



Improving Solar Cell Efficiency: A New Combination of Natural Dyes in Dye-Sensitized Solar Cells

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Abstract

Dye-sensitized solar cells (DSSCs) are an environmentally friendly and inexpensive photovoltaic technology that shows great promise. This study combines natural dyes that can absorb light in various wavelength regions, such as a combination of lavender and peony dyes; safflower and butterfly pea dyes, to improve the effectiveness of DSSCs. This combination is expected to expand the range of light absorption and improve solar cell performance. The dyes were extracted from various plants and tested using UV-vis spectroscopy. Results showed that the butterfly pea-safflower and lavender-peony combinations had efficiencies of 0.124% and 0.041%, respectively, while apple blossom was only 0.0064%. The combination of natural dyes showed a relative efficiency increase of 5.2% over the baseline cell. These findings indicate that the use of natural dyes has significant potential to increase DSSC performance and become a sustainable solution for renewable energy development. The use of NaCl as an electrolyte in this study represents a preliminary demonstration; therefore, the reported efficiency cannot be directly compared with that of conventional DSSCs employing iodide/triiodide or cobalt redox couples.

Keywords: DSSC, efficiency, natural dye, renewable energy, solar cell

1. INTRODUCTION

The use of renewable energy has drawn a lot of attention globally due to the problems caused by the exploitation of fossil fuels [1][2]. One renewable energy technology that may help reduce dependency on conventional energy sources is solar cells [3]. One photovoltaic technology that has attracted the attention of researchers is dye-sensitized solar cells (DSSC), which are inexpensive, simple to fabricate, and environmentally benign [4]. Nevertheless, despite their many benefits, DSSCs are still not as efficient as silicon-based solar cell technologies. As a result, studies to increase DSSC efficiency are still being conducted, one of which is the use of dyes as photosensitizers [5][6].

As one of the important parts of DSSCs, photosensitizers are in charge for absorbing light and using electron excitation to transform it into

electrical energy [7]. Although synthetic dyes like the ruthenium complex are efficient photosensitizers, their usage is recently restricted due to issues with cost, availability, and the environment [8]. Natural dyes are becoming a viable and environmentally responsible solution to these problems [9]. Fruits, leaves, flowers, and other plant materials that absorb light well in a particular spectrum are used to make natural dyes [10][11]. Because of their numerous sources and potential optical characteristics, dyes including anthocyanins [12][13], chlorophylls [14][15], and curcumin [16] have been the subject of extensive research. Nevertheless, DSSCs employing natural dyes continue to have inferior efficiency compared to synthetic dyes [17][18]. The narrow absorption spectrum of natural dyes, which often falls within a specific range, is one of the limiting considerations [19]. For instance, chlorophyll absorbs more light in the red spectrum, whereas anthocyanins are better at absorbing light in the blue and green spectra [20]-[22]. Therefore, one of the main challenges in the use of DSSCs is the use of various natural dyes to broaden the spectrum of light absorption and improve the overall effectiveness of DSSCs.

A mix of natural dyes can assist in getting beyond this restriction, according to earlier studies [23][24]. Solar cells may absorb light across a broad spectrum by combining several kinds of natural dyes, which increases the possibility of

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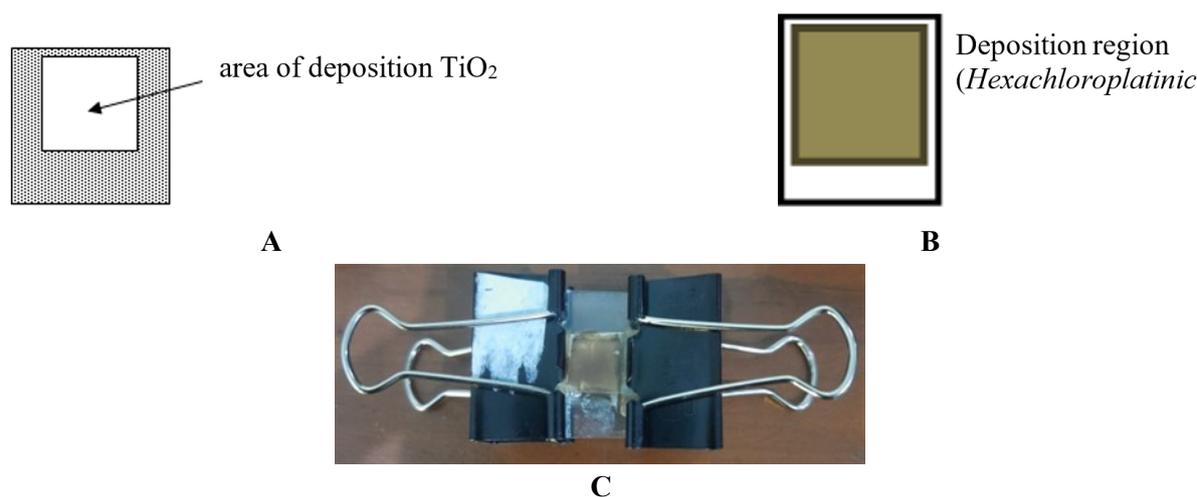


Figure 1. (A) Area of TiO_2 paste deposition schematic, (B) Area scheme for platinum deposition, and (C) Findings from the DSSC compilation.

electron excitation and energy transmission [25] [26]. In addition to expanding the absorption spectrum, this method may boost the solar process's overall efficiency [27][28]. Therefore, to investigate the possibility of increasing efficiency, more studies on the innovative combination of natural dyes in DSSCs are necessary [29]. The purpose of this study is to look at how natural color mixtures can increase DSSC efficiency. Several natural dyes, such as anthocyanins (extracted from fruits), chlorophyll (from green leaves), and curcumin (from turmeric), will be explored in various combinations to find the most effective formulations in absorbing light and converting energy. These dyes are not only selected based on their spectral absorption capabilities but also due to their abundance in natural sources and environmentally friendly characteristics [30]. In addition, the interaction effects between dyes and their influence on the stability and efficiency of DSSCs will be comprehensively analyzed.

Using safe organic solvents, this study process extracts natural pigments from a variety of plant sources [31]. Each dye will be characterized using UV-visible (UV-vis) spectroscopy to determine its light absorption ability at various wavelengths [32]. Afterward, these dyes will be applied as photosensitizers in DSSCs, and the energy conversion efficiency will be measured using voltage-current (I-V) testing [33]. The results obtained from the combination of natural dyes will be compared with DSSCs using only a single dye to

evaluate the efficiency improvement. It is anticipated that this study will make a substantial contribution to the creation of DSSC technology that is more sustainable and effective [34]. The novel combination of natural dyes has the potential to broaden the light absorption spectrum, which in turn can enhance electron excitation and energy transfer in solar cells [35]. By utilizing abundant and environmentally friendly natural resources, this research also supports global efforts to create greener and more sustainable energy solutions [36] [37]. In addition, the results from this study can pave the way for wider applications of natural dyes in other fields related to renewable energy and environmentally friendly technologies. To reduce adverse environmental effects and speed up the switch to cleaner energy sources, innovation in the use of natural dyes in DSSCs can be a significant step [38]. This study also emphasizes how crucial it is to work across disciplines to investigate natural materials as essential building blocks for the creation of more effective and sustainable energy technologies. Therefore, combining novel natural dyes may be one of the practical ways to increase the effectiveness of DSSCs, and the purpose of this study is to test the theory empirically.

2. MATERIALS AND METHODS

2.1. Tools and Materials

Among the materials used in this study were fluorine-doped tin oxide (FTO) glass substrate (DN-

HG15 dyenamo), titanium(IV) dioxide (TiO_2) paste DSL 18NR-AO (DyeSol), sodium chloride (NaCl), ethanol, screen-printable Pt paste (dyenamo), isopropanol, 70% alcohol, and natural dyes. A digital multimeter, dryer, ultrasonic cleaner, hot plate with magnetic stirrer, beakers, dropper, digital scales, filter paper, Whatman no.42, mortar chromatography column, furnace, and spin coater are some of the devices used.

2.2. Preparation

This preparation step includes cleaning the equipment used for the extraction and preparation of TiO_2 paste. The extraction preparation process involves cleaning the mortar, glass bottle, beaker, dropper, and FTO glass with ethanol solution and an ultrasonic cleaner to get rid of any impurities that can't be removed with water alone. Clean glass affects the test results of samples that will be superimposed on the glass substrate.

2.3. Glass Cleaning with FTO

In the chemical glass, up to 100 mm of 70% alcohol was added. The 2×2 cm FTO glass that needs to be cleaned is placed within a glass that is loaded with chemicals. Filling the ultrasonic cleaner corresponds to the stated limitations. After 30 min, the FTO glass and the chemical glass with alcohol are placed in the ultrasonic cleaner. A dryer is used to dry the glass for 90 min. Then, a digital multimeter was used to test the resistance to the FTO glass.

2.4. Production of TiO_2 Nano Paste

After dissolving 0.5 g of TiO_2 nanopowder in 2 mL of ethanol, the mixture is agitated for 30 min at 200–300 rpm using a stirrer vortex. The pre-formed TiO_2 paste is moved into bottles wrapped with aluminum foil and kept out of direct sunlight to slow down the evaporation process.

2.5. Extraction of Natural Dye

A 10-g of digital scales were used to weigh the natural coloring. After dissolving the finely ground natural dye in 50 mL of ethanol solvent in a ratio of 1:5, the mixture was agitated for 60 min at 60 °C using a stirrer vortex spinning at 300 rpm. Whatman no. 42 filter paper was used to filter the solvent after it had dissolved for 24 h. The

extraction products were placed into chromatographic columns, chromatographed, and then allowed to turn dark red.

2.6. Creating a Functional Electrode

The spin coating method is used to apply the TiO_2 nano paste to a glass working electrode that is FTO conductive. In FTO glass, a 2×2 cm area was made that was 1×1 cm above the conductive surface. The FTO side taped the tape as a barrier. After the FTO glass has been attached, the TiO_2 paste is applied to it in the spinner and then in the stirrer for a predetermined period at 200–300 rpm. The coated TiO_2 FTO glass is heated to 500 °C for 1 h on a hotplate, and then it is left to cool to room temperature. The design of the TiO_2 paste deposition area is shown in [Figure 1 \(A\)](#).

2.7. Electrolyte Solution Preparation

A 800 mL of distilled or deionized water is combined with 52.6 g (0.9 M) of solid NaCl, and the mixture is then swirled. After that, add deionized or distilled water until the volume equals 1 L. A sealed container covered with aluminum foil is used to keep the completed electrolyte solution [39].

2.8. Construction of the Counter Electrode

A thin layer of Pt (10% H_2PtCl_6) is applied to the FTO conductive glass used as the counter electrode. The counter electrode is made by mixing 1 mL of 10% H_2PtCl_6 with 207 mL of isopropanol. The FTO glass is heated at 250 °C for 15 min, after which 3 mL of platinum solution is dropped onto the surface of the FTO glass substrate. The glass is then allowed to cool to room temperature. [Figure 1\(B\)](#) shows the platinum deposition area plan.

2.9. The TiO_2 Layer's Absorption of Dye

The drip approach was used to soak the FTO conductive glass substrate in a natural extract dye after a TiO_2 layer was formed on it.

2.10. Making DSSC Sandwiches

The DSSC layer of FTO glass covered with TiO_2 and dripping with extracted dye is the working electrode; the Pt-coated glass coating is the opposing electrode, is then placed over the working electrode after it has been dripped with electrolyte

solution. Then, to prevent shifting, the DSSC configuration is fastened using clamps on both the left and right sides. Figure 1 (C) displays the final DSSC results.

2.11. Analysis of Absorption

Anthocyanins were determined simultaneously using the spectrophotometric technique. A Shimadzu 1800 PC Visible UV spectrophotometer was used to examine the content of each extracted material to ascertain the materials' absorbance characteristics. In visible light, the wavelength range for the absorption spectrum study is 200–800 nm. The type of dye content of natural materials can then be determined by measuring the absorbance characteristics.

2.12. Material Conductivity

To create a dark environment for the conductivity measurements using the Elkahfi 100/IV-Meter, aluminum foil was placed over the entire container. The container was then exposed to a 100 W halogen light source with an energy intensity of 680.3 W/m². Halogen lamps are used because they have a broad spectrum that mimics visible light from sunlight. The conductivity (σ) of different materials was then

calculated from the I-V measurement results. The following formula can be used to find the conductivity of an organic solution (Equations 1 and 2).

$$\rho = \frac{R.A}{l} \quad (1)$$

$$\sigma = \frac{1}{\rho} = \frac{l}{R.A} \quad (2)$$

where σ is the conductivity (ohm⁻¹ m⁻¹), R is the resistance (ohm), l is the distance between the two electrodes (m), and A is the electrode's cross-sectional surface area (m²).

3. RESULTS AND DISCUSSIONS

Through the application of a novel combination of natural dyes, this study intends to boost the efficiency of DSSCs. The selected natural dye combinations include butterfly pea flower extract (*Clitoria ternatea*), safflower flower extract (*Carthamus tinctorius* L.), lavender flower extract (*Lavandula officinalis*), and peony flower extract (*Paeonia*). These natural dyes were chosen because they include flavonoids, anthocyanins, and other polyphenolic chemicals that aid in electron

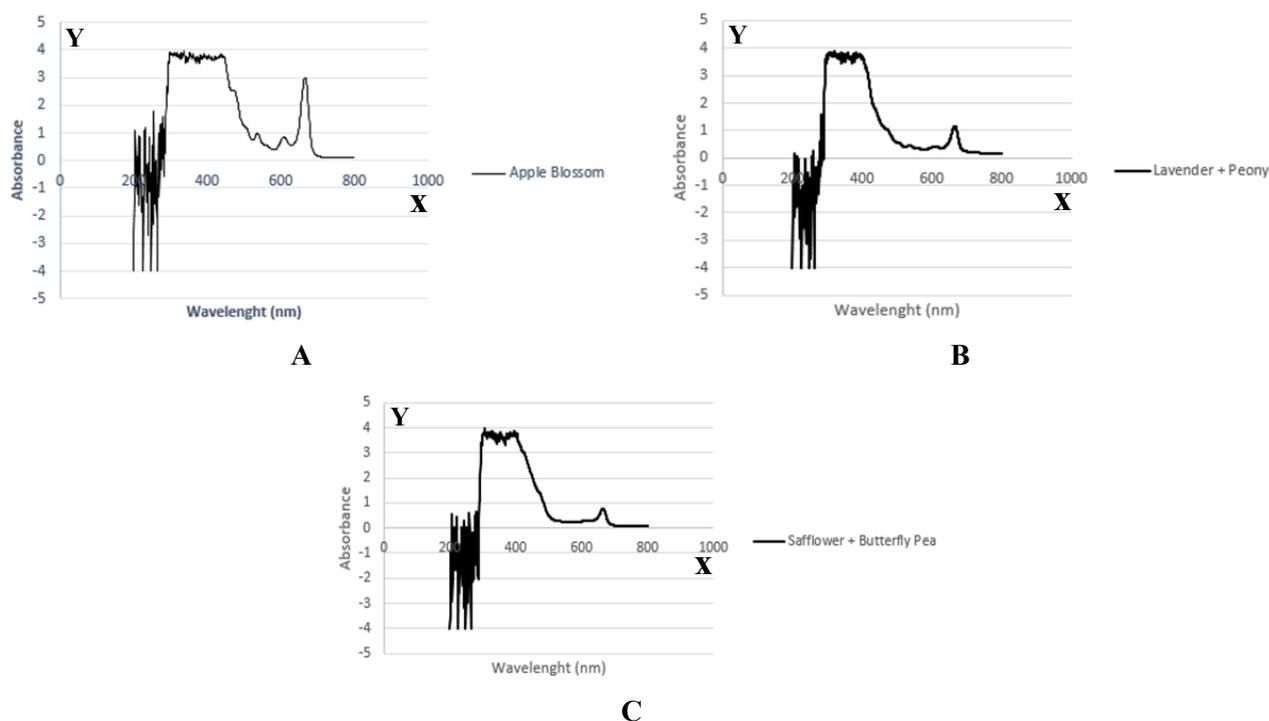


Figure 2. Absorbance of dyes from (A) apple blossom, (B) lavender and peony, and (C) safflower and butterfly pea extracts.

transport and light absorption.

3.1. Characterization of Natural Dyes

A fixed ratio of 0.5 g of natural materials and 2 mL of solvent is utilized in the research to make the anthocyanin extract from the color that is naturally extracted using ethanol PA. The absorbance was then measured, and the voltages were also measured. The dye conductivity value produced using the natural dyes was apparent from I to V. The absorbance graph is shown in [Figure 2](#).

Each dye combination's UV-Vis absorption spectra showed distinct absorption peaks. The combination of butterfly pea extract with safflower revealed absorption peaks at wavelengths of 305, 614, and 664 nm, while the combination of lavender flower extract with peony flower showed absorption peaks at wavelengths of 381, 536, 608, and 666 nm. When these dyes were combined, the absorption spectra expanded to include wavelengths between 305 and 666 nm. At wavelengths of 260, 336, 471, 537, 608, and 666 nm, the apple blossom dye exhibits absorption peaks. The absorption spectrum of this single dye is lower, spanning from 260 to 666 nm.

3.2. DSSC Solar Cell Conversion Efficiency

At a light intensity of 100 mW/cm², the DSSC efficiency was evaluated using a solar simulator. The data shows that solar cells using a single dye (apple blossom) have an average efficiency of 0.0064%. The data shows that solar cells using a combination of dyes have an average efficiency of 0.041% (lavender and peony) and 0.124% (safflower and butterfly pea), respectively. However, solar cells using a combination of both natural dyes showed a significant increase in efficiency of up to 5.2%. This suggests that the combination of dyes can expand the absorption range of the light spectrum and improve electron transfer to the working electrode. This has been completed, and [Table 1](#) shows the effectiveness of each dye, both alone and in combination. According to Indri et al. [6], the dye (c) beetroot/ethanol and turmeric/distilled water have the highest efficiency, reaching 2.71%. This study supports their findings.

[Table 1](#) presents the efficiency performance of three natural dyes used in DSSC systems, showing variations in photovoltaic parameters. The safflower

and butterfly pea combination exhibited the highest efficiency ($0.124 \pm 0.005\%$) with superior Voc (1.000 ± 0.015 V) and Isc values, indicating effective electron injection and charge transfer at the dye–TiO₂ interface. The lavender and peony dye showed moderate performance ($0.041 \pm 0.002\%$), suggesting fair light absorption but limited electron mobility. Meanwhile, apple blossom recorded the lowest efficiency ($0.0064 \pm 0.0003\%$), likely due to weaker light-harvesting capability and lower charge separation efficiency. Overall, the data highlight that differences in molecular composition and pigment type significantly influence current density and voltage generation, thereby affecting total DSSC efficiency. Although these efficiencies are relatively low, the results demonstrate the potential of natural dyes as eco-friendly sensitizers in early-stage DSSC research using NaCl electrolytes.

3.3. Electrochemical Analysis

Measurements of the electrochemical impedance spectrum reveal that solar cells employing a combination of dyes have a lower electron transfer resistance (R_{ct}) than solar cells employing just one dye ([Table 1](#)). This suggests that the dyes' synergistic interaction may improve the dye's ability to transport electrons to the TiO₂ electrode.

3.4. The Role of Natural Colorant Combinations

The higher efficiency of DSSCs using a combination of natural dyes can be explained through several mechanisms. The combination of dyes with different absorption spectra allows light absorption in a wider wavelength range. The combination of butterfly pea flower extract with safflower flower can absorb light at higher wavelengths (305–664 nm), while the combination of lavender flower extract with peony flower absorbs light at shorter wavelengths (381–666 nm). Thus, this combination allows the DSSC to absorb more energy from the solar spectrum. In addition, the active components in each dye, such as anthocyanins in butterfly peas, carthamine in safflower flowers, flavonoids in lavender flowers, and flavonoids in peony flowers, act as effective electron donors. Energy loss from electron recombination is decreased by more effective electron transport between the dye and the TiO₂ electrode, thereby increasing the efficiency of

Table 1. Efficiency of the dye (mean \pm SD).

Dye	I _{max} (A)	V _{max} (V)	I _{sc} (A)	V _{oc} (V)	Factor of Fill	Efficiency (%)
Apple blossom	$(7.0 \pm 0.3) \times 10^{-6}$	0.200 ± 0.005	$(7.0 \pm 0.4) \times 10^{-6}$	0.880 ± 0.010	0.55 ± 0.02	0.0064 ± 0.0003
Lavender and peony	$(2.3 \pm 0.1) \times 10^{-5}$	0.650 ± 0.006	$(1.5 \pm 0.1) \times 10^{-5}$	1.000 ± 0.020	0.63 ± 0.03	0.041 ± 0.002
Safflower and butterfly pea	$(9.8 \pm 0.2) \times 10^{-5}$	0.900 ± 0.010	$(3.2 \pm 0.1) \times 10^{-5}$	1.000 ± 0.015	0.74 ± 0.04	0.124 ± 0.005

photon conversion into electrical energy.

3.5. Stability of Natural Dyes

Stability testing of the natural dyes was carried out by exposing the fabricated solar cells under a halogen lamp continuously for 2 h. The results show that the dye combination exhibits a slower decrease in efficiency compared to the single dye. This indicates that the combination of dyes can improve the stability of DSSCs against light degradation. This may be due to the presence of antioxidant compounds in natural dyes, which can protect the dyes from oxidation during sunlight exposure.

3.6. Synergistic Interaction and Electron Transfer

The electrochemical impedance spectrum results demonstrate that the addition of natural dyes lowers the electron transfer resistance at the dye-TiO₂ contact. This is due to the synergistic interaction between the active components in each dye, which creates a more efficient electron transfer pathway. For example, anthocyanins from butterfly pea flowers can act as an electron bridge between flavonoids from safflower flowers and flavonoids from lavender and peony flowers, allowing for smoother electron flow.

3.7. Advantages of Using Natural Dyes

Natural dyes have several advantages over synthetic dyes commonly used in DSSCs, such as ruthenium complex. First, natural dyes are environmentally friendly, easy to obtain, and have lower production costs. In addition, some components in natural dyes have antioxidant properties that can help improve the stability of solar cells against degradation [40]. Nevertheless, a significant disadvantage of natural dyes is their propensity to deteriorate when exposed to UV light. In this study, the combination of dyes proved to be more stable than the single dye, but degradation still occurred after a long exposure time. Thus, more investigation is required to increase the natural dyes' long-term durability.

3.8. Implications for the Development of Eco-Friendly Solar Cells

This study shows that a novel combination of natural dyes can significantly improve DSSC

efficiency and stability against light degradation. These results have important implications for the development of environmentally friendly solar cells using easily accessible, affordable, and non-toxic materials. The efficiency improvements produced in this study are still below the efficiency levels of synthetic dyes, but the potential sustainability and abundance of natural resources provide significant added value. The DSSCs fabricated in this study demonstrated distinct variations in photovoltaic performance depending on the natural dye used as sensitizer. The differences in I_{sc} and V_{oc} among the samples are closely associated with the pigment composition, molecular structure, and electron-donating ability of each dye. The safflower and butterfly pea combination exhibited the best efficiency, attributed to strong anthocyanin and flavonoid content that enhance light absorption and charge transfer. The TiO_2 layer thickness in this work was estimated using adhesive tape spacers as a preliminary approach. Although this method allows reproducible fabrication of working electrodes, we acknowledge that the absence of scanning electron microscopy (SEM) or profilometry analysis limits the accuracy of surface morphology and thickness characterization. Future studies will incorporate these techniques to provide more precise and quantitative structural data.

4. CONCLUSIONS

This study demonstrated the feasibility of using natural pigments as alternative sensitizers for eco-friendly DSSCs employing NaCl electrolyte. Among the tested dyes, the safflower and butterfly pea extract showed the highest efficiency ($0.124 \pm 0.005\%$), followed by lavender and peony ($0.041 \pm 0.002\%$), and apple blossom ($0.0064 \pm 0.0003\%$). The use of NaCl as an electrolyte represents an early demonstration stage; therefore, the reported efficiencies cannot be directly compared with conventional DSSCs using iodide/triiodide or cobalt redox systems. A major limitation of this work is the lack of quantitative stability data. Although the stability test was not the main focus, we recognize that providing approximate photocurrent or efficiency loss values over several hours of exposure would strengthen the study. This limitation has been explicitly stated to guide future

investigations. Furthermore, the absence of SEM/profilometry data for TiO_2 layer characterization is acknowledged as a methodological constraint, which will be addressed in subsequent research. Overall, this preliminary investigation highlights the potential of natural dyes for low-cost, environmentally friendly DSSCs and provides a foundation for future optimization involving improved stability assessment, electrode morphology analysis, and electrolyte system refinement.

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methodology, formal analysis, writing—original draft; H. H., G. G., A. S. Supervision, resources, project administration; H. H., R. W., M. I. D., A. A., G. G., A. S. Writing—review and editing, project administration, validation; H. H., R. W., M. I. D. Writing—review and editing, project administration, validation. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

All authors declare that there are not any conflicts of interest.

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DECLARATION OF GENERATIVE AI

Not applicable.

REFERENCES

- [1] H. M. Saleh and A. I. Hassan. (2024). "The challenges of sustainable energy transition: A focus on renewable energy". *Applied Chemical Engineering*. **7** (2): 2084. [10.59429/ace.v7i2.2084](https://doi.org/10.59429/ace.v7i2.2084).
- [2] J. L. Holechek, H. M. E. Geli, M. N. Sawalhah, and R. Valdez. (2022). "A global assessment: Can renewable energy replace fossil fuels by 2050?". *Sustainability*. **14** (8): 4792. [10.3390/su14084792](https://doi.org/10.3390/su14084792).
- [3] M. M. Hasan, S. Hossain, M. Mofijur, Z. Kabir, I. A. Badruddin, T. M. Y. Khan, and E. Jassim. (2023). "Harnessing solar power: A review of photovoltaic innovations, solar thermal systems, and the dawn of energy storage solutions". *Energies*. **16** (18): 6456. [10.3390/en16186456](https://doi.org/10.3390/en16186456).
- [4] N. Shah, A. A. Shah, P. K. Leung, S. Khan, K. Sun, X. Zhu, and Q. Liao. (2023). "A review of third generation solar cells". *Processes*. **11** (6): 1852. [10.3390/pr11061852](https://doi.org/10.3390/pr11061852).
- [5] L. R. B. da Conceição, H. O. da Cunha, A. M. B. Leite, R. Suresh Babu, S. Raja, C. Ribeiro, and A. L. F. de Barros. (2023). "Evaluation of solar conversion efficiency in dye-sensitized solar cells using natural dyes extracted from *Alpinia purpurata* and *Alstroemeria* flower petals as novel photosensitizers". *Colorants*. **2** (4): 618-631. [10.3390/colorants2040032](https://doi.org/10.3390/colorants2040032).
- [6] I. W. Estiningtyas, N. Kusumawati, P. Setiarso, S. Muslim, N. T. Rahayu, R. N. Safitri, N. Zakiyah, and F. F. Fachrirakarsie. (2023). "Effect of natural dye combination and extraction pH on the performance of dye-sensitized photovoltaic solar cells". *International Journal of Renewable Energy Development*. **12** (6): 1054-1060. [10.14710/ijred.2023.56172](https://doi.org/10.14710/ijred.2023.56172).
- [7] A. K. N. M. Yusuf, S. Mustafar, M. L. Borines, E. N. Kusumawati, and N. Hashim. (2021). "Versatility of photosensitizers in dye-sensitized solar cells (DSSCs)". *Biointerface Research in Applied Chemistry*. **12** (6): 8543-8560. [10.33263/BRIAC126.85438560](https://doi.org/10.33263/BRIAC126.85438560).
- [8] Hardani, M. R. Harahap, and A. Suhada. (2022). "Ruthenium (N719) optimization to improve dye-sensitized solar cell efficiency". *International Journal of Thin Film Science and Technology*. **11** (1): 47-53. [10.18576/ijtfst/110106](https://doi.org/10.18576/ijtfst/110106).
- [9] S. Rahman, A. Haleem, M. Siddiq, M. K. Hussain, S. Qamar, S. Hameed, and M. Waris. (2023). "Research on dye-sensitized solar cells: Recent advancements toward the various constituents for efficiency enhancement and prospects". *RSC Advances*. **13** (28): 19508-19529. [10.1039/D3RA00903C](https://doi.org/10.1039/D3RA00903C).
- [10] N. Li, Q. Wang, J. Zhou, S. Li, J. Liu, and H. Chen. (2022). "Insight into the progress on natural dyes: Sources, structural features, health effects, challenges, and potential".

- Molecules*. **27** (10): 3291. [10.3390/molecules27103291](https://doi.org/10.3390/molecules27103291).
- [11] M. Salauddin Sk, R. Mia, M. A. Haque, and A. M. Shamim. (2021). "Review on extraction and application of natural dyes". *Textile and Leather Review*. **4** (4): 218-233. [10.31881/TLR.2021.09](https://doi.org/10.31881/TLR.2021.09).
- [12] V. Pramananda, T. A. H. Fityay, and E. Misran. (2021). "Anthocyanin as a natural dye in DSSC fabrication: A review". *IOP Conference Series: Materials Science and Engineering*. **1122** (1): 012104. [10.1088/1757-899X/1122/1/012104](https://doi.org/10.1088/1757-899X/1122/1/012104)
- [13] N. Y. Amogne, D. W. Ayele, and Y. A. Tsigie. (2020). "Recent advances in anthocyanin dyes extracted from plants for dye-sensitized solar cells". *Materials for Renewable and Sustainable Energy*. **9** (4): 23. [10.1007/s40243-020-00183-5](https://doi.org/10.1007/s40243-020-00183-5).
- [14] T. Martins, A. N. Barros, E. Rosa, and L. Antunes. (2023). "Enhancing health benefits through chlorophylls and chlorophyll-rich agro-food: A comprehensive review". *Molecules*. **28** (14): 5344. [10.3390/molecules28145344](https://doi.org/10.3390/molecules28145344).
- [15] P. Ebrahimi, Z. Shokramraji, S. Tavakkoli, D. Mihaylova, and A. Lante. (2023). "Chlorophylls as natural bioactive compounds existing in food by-products: A critical review". *Plants*. **12** (7): 1533. [10.3390/plants12071533](https://doi.org/10.3390/plants12071533).
- [16] P. Setiarso, R. V. Harsono, and N. Kusumawati. (2023). "Fabrication of dye-sensitized solar cell (DSSC) using a combination of dyes extracted from Curcuma xanthorrhiza rhizome and Anredera cordifolia leaf with pH-treated extraction". *Indonesian Journal of Chemistry*. **23** (4): 924. [10.22146/ijc.77860](https://doi.org/10.22146/ijc.77860).
- [17] M. Dhorkule, P. Lamrood, S. Ralegankar, S. P. Patole, S. S. Wagh, and H. M. Pathan. (2024). "Unveiling the efficiency of dye-sensitized solar cells: A journey from synthetic to natural dyes". *ES Food and Agroforestry*. **16**. [10.30919/esfaf1086](https://doi.org/10.30919/esfaf1086).
- [18] H. Hardani, A. Hidayatulloh, and A. L. M. (2018). "The efficiency improvement of dye-sensitized solar cells (DSSC) using TiO₂ nanoparticles with mangosteen peel pigment under various solvents". *Jurnal Bahan Alam Terbarukan*. **7** (2): 142-148. [10.15294/jbat.v7i2.14488](https://doi.org/10.15294/jbat.v7i2.14488).
- [19] Sakshi, P. K. Singh, and V. K. Shukla. (2022). "Widening spectral absorption using natural dyes: Applications in dye-sensitized solar cells". *Materials Today: Proceedings*. **49** : 3235-3238. [10.1016/j.matpr.2020.12.287](https://doi.org/10.1016/j.matpr.2020.12.287).
- [20] F. S. Seyedi, M. G. Nafchi, and S. Reezi. (2024). "Effects of light spectra on morphological characteristics and metabolites of *Thymus vulgaris* L". *Heliyon*. **10** (1): e23032. [10.1016/j.heliyon.2023.e23032](https://doi.org/10.1016/j.heliyon.2023.e23032).
- [21] B. Enaru, G. Dreţcanu, T. D. Pop, A. Stănilă, and Z. Diaconeasa. (2021). "Anthocyanins: Factors affecting their stability and degradation". *Antioxidants*. **10** (12): 1967. [10.3390/antiox10121967](https://doi.org/10.3390/antiox10121967).
- [22] L. A. Stetsenko, P. P. Pashkovsky, R. A. Voloshin, V. D. Kreslavski, V. V. Kuznetsov, and S. I. Allakhverdiev. (2020). "Role of anthocyanins and carotenoids in adaptation of the photosynthetic apparatus of sweet basil to high-intensity light". *Photosynthetica*. **58** (4): 890-901. [10.32615/ps.2020.048](https://doi.org/10.32615/ps.2020.048).
- [23] S. Kumar, P. Gowthaman, and J. Deenathayalan. (2023). "Fabrication of nanostructured TiO₂ dye-sensitized solar cells using extracted organic dyes". *AIP Conference Proceedings*. **2831** (1): 050001. [10.1063/5.0163135](https://doi.org/10.1063/5.0163135)
- [24] J. H. Kim, S. Y. Park, D. H. Lim, S. Y. Lim, J. Choi, and H. J. Koo. (2021). "Eco-friendly dye-sensitized solar cells based on water electrolytes and chlorophyll". *Materials*. **14** (9): 2150. [10.3390/ma14092150](https://doi.org/10.3390/ma14092150).
- [25] S. A. Badawy, E. Abdel-Latif, and M. R. Elmorsy. (2024). "Tandem dye-sensitized solar cells achieving 12.89% efficiency using novel organic sensitizers". *Scientific Reports*. **14** (1): 26072. [10.1038/s41598-024-75959-0](https://doi.org/10.1038/s41598-024-75959-0).
- [26] E. C. Prima, P. F. Rusliani, E. Suhendi, and B. Yulianto. (2024). "Performance of dye-sensitized solar cells with mixed natural pigments and reduced graphene oxide counter electrode". *Results in Optics*. **14** : 100592. [10.1016/j.rio.2023.100592](https://doi.org/10.1016/j.rio.2023.100592).

- [27] O. B. Ogundipe, A. C. Okwandu, and S. A. Abdulwaheed. (2024). "Recent advances in solar photovoltaic technologies: Efficiency, materials, and applications". *GSC Advanced Research and Reviews*. **20** (1): 159-175. [10.30574/gscarr.2024.20.1.0259](https://doi.org/10.30574/gscarr.2024.20.1.0259).
- [28] A. Machín and F. Márquez. (2024). "Advancements in photovoltaic cell materials: Silicon, organic, and perovskite solar cells". *Materials*. **17** (5): 1165. [10.3390/ma17051165](https://doi.org/10.3390/ma17051165).
- [29] M. Onyemowo, Y. Unpaprom, and R. Ramaraj. (2023). "Low-cost solar energy harvesting using Inthanin leaf extract as a natural photosensitizer in DSSCs". *Asian Journal of Applied Research for Community Development and Empowerment*. **7** (3): 28-33. [10.29165/ajarcde.v7i3.329](https://doi.org/10.29165/ajarcde.v7i3.329).
- [30] N. I. A. Shukor, K. Y. Chan, G. S. H. Thien, M. E. Yeoh, P. L. Low, N. K. Devaraj, Z. N. Ng, and B. K. Yap. (2023). "A green approach to natural dyes in dye-sensitized solar cells". *Sensors*. **23** (20): 8412. [10.3390/s23208412](https://doi.org/10.3390/s23208412).
- [31] N. Bekele, M. Abewaa, A. Mengistu, E. Adino, T. Takele, M. Yilma, T. Temesgen, and K. Angassa. (2024). "Optimization of natural dye extraction from Rumex abyssinicus root using response surface methodology". *Results in Chemistry*. **8** : 101577. [10.1016/j.rechem.2024.101577](https://doi.org/10.1016/j.rechem.2024.101577).
- [32] A. Szarwaryn, W. Bartkowiak, and U. Bazylińska. (2023). "UV-visible study on solubilization of solvatochromic-origin dyes in micellar systems". *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. **675** : 132083. [10.1016/j.colsurfa.2023.132083](https://doi.org/10.1016/j.colsurfa.2023.132083).
- [33] M. Pratiwi, L. Kalsum, and R. Rusdianasari. (2024). "Impact of silicon dioxide purity derived from coal fly ash on dye-sensitized solar cell photoelectric performance". *Journal of Ecological Engineering*. **25** (11): 210-220. [10.12911/22998993/192896](https://doi.org/10.12911/22998993/192896).
- [34] D. Spadaro, J. Barichello, I. Citro, and G. Calogero. (2023). "Environmentally friendly water-based electrolytes for dye-sensitized solar cells: Future prospects and outlook". *Solar*. **3** (2): 229-252. [10.3390/solar3020015](https://doi.org/10.3390/solar3020015).
- [35] V. Seithanabutara, N. Chumwangwapee, A. Suksri, and T. Wongwuttanasatian. (2023). "Combined natural dye pigments from ivy gourd leaves, black glutinous rice, and turmeric for DSSC applications". *Heliyon*. **9** (11): e21533. [10.1016/j.heliyon.2023.e21533](https://doi.org/10.1016/j.heliyon.2023.e21533).
- [36] J. H. Kim, D. H. Kim, J. H. So, and H. J. Koo. (2021). "Toward eco-friendly dye-sensitized solar cells (DSSCs): Natural dyes and aqueous electrolytes". *Energies*. **15** (1): 219. [10.3390/en15010219](https://doi.org/10.3390/en15010219).
- [37] N. Mariotti, M. Bonomo, L. Fagiolari, N. Barbero, C. Gerbaldi, F. Bella, and C. Barolo. (2020). "Recent advances in eco-friendly and cost-effective materials toward sustainable dye-sensitized solar cells". *Green Chemistry*. **22** (21): 7168-7218. [10.1039/D0GC01148G](https://doi.org/10.1039/D0GC01148G).
- [38] F. Schoden, A. K. Schnatmann, T. Blachowicz, H. Manz-Schumacher, and E. Schwenzfeier-Hellkamp. (2022). "Circular design principles applied to dye-sensitized solar cells". *Sustainability*. **14** (22): 15280. [10.3390/su142215280](https://doi.org/10.3390/su142215280).
- [39] D. Y. Rahman, F. D. Utami, N. Amalia, R. Sulistyowati, E. Sustini, and M. Abdullah. (2021). "Low-cost solar cells using PVA-NaCl polymer electrolyte and graphite/TiO₂ composite photon absorbers". *Materials Today: Proceedings*. **44** : 3301-3304. [10.1016/j.matpr.2020.11.531](https://doi.org/10.1016/j.matpr.2020.11.531).
- [40] H. Hardani, H. Soonmin, K. Syahidi, A. Zaidah, S. Sulistiyana, A. Hidayatulloh, A. Fudholi, and L. M. Angraini. (2025). "Optimizing solar power: Impact of N719 dye concentration on DSSC efficiency with TiO₂ nanoparticles". *Journal of Multidisciplinary Applied Natural Science*. **5** (1): 254-266. [10.47352/jmans.2774-3047.245](https://doi.org/10.47352/jmans.2774-3047.245).