidation and reduction peak potentials obtained from cyclic voltammetry according to Sinha et al. [30] using the following equations:

$$E_{HOMO} = -e(E_{ox} + 4.4)\ \text{eV}$$
$$E_{LUMO} = -e(E_{red} + 4.4)\ \text{eV}$$

where $E_{ox}$and E_{red}represent the oxidation and reduction peak potentials, respectively. The calculated HOMO and LUMO energy levels are summarized in Table 1.

Table 1. Summary of calculated energy levels of the extracted dyes.

No	Sample	E_{ox} (V)	E_{red} (V)	LUMO (eV)	HOMO (eV)
1	Dye Aceton	0.4635	−0.1048	−4.29	−4.86
2	Dye Ethanol	0.5078	0.0473	−4.44	−4.90

Table 1 shows that the acetone extract has a HOMO energy level of −4.86 eV and a LUMO of −4.29 eV, while the ethanol extract has a HOMO energy level of −4.90 eV and a LUMO of −4.44 eV. These energy levels provide information about the possible electron transfer processes between the dye, TiO_2 semiconductor, and electrolyte in the DSSC system [4]. For efficient DSSC operation, the LUMO energy level of the sensitizer should be higher than the TiO_2 conduction band edge, which is typically located around −4.0 to −4.2 eV compared to the vacuum level, thus providing sufficient driving force for electron injection [26], [29]. Meanwhile, the HOMO energy level should be lower than the electrolyte redox potential I^-/I_3^- (around −4.8 eV) to allow efficient regeneration of oxidized dye molecules [26], [29]. As shown in Table 1, both extracts meet these basic energy requirements. The acetone extract has a LUMO level of −4.29 eV, which is closer to the TiO_2 conduction band than the ethanol extract. This smaller energy difference is expected to facilitate electron injection while minimizing excessive energy loss during charge transfer. Furthermore, the HOMO levels of both extracts remained below the redox potential of the electrolyte, indicating that dye regeneration by the I^-/I_3^- electrolyte is thermodynamically favorable.

The superior electrochemical characteristics of the acetone extract are consistent with the optical characterization discussed previously. UV–Vis analysis showed that the acetone extract exhibited slightly higher absorbance and higher chlorophyll-a content than the ethanol extract. Chlorophyll-*a* has a nebulous conjugated porphyrin structure that promotes efficient π-electron delocalization, enhancing visible light absorption and intermolecular electron transfer [26], [27]. Consequently, the higher chlorophyll-*a* content extracted by acetone is likely responsible for the more favorable HOMO–LUMO alignment observed in the CV measurements. The obtained energy levels are also comparable to those reported for other chlorophyll-based natural sensitizers. Sova and Setiarso reported HOMO and LUMO levels of −5.68 eV and −3.17 eV, respectively, for suji leaf dye extracted with ethanol [18], indicating that solvent selection significantly influences the electrochemical properties of chlorophyll pigments. Compared with previous studies, the HOMO levels obtained in this study (−4.86 to −4.90 eV) are within the typical range reported for chlorophyll-based sensitizers, while the LUMO levels show slight variations that may arise from differences in extraction conditions, chlorophyll composition, solvent polarity, and electrochemical measurement parameters.

Overall, the electrochemical characterization confirmed that suji leaf extract has suitable redox activity and energy level alignment for DSSC applications. Among the two extraction solvents, acetone provided a more favorable electronic structure by producing a higher LUMO level along with stronger optical absorption, indicating greater potential for efficient electron injection in TiO_2. These findings support the use of acetone as a more suitable extraction solvent for chlorophyll-based natural sensitizers, although the practical effectiveness of charge transfer must ultimately be established through photovoltaic performance measurements of the fabricated DSSC devices.

3.3. Performance of DSSC

The photovoltaic characteristics of the DSSC sensitized with suji leaf extract were evaluated from the current density–voltage (J–V) curves constructed (Figure 6) by normalizing the measured current–voltage (I–V) data to the active cell area (1.5 cm^2). The photovoltaic parameters, including the open-circuit voltage (V_{oc}), short-circuit current density (J_{sc}), maximum output power (P_{max}), fill factor (FF), and power conversion efficiency (η), are summarized in Table 2. The maximum output power was determined from the maximum power point of the I–V characteristics, corresponding to V_{max} = 17.2 mV and I_{max} = 0.06 mA for the ethanol extract, and V_{max} = 16.9 mV and I_{max} = 0.06 mA for the acetone extract, resulting in P_{max} values of 1.032 µW and 1.014 µW, respectively.

The J–V curves in Figure 6 show that both DSSC have similar characteristic patterns as the current density decreases gradually with increasing voltage until it reaches the V_{oc} condition. The shape of the curve indicates that the process of light absorption, electron injection from the dye molecule into the TiO_2 conduction band, and dye regeneration by the electrolyte has occurred. However, the relatively shallow slope of the curve indicates that losses due to electron recombination and internal cell resistance are still quite large, thus limiting the output power of the DSSC. Such characteristics are generally found in natural dye-based DSSC because chlorophyll molecules have lower photochemical stability and electron transfer efficiency than synthetic sensitizers based on ruthenium complexes or modern organic dyes [31], [32].

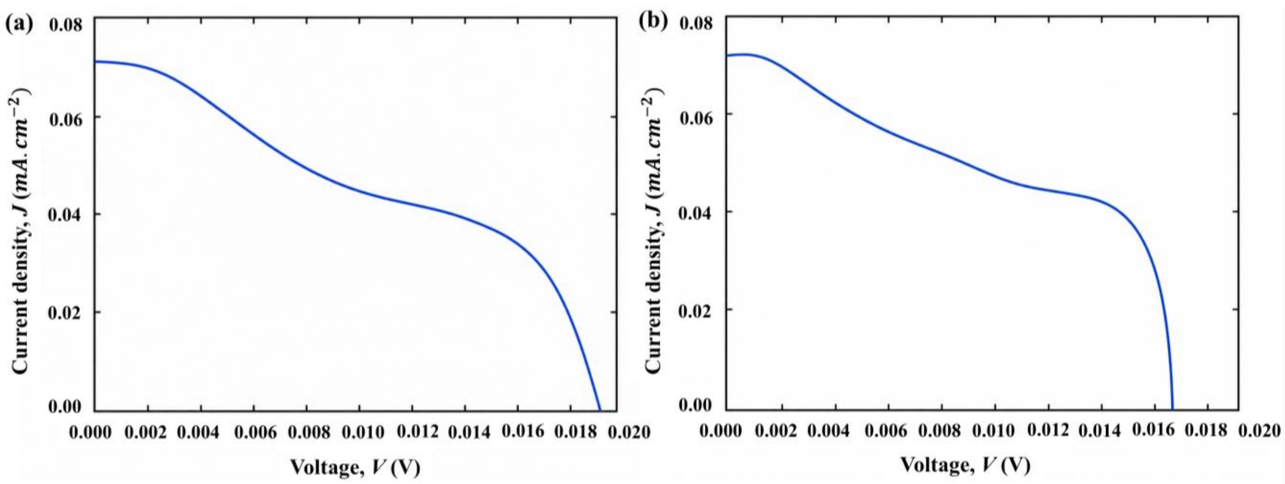

Figure 6. J–V curve of DSSC using suji leaf extract with solvents (a) aceton and (b) ethanol.

Table 2. Photovoltaic parameters of TiO_2-based DSSC with various dye extraction solvents.

Sample	V_{oc} (V)	J_{sc} ($mA.cm^{-2}$)	FF (%)	η (%)
TiO_2 : Dye-aseton	0.0194	0.0667	53.2	0.050
TiO_2 : Dye-etanol	0.0175	0.0667	57.9	0.049

Based on Table 2, the DSSC using acetone extract produced a V_{oc} value of 0.0194 V, higher than the ethanol extract of 0.0175 V, while both samples produced the same J_{sc}, which was 0.0667 $mA.cm^{-2}$. Conversely, the fill factor value of the ethanol extract (57.9%) was higher than that of the acetone extract (53.2%). The combination of these parameters resulted in a power conversion efficiency of 0.050% for the acetone extract and 0.049% for the ethanol extract. Although the difference is relatively small, these results indicate that increasing V_{oc} makes a greater contribution to efficiency than increasing the fill factor in the developed DSSC system.

The difference in performance is consistent with the UV–Vis characterization results which show that the acetone extract contains 35.23 mg/L of chlorophyll-*a*, slightly higher than the ethanol extract which contains 33.74 mg/L of chlorophyll-*a*. Conversely, the chlorophyll-*b* content in the ethanol extract (39.20 mg/L) is higher than the acetone extract (34.92 mg/L), so the total chlorophyll content of the ethanol extract (72.94 mg/L) is also greater than the acetone extract (70.15 mg/L). However, the photovoltaic results show that increasing total chlorophyll does not directly improve DSSC performance. Instead, the parameter that shows a better correlation with cell performance is the chlorophyll-*a* content, because this pigment is the primary photosynthetic pigment that functions as a reaction center in absorbing photons and triggering primary charge separation. Meanwhile, chlorophyl-*b* acts as an accessory pigment that broadens the light absorption spectrum and transfers excitation energy to chlorophyll-*a*. Therefore, a higher proportion of chlorophyll-*a* will increase the efficiency of photon harvesting and the chance of electron photoexcitation when exposed to visible light [21], [25]. In addition, chlorophyll molecules have a porphyrin ring structure with an extended π-conjugated electron system. This structure allows the molecule to absorb visible light efficiently while facilitating the excitation of electrons from the ground energy level to higher energy levels [25]. The UV–Vis results in this study showed that the acetone extract had a higher absorption intensity in the main absorption region of chlorophyll-*a*. This condition indicates that more electrons are excited during the irradiation process, thus increasing the opportunity for electron transfer to the TiO_2 conduction band and ultimately resulting in a higher V_{oc} value compared to the ethanol extract. The relationship between increased absorbance, the number of excited electrons, and electron transfer efficiency in DSSC has also been reported by several previous studies [4], [26], [27].

Although the chlorophyll-*a* content in the acetone extract is higher, the fill factor value is actually greater in the ethanol extract. This indicates that the performance of DSSC is not only influenced by the ability of dye to absorb light, but also by the charge transport process within the cell [11], [33]. The FF value represents the quality of the DSSC electrical characteristics and influenced by series resistance, shunt resistance, and electron recombination at the TiO_2–dye–electrolyte interface [31]. Therefore, although the acetone extract produces more excited molecules, losses during the electron transport process can still limit the increase in the fill factor, so that the difference in efficiency between the two samples is relatively small. This interpretation is also in line with the results of cyclic voltammetry characterization which shows that the HOMO and LUMO energy levels of suji leaf extract meet the requirements for the electron injection process into the TiO_2 conduction band. The suitability of these energy levels allows excited electrons from chlorophyll molecules to be transferred spontaneously to TiO_2 before being regenerated by the electrolyte redox couple, so that the photovoltaic cycle can take place repeatedly.

For comparison, the DSSC efficiency obtained in this study is compared with previous research, as presented in Table 3.

Table 3. Comparison of the efficiency of DSSC based on suji leaf extract with previous research.

Study	Sensitizer	Solvent	η (%)	Highlights
Ahliha *et al.*	Suji leaf extract	Acetone	0.058	Reported the highest efficiency among DSSC sensitized with suji leaf extract and serves as a reference for comparison.
This study	Suji leaf extract	Ethanol	0.049	Achieved the highest fill factor (57.9%), indicating improved charge transport and overall device quality.
This study	Suji leaf extract	Acetone	0.050	Produced the highest chlorophyll-*a* content and slightly higher efficiency than the ethanol extract, suggesting enhanced light-harvesting capability.

The DSSC efficiency obtained in this study is still in the same range as the study by Ahliha et al. [17]. The difference in efficiency is likely influenced by differences in extraction methods, chlorophyll content obtained, TiO_2 electrode fabrication techniques, electrolyte composition, irradiation intensity, and the number of dye molecules successfully adsorbed on the TiO_2 surface [31], [32]. Compared with other natural dye-based DSSCs, the efficiencies obtained in this study are also consistent with the performance generally reported for chlorophyll-based sensitizers. Calogero et al. reported that chlorophyll-based DSSC typically exhibit efficiencies below 1% because of the limited photostability of natural pigments and significant charge recombination losses [27]. Similarly, Unwakoly et al. reported efficiencies of approximately 0.019–0.020% using macroalgal chlorophyll extract as a sensitizer, while co-sensitization strategies combining multiple natural pigments have been shown to improve efficiency by broadening the light absorption range and enhancing photon utilization [14], [34].

Despite favorable optical absorption characteristics and thermodynamically matched HOMO and LUMO energy levels obtained in this study, the overall efficiency of DSSC remains relatively low, indicating that proper energy level alignment alone is not sufficient to achieve high photovoltaic performance. The efficiency of natural dye-sensitized solar cells is strongly influenced by the physicochemical properties of the sensitizer, the dye–TiO_2 interfacial interactions, and the charge transfer processes occurring within the device. Previous studies have reported that the relatively low efficiency of chlorophyll-based DSSC is mainly due to inefficient electron injection, rapid charge recombination, and limited photochemical stability of natural pigments under prolonged illumination [35], [36]. The suji leaf extract used in this study is a crude extract containing not only chlorophyll pigments but also carotenoids, flavonoids, phenolic compounds, and other secondary metabolites. Although chlorophyll acts as the main photoactive molecule responsible for electron injection into the conduction band of TiO_2, the presence of other constituents can reduce the effective adsorption of chlorophyll molecules on the TiO_2 surface and decrease the fraction of photoactive molecules participating in charge transfer [35], [37]. As a result, the number of injected electrons is reduced, resulting in a lower photoelectric current.

Another important factor affecting DSSC performance is the interaction between the sensitizer and the semiconductor surface. Efficient DSSC operation requires strong adsorption of dye molecules onto TiO_2 via suitable tethering functional groups, which allows rapid electron injection before excited-state relaxation occurs. Compared with conventional synthetic sensitizers, natural chlorophyll molecules generally exhibit weaker adsorption on TiO_2 due to having fewer effective tethering groups, resulting in less efficient interfacial electron transfer and increased charge recombination losses [38]. Consequently, most of the electrons excited by light undergo recombination before reaching the external circuit, thereby reducing the photocurrent and overall power conversion efficiency. Furthermore, chlorophyll pigments are susceptible to photodegradation and chemical degradation upon prolonged irradiation, leading to a gradual decrease in light-harvesting capability and photovoltaic performance [35], [36]. This intrinsic limitation has been widely recognized as a major challenge preventing chlorophyll-based DSSC from achieving efficiencies comparable to synthetic ruthenium complexes or metal-free organic dyes [35], [36].

Although the efficiency obtained is still lower than that of synthetic dye-based DSSC, the use of natural dyes remains attractive because it is environmentally friendly, readily available, and low-cost [11], [33]. Overall, the results of this study indicate that acetone solvent is more effective in extracting chlorophyll a from suji leaves than ethanol, as evidenced by the higher chlorophyll a content and followed by an increase in V_{oc} and DSSC efficiency. On the other hand, ethanol extract produces a higher fill factor, indicating that the quality of charge transport in cells is better. These findings confirm that DSSC performance is not only determined by the amount of pigment extracted, but is the result of synergy between the ability to absorb light by chlorophyll a, the suitability of electron energy levels, the adsorption of molecules on the TiO_2 surface, and the efficiency of charge transfer and recombination during the energy conversion process.

4. Conclusion

This study evaluated the potential of suji leaf (*Dracaena angustifolia*) extract as a natural sensitizer for TiO_2-based DSSC using acetone and ethanol as extraction solvents. Optical characterization revealed that both extracts exhibited maximum absorption at approximately 655 nm, indicating the dominance of chlorophyll pigments. The acetone extract showed higher absorbance and a greater chlorophyll-*a* content than the ethanol extract. Electrochemical analysis confirmed the redox activity of both extracts and demonstrated that their HOMO and LUMO energy levels were compatible with the charge transfer mechanism in DSSC. Photovoltaic measurements showed that the DSSC sensitized with the acetone extract achieved the highest power conversion efficiency of 0.050%, slightly higher than that of the ethanol extract (0.049%). The improved performance of the acetone extract was attributed to its superior light-harvesting capability, higher chlorophyll-a concentration, and more favorable electrochemical characteristics. These findings demonstrate that suji leaf extract has potential as an environmentally friendly and low-cost natural sensitizer for DSSC applications.

References

[1] N. A. Pambudi *et al.*, “Renewable Energy in Indonesia: Current Status, Potential, and Future Development,” *Sustain.*, vol. 15, no. 3, p. 2342, 2023, doi: 10.3390/su15032342.

[2] N. A. Handayani and D. Ariyanti, “Potency of solar energy applications in Indonesia,” *Int. J. Renew. Energy Dev.*, vol. 1, no. 2, pp. 33–38, 2012, doi: 10.14710/ijred.1.2.33-38.

[3] N. Shah *et al.*, “A Review of Third Generation Solar Cells,” *Processes*, vol. 11, no. 6, p. 1852, 2023, doi: 10.3390/pr11061852.

[4] K. Sharma, V. Sharma, and S. S. Sharma, “Dye-Sensitized Solar Cells: Fundamentals and Current Status,” *Nanoscale Res. Lett.*, vol. 13, p. 381, 2018, doi: 10.1186/s11671-018-2760-6.

[5] P. S. Saud *et al.*, “Dye-sensitized solar cells: Fundamentals, recent progress, and Optoelectrical properties improvement strategies,” *Opt. Mater. (Amst).*, vol. 150, p. 115242, 2024, doi: 10.1016/j.optmat.2024.115242.

[6] B. Korir K, J. Kibet K, and S. Ngari M, “A review on the current status of dye-sensitized solar cells:,” *Energy Sci. Eng.*, vol. 12, pp. 3188–3226, 2024, doi: 10.1002/ese3.1815.

[7] T. Syed Hussain and W. Wei, “Technoeconomic Analysis of Dye Sensitized Solar Cells (DSSCs) with WS2/Carbon Composite as Counter Electrode Material,” *Inorganics*, vol. 10, no. 11, p. 191, 2022, doi: 10.3390/ inorganics10110191.

[8] J. Gong, J. Liang, and K. Sumathy, “Review on dye-sensitized solar cells (DSSCs): Fundamental concepts and novel materials,” *Renew. Sustain. Energy Rev.*, vol. 16, no. 8, pp. 5848–5860, 2012, doi: 10.1016/j.rser.2012.04.044.

[9] N. Tomar, A. Agrawal, V. S. Dhaka, and P. K. Surolia, “Ruthenium complexes based dye sensitized solar cells: Fundamentals and research trends,” *Sol. Energy*, vol. 207, pp. 59–76, 2020, doi: 10.1016/j.solener.2020.06.060.

[10] L. Olteanu, R.-M. Ion, M. N. Ardeleanu, and A. I. Gheboianu, “Dyes for Dye-Sensitized Solar Cells (DSSCs): A Review,” *Sci. Bull. Valahia Univ. - Mater. Mech.*, vol. 21, no. 24, pp. 7–12, 2025, doi: 10.2478/bsmm-2025-0001.

[11] S. Rahman *et al.*, “Research on dye sensitized solar cells: recent advancement toward the various constituents of dye sensitized solar cells for efficiency enhancement and future prospects,” *RSC Adv.*, vol. 13, no. 28, pp. 19508–19529, 2023, doi: 10.1039/d3ra00903c.

[12] P. Prakash and B. Janarthanan, “Review on the progress of light harvesting natural pigments as DSSC sensitizers with high potency,” *Inorg. Chem. Commun.*, vol. 152, p. 110638, 2023, doi: 10.1016/j.inoche.2023.110638.

[13] U. Mahajan, K. Prajapat, M. Dhonde, K. Sahu, and M. Shirage, “Nano-Structures & Nano-Objects Natural dyes for dye-sensitized solar cells (DSSCs): An overview of extraction, characterization and

performance," *Nano-Structures & Nano-Objects*, vol. 37, p. 101111, 2024, doi: 10.1016/j.nanoso.2024.101111.

[14] S. Unwakoly, S. Hartati, H. Siti, H. Munawaroh, and P. Fitri, "Natural pigment-based dye-sensitized solar cells utilizing Caulerpa racemose and Gymnogongrus flabelliformis as photosensitizers," *Int. J. Renew. Energy Dev. J.*, vol. 14, no. 3, pp. 554–562, 2025, doi: 10.61435/ijred.2025.61083.

[15] D. Indrasti and N. Andarwulan, "Current Research in Nutrition and Food Science Stability of Chlorophyll as Natural Colorant: A Review for Suji (Dracaena angustifolia (Medik.) Roxb.) Leaves ' Case," *Curr. Res. Nutr. Food Sci.*, vol. 06, no. 3, pp. 609–625, 2018, doi: 10.12944/CRNFSJ.6.3.04.

[16] E. Rahayuningsih, M. S. Pamungkas, M. Olvianas, and A. D. P. Putera, "Chlorophyll extraction from suji leaf (Pleomele angustifolia Roxb.) with $ZnCl_2$ stabilizer," *J. Food Sci. Technol.*, vol. 55, no. 3, pp. 1028–1036, 2018, doi: 10.1007/s13197-017-3016-7.

[17] A. H. Ahliha, F. Nurosyid, and A. Supriyanto, "The Chemical Bonds Effect of Amaranthus Hybridus L . and Dracaena Angustifolia on TiO_2 as Photo-sensitizer for Dye- Sensitized Solar Cells (DSSC)," in *The 4th International Conference on Research, Implementation, and Education of Mathematics and Science (4th ICRIEMS)*, 2017, pp. 1–6. doi: 10.1063/1.4995165.

[18] R. R. Sova and P. Setiarso, "Studi Elektrokimia Klorofil dan Antosianin Sebagai Fotosensitizer DSSC (Dye-Sensitized Solar Cell): Electrochemical Study of Chlorophyll and Anthocyanin as DSSC (Dye-Sensitized Solar Cell) Photosensitizer," *Unesa J. Chem.*, vol. 10, no. 2, pp. 191–199, 2021, doi: 10.26740/ujc.v10n2.p191-199.

[19] P. Singh *et al.*, "Dye-sensitized solar cells : Fundamentals, recent progress, and Optoelectrical properties improvement strategies," *Opt. Mater. (Amst).*, vol. 150, p. 115242, 2024, doi: 10.1016/j.optmat.2024.115242.

[20] A. Kume, "Importance of the green color, absorption gradient, and spectral absorption of chloroplasts for the radiative energy balance of leaves," *J. Plant Res.*, vol. 130, no. 3, pp. 501–514, 2018, doi: 10.1007/s10265-017-0910-z.

[21] Y. Koyama, T. Miki, X. F. Wang, and H. Nagae, "Dye-sensitized solar cells based on the principles and materials of photosynthesis: Mechanisms of suppression and enhancement of photocurrent and conversion efficiency," *Int. J. Mol. Sci.*, vol. 10, no. 11, pp. 4575–4622, 2009, doi: 10.3390/ijms10114575.

[22] D. Arnon, "Copper Enzymes in Isolated Chloroplast Polyphenoloxidase in Beta Vulgaris," *Plant Physiol.*, vol. 24, no. 1, pp. 1–15, 1949, doi: 10.1104/pp.24.1.1.

[23] H. K. B. T.-M. in E. Lichtenthaler, "[34] Chlorophylls and carotenoids: Pigments of photosynthetic biomembranes," in *Plant Cell Membranes*, vol. 148, Academic Press, 1987, pp. 350–382. doi: 10.1016/0076-6879(87)48036-1.

[24] A. R. Wellburn, "The Spectral Determination of Chlorophylls a and b, as well as Total Carotenoids, Using Various Solvents with Spectrophotometers of Different Resolution," *J. Plant Physiol.*, vol. 144, no. 3, pp. 307–313, 1994, doi: 10.1016/S0176-1617(11)81192-2.

[25] H. Tamiaki, "Chlorophyll Pigments and Their Synthetic Analogs Special Issue - Review," vol. 00, no. 00, pp. 153–167, 2025, [Online]. Available: https://doi.org/10.1093/pcp/pcae094

[26] N. T. R. N. Kumara, A. Lim, C. M. Lim, M. I. Petra, and P. Ekanayake, "Recent progress and utilization of natural pigments in dye sensitized solar cells: A review," *Renew. Sustain. Energy Rev.*, vol. 78, pp. 301–317, 2017, doi: 10.1016/j.rser.2017.04.075.

[27] G. Calogero, J. Yum, A. Sinopoli, G. Di, and M. Gra, "Anthocyanins and betalains as light-harvesting pigments for dye-sensitized solar cells," *Sol. Energy*, vol. 86, pp. 1563–1575, 2012, doi: 10.1016/j.solener.2012.02.018.

[28] S. Qamar and S. E. Ela, "ScienceDirect Dye-sensitized solar cells (DSSC): Principles , materials and working mechanism," *Curr. Opin. Colloid Interface Sci.*, vol. 74, p. 101871, 2024, doi: 10.1016/j.cocis.2024.101871.

[29] M. Grätzel, "Dye-sensitized solar cells," vol. 4, pp. 145–153, 2003, doi: 10.1016/S1389-5567(03)00026-1.

[30] D. Sinha, D. De, and A. Ayaz, "Performance and stability analysis of curcumin dye as a photo sensitizer used in nanostructured ZnO based DSSC," *Spectrochim. Acta Part A Mol. Biomol. Spectrosc.*, vol. 193, pp. 467–474, 2018, doi: 10.1016/j.saa.2017.12.058.

[31] K. Prajapat, U. Mahajan, K. Sahu, M. Dhonde, and P. M. Shirage, "The Evolution of natural Dye-Sensitized solar Cells : Current Advances and future outlook," *Sol. Energy*, vol. 284, no. July, p. 113081, 2024, doi: 10.1016/j.solener.2024.113081.

[32] A. Triyanto, N. Ali, H. Salleh, J. Setiawan, and N. I. Yatim, "Development of natural dye

photosensitizers for dye-sensitized solar cells: a review," *Environ. Sci. Pollut. Res.*, vol. 31, no. 22, pp. 31679–31690, 2024, doi: 10.1007/s11356-024-33360-4.

[33] S. Malhotra, M. Ahmed, M. Gupta, and A. Ansari, "Metal-free and natural dye sensitized solar cells: Recent advancement and future perspectives," *Sustain. Energy Fuels*, no. 18, pp. 4127–4163, 2024, doi: 10.1039/D4SE00406J.

[34] E. Cahya, P. Fitri, E. Suhendi, and B. Yuliarto, "Results in Optics Performance of dye-sensitized solar cells with mixed three natural pigments and reduced graphene oxide as a counter electrode," *Results Opt.*, vol. 14, p. 100592, 2024, doi: 10.1016/j.rio.2023.100592.

[35] S. Shalini, R. Balasundara, S. Prasanna, T. K. Mallick, and S. Senthilarasu, "Review on natural dye sensitized solar cell : Operation, materials and methods," *Renew. Sustain. Energy Rev.*, vol. 51, pp. 1306–1325, 2015, doi: 10.1016/j.rser.2015.07.052.

[36] G. Calogero, A. Bartolotta, G. Di Marco, A. Di Carlo, and F. Bonaccorso, "Vegetable-based dye-sensitized solar cells," *Chem. Soc. Rev.*, vol. 44, no. 10, pp. 3244–3294, 2015, doi: 10.1039/c4cs00309h.

[37] N. T. R. N. Kumara, A. Lim, C. Ming, and M. Iskandar, "Recent progress and utilization of natural pigments in dye sensitized solar cells : A review," *Renew. Sustain. Energy Rev.*, vol. 78, no. April, pp. 301–317, 2017, doi: 10.1016/j.rser.2017.04.075.

[38] L. Zhang and J. M. Cole, "Anchoring Groups for Dye-Sensitized Solar Cells," *ACS Appl. Mater. Interfaces*, vol. 7, no. 6, pp. 3427–3455, 2015, doi: 10.1021/am507334m.