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# Review: Synthesis and Characterization of Dye Combination as Photosensitizer Dye-Sensitized Solar Cell

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## ABSTRACT

The need for energy that continues to increase has led to research processes to create renewable technologies. One of them is manufacturing a Dye-Sensitized Solar Cell with a photosensitizer derived from great natural ingredients, easy to extract and environmentally friendly. Although the resulting efficiency is not as excellent as synthetic materials, combining these natural pigments can expand the absorption area. The efficiency of a combination dye is more significant than a single dye. This review analyses the synthesis process and characterization of the dye combination as a DSSC photosensitizer starting from dye extraction and TiO2 deposition to characterization using various tools. In addition, there are results of research with dye combinations that can be prospects for further study.

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## I. Introduction

Energy scarcity has become an essential spotlight globally caused by an imbalance between demand and available energy. Although solar energy is abundant, the conversion process becomes challenging in achieving technological novelty [1]. Various studies using photochemical processes to convert solar energy into electrical energy continue to be carried out [2]. The resulting solar cells can be made into Dye-Sensitized Solar Cells (DSSC) generation. Gratzel and O'Regan initiated these three solar cells in 1991. The renewable technology of this solar cell variant can be developed to increase absorbance [3].

DSSC is in a sandwich configuration consisting of transparent conduction glass, photoelectrode, photosensitizer, electrolyte, and counter electrode [4]. *Photoelectrode* is a semiconductor material that absorbs energy from sunlight, for example, nanocrystalline Titanium dioxide ($TiO_2$). In $TiO_2$, a current is generated when the dye molecule absorbs photons as a photosensitizer with a wide bandgap in the visible light spectrum to produce electron-hole pairs, which become a source of electric power. The electrons move to the photoelectrode while holes move to the counter electrode through a redox reaction in the electrolyte [5]. Therefore, the absorbance of the photosensitizer above the $TiO_2$ surface becomes an essential parameter in determining the efficiency of DSSC [6].

The photosensitizer often used was initially a transition metal compound Ruthenium polypyridyl complex, resulting in a DSSC efficiency of 13% [7]. However, the presence of heavy metals and their rarity caused this compound to be slowly abandoned. Instead, the researchers turned to readily available natural materials with many color variants that are easy to extract and friendly to the environment even though their efficiency is lower than synthetic materials [8]. Raw materials such as fruits and vegetables overcome this problem [9].

Natural ingredients processed into dyes contain anthocyanin, carotenoid, or chlorophyll pigments [10]. Anthocyanin pigments reach almost all visible light spectrums, from orange and red to purple and blue [11]. Furthermore, anthocyanins can absorb light at 500-700 nm and transmit light throughout the wavelength if the anthocyanin is at a high pH [12]. Following the research results by Reza Hemmatzadeh et al., the performance of DSSC with anthocyanin dye produces an open-circuit voltage ($V_{oc}$) and a short-circuit current density ($J_{sc}$) of 0.29-0.66 V and 6.14 mA/cm$^2$, respectively [13].

While carotenoids can be obtained from fruits or vegetables that are yellow, orange, or red, the absorption range of carotenoids lies in the wavelength of 400-500 nm [14]. Therefore, DSSC synthesized using carotenoids as dye pigments produces solar cell performance with an open-circuit voltage ($V_{oc}$) of 0.4 V, short-circuit current density ($J_{sc}$) of 0.27 mA/cm$^2$ and efficiency of 0.074% [15].

Unlike the case with Chlorophyll which is widely found in leaves, the absorption range is 460-650 nm [16]. The working principle of solar cells with this pigment is similar to photosynthesis in plants [17]. Based on research conducted by Zainal Arifin et al., DSSC with open-circuit voltage ($V_{oc}$), short-circuit current density ($J_{sc}$), and efficiency of 500 mV, 0.62 mA/cm$^2$, 0.16%, respectively [18].

In various studies, the efficiency of DSSC can be increased by combining two or many dye pigments [19]. The combination of pigments can expand the absorption range, which results in high electron excitation energy in photoelectric conversion. In addition, combining pigments can increase the current density produced by the photon dissociation of dye molecules [20]. For example, combining anthocyanin and chlorophyll pigments can increase the efficiency of DSSC from 0.042% to 0.154%. In this review, we will explain the synthesis and characterization process of DSSC using a combination of pigments as a photosensitizer. First, we will briefly explain the structure and working principle of DSSC and the photosensitizer. Then, we will also explain the synthesis process starting from dye extraction, making $TiO_2$, cleaning transparent conductive glass, and making $TiO_2$ thin films, and describe the DSSC characterization process and its results. Finally, show a comparison of the performance of DSSC using a single dye and a dye combination from research carried out in the last ten years, which can provide the latest information on increasing the efficiency of DSSC using a dye combination.

## II. Theory

### Structure and Working Principles of DSSC

DSSC is a solar cell assembled using a sandwich-type approach, successive nanocrystalline mesoporous layer sensitive to dye molecules, an electrolyte solution containing a redox system, and a catalyst superimposed onto a transparent conductive glass [5]. Transparent conductive glass is often used in DSSC as Fluorine-doped Tin Oxide (FTO) or Indium Tin Oxide (ITO) [21]. The use of ITO is currently extensive in optoelectronic applications. However, the complicated manufacturing process and the scarcity of indium have caused ITO prices to rise. In contrast, the photoelectrode is usually a semiconductor material with a wide bandgap, such as an n-type semiconductor Titanium dioxide ($TiO_2$) with a bandgap of 3.2 eV. This photoelectrode is made sensitive by a layer of dye molecules (photosensitizer) added to the surface of the semiconductor. The photosensitizer is an electron pump that absorbs visible light, pumps electrons into the semiconductor, accepts electrons from the electrolyte, and continuously performs the cycle [5].

The electrolyte containing the redox system ($I^-/I^{3-}$) is usually a solution or a solid. DSSC usually uses an electrolyte solution between the photoelectrode and the counter electrode (catalyst). However, the electrolyte solution has a high viscosity and low ion mobility of the liquid, affecting the DSSC's efficiency. It can limit the diffusion rate of iodide and triiodide and reduce DSSC resistance. To overcome this limitation, currently found electrolytes in solid form (¬quasi solid-state). These solid electrolytes comprise a matrix of organic polymers, which combine the liquid electrolyte to form a network of stable gel structures through physical and chemical interactions. Therefore, these sol-gel electrolyte properties have cohesive and diffusion transport properties as properties of liquids. It can overcome the volatility of the liquid electrolyte [22].

The last component of the DSSC is a counter electrode whose role is to return electrons received from the external circuit to the redox system [5] and catalyze redox processes in the electrolyte. Counter electrodes often used in DSSC are Platinum (Pt) and Carbon (C). However, Pt degradation tends to be faster when interacting with a liquid electrolyte to reduce the efficiency of DSSC [23].

The working principle of DSSC uses the photovoltaic effect, which is briefly described in Figure 1. When sunlight hits the DSSC, the electrons in the dye molecule will absorb its energy (hυ) to help it excite and produce electron-hole pairs [5]. The excited photoelectrons are located above the edge of the conduction band on the $TiO_2$ semiconductor. At a fast rate of about $10^{-12}$ under sunlight (power 100 mW.cm$^{-2}$), temperature 25℃, and the intensity distribution of the light source spectrum is 1.5 AM standard solar. The photoelectrons will be injected into the $TiO_2$ conduction band, leaving a vacancy in the dye molecules (oxidized) and increasing the electron density of $TiO_2$ and the potential difference between $TiO_2$ and the electrolyte [24]. Electron donors will regenerate the oxidized dye molecules from the electrolyte. The counter electrode will accelerate the $I_3^-$ Reduction reaction, which produces $I^-$ which will carry out the oxidation reaction and produce electron donors. The entire cycle is regenerative (i.e. regeneration of the oxidized sensitizer). The balance of the whole process will be the conversion of photons to electrons without permanent chemical transformation [25].

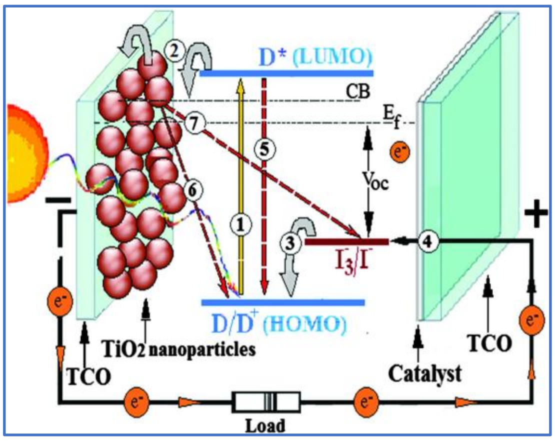

**Figure 1.** Schematic of a cross-sectional view of the DSSC and the electron transfer processes in converting light to electricity [22].

## Photosensitizer

The photosensitizer can be adsorbed on the surface of the semiconductor through electrostatic bonding, hydrophobicity, or chemical interactions. During excitation, electrons are injected into the conduction band of the semiconductor. The dye used as a photosensitizer must meet the following requirements: (i) The absorption spectrum must cover a wide range of wavelengths from the visible to the IR region of the solar spectrum, (ii) The coefficient of molar extinction ($\varepsilon$, $M^{-1}.cm^{-1}$) must be as high as possible for light harvesting to be efficient. To ensure efficient electron injection and regeneration, (iii) The lowest unoccupied molecular orbital (LUMO) dye must be above the edge of the conduction band of the semiconductor [26], (iv) The highest occupied molecular orbital (HOMO) dye must be below the energy level of the redox mediator for the regeneration process to run optimally [27], (v) The dye must be tightly bound to the semiconductor surface for optimal electron injection.

The dye extraction process usually uses the maceration method, which is most often used in the dye extraction process. This method utilizes the solvent's diffusion process and extraction material. High osmotic pressure will release the active compounds in the material. The solvent used can be ethanol, acetone, or n-hexane. This method is used because it is simple and does not require high costs [15].

The dye extraction process can be started by washing the material and then drying the material to reduce the water and other content that is not needed. Then the fabric is cut into small pieces or crushed with the help of a mortar or blender. A more detailed explanation is shown in Table 1.

After the maceration process, the solution was centrifuged for 10 minutes at 4000 rpm to separate the precipitate and filtrate. Then filtered using Whatman paper and stored at room temperature in the dark [34].

## III. Method

This review provides a comprehensive analysis and synthesis of existing literature on a natural dye-sensitized solar cell topic for 10 years. The analysis focuses on the investigation of combined dyes as natural sensitizers for dye sensitized solar cells. To ensure the quality and credibility of a review article, a systematic and rigorous method for reviewing and selecting articles is essential based on Scopus documents. The analysis includes the chemical material synthesis and characterization for natural dye-sensitized solar cells.

**Table 1.** Dye Extraction Method

| Materials | Method | Ref. |
|---|---|---|
| *Talinum fruticosum, Telfairia occidentalis* (Chlorophyll),<br>*Caesalpinia pulcherrima* (anthocyanin), 100 ml ethanol. | Maceration, dried for 30 days at room temperature. The dye solution was stored in a dark room for 18 hours. Then stir for 5 minutes at 1000 rpm at a temperature of 65°C. | [28] |
| Jengkol peel, ethanol 96% 50 ml and HCl 1M 10 ml | Maceration, the solution is stored for 24 hours in a dark room. | [29] |
| Shallots, red cabbage, and eggplant, 100 ml *ethanol* | In the maceration, the solution is stirred for 1 hour at 50°C. | [13] |
| Black rice, 400 ml *ethanol*, 5 ml *hydrochloric acid*, 95 ml distilled water | Maceration for three weeks in a dark room, with the material in the form of powder. | [30] |
| Black rice, 100 ml of ethanol, and a few drops of *acetic acid* | Maceration for three weeks in a dark room with a temperature below 25°C. | [31] |
| Katuk leaves, carrots, tomatoes, 100 ml of *acetone* | Maceration for 24 hours after stirring using a shaker for 1 hour. | [32] |
| Algae, 100 ml *ethanol* | The maceration process was held overnight in a cooler with a temperature of 3°C. | [33] |

## IV. Results and Discussion

### Synthesis of DSSC

The DSSC synthesis process consists of several steps.

Step 1: *Cleaning of transparent conductive glass.* Before use, the conductive glass was cleaned by sonification for 15 minutes in a Double Deionized Water (DDW) solution, then washed again with acetone [35]. According to [36], conductive glass can be cleaned with water and soap and immersed in isopropanol: acetylacetone (1:1) solution for 30 minutes in an ultrasonic cleaner. The sonification process aims to ensure no impurities on the glass surface and as an initial test before being heated to prevent cracking. Meanwhile, Djaeni M. et al. [37] is sufficient to immerse the conductor glass in isopropyl alcohol. In addition, the conductive glass cleaning process can be carried out by placing the glass in a beaker containing 70% alcohol. Then the glass is put in an ultrasonic cleaner for 30 minutes [37]. Then it is dried using a tissue or nitrogen gas or left in an open room. Both sides of the glass were tested for conductivity using a multitester. The conductive side deposits the $TiO_2$ semiconductor [38-41].

Step 2: *$TiO_2$ semiconductor synthesis.* Based on research conducted by K. B. Erande et al. [35], $TiO_2$ solution was prepared from 0.5M Titanium (IV) isopropoxide (TTIP) dissolved in 40 ml of water, which became a cationic precursor. This cationic precursor is made at pH five by adding a few drops of ammonium hydroxide ($NH_4OH$). Meanwhile, TTIP was dissolved in acetyl acetone-ethanol (1:1) [42] based on another study. $TiO_2$ solution can be made from 1 gram of Titanium dioxide powder dissolved in water. Then, 2 ml of deionized water and 1 ml of Triton-X 100. Then the solution was sonicated for 1 hour [43]. In addition, $TiO_2$ can be made into a paste by adding 2.5 ml of acetic acid and stirring using a hot plate stirrer for 30 minutes. Next, good acetyl trimethyl ammonium bromide (CTAB) and stirred to help strengthen the $TiO_2$ bond with the conductive glass used. Then stir again for 30 minutes. Finally, the formed $TiO_2$ paste was put into a bottle and closed [29].

Step 3: *$TiO_2$ thin film deposition on a transparent conductive glass substrate.* It has been done using the doctor blade method, spin coating, or screen printing. The screen-printing process involves depositing $TiO_2$ on conductive glass with the T77 screen into three layers [44]. Meanwhile, using a stainless spoon, the doctor blade method is done by depositing TiO2 on a conductive glass. The disadvantage of this method is that the thickness of the layer cannot be determined with precision. The solution to overcome the weakness, a spin coating method, emerged by pouring $TiO_2$ paste on a conductive glass placed on a spin coater and then rotating it at 200-300 rpm in a predetermined time. [45]. In addition, this deposition process can be carried out by dripping 1 ml of $TiO_2$ solution on the glass and rotating it at 1100 rpm for 90 seconds [46]. Repetition can be carried out according to the desired layer thickness.

Step 4: *Sintering of $TiO_2$ thin film.* The $TiO_2$ layer was heated for 5 minutes at a temperature of 325℃, then increased to 375℃ for 5 minutes, 450℃, and 500℃ for 15 minutes, respectively [44]. In another research, $TiO_2$ thin film was heated at 200℃ for 30 minutes in a furnace at 500℃ for 60 minutes [47, 48]. Meanwhile, in Gareso et al. research, the thin film is heated at 100℃ for 1 hour and reheated about 300-600℃ using a furnace [46].

Step 5: *Immersion of $TiO_2$ thin film into the dye solution.* The thin film $TiO_2$ is immersed in the previously extracted dye solution for 3-5 days [49].

Step 6: *Electrolyte synthesis.* An electrolyte solution containing redox ions that are useful as a liaison between electrodes can be prepared by mixing 0.1 M Iodine, 0.05 M Lithium Iodine, and 0.05 M 3-methoxypropionitrile into 50 ml of acetonitrile ($C_2H_3N$) [50], then stir for 60 minutes. In addition, electrolytes can be prepared from LiI, NaI, KI, tetraalkylammonium iodide ($R_4NI$), and imidazolium-derivative iodides in concentrations of 0.1 to 0.5 M and 0.05 to 0.1 M for aqueous iodide mixed into aqueous solution. Non-protonic such as acetonitrile, propionitrile, methoxy acetonitrile, and propylene carbonate [51].

Step 7: *Counter electrode deposition.* This process can use platinum, carbon, or rGO materials deposited by doctor blades, screen printing, or droplet methods [52-55].

Step 8: *DSSC fabrication.* This process can be done by arranging the prepared materials according to the sandwich configuration in Figure 2 [56-58].

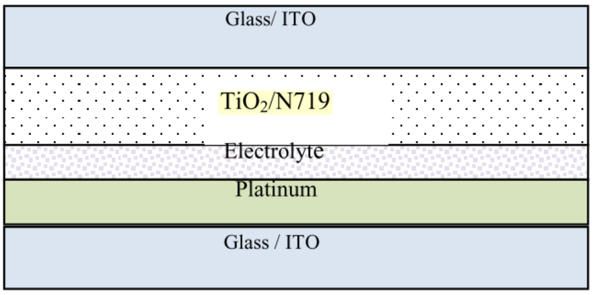

**Figure 2.** Sandwich configuration of DSSC [59].

### The Characterizations of DSSC

The DSSC characterization process can be carried out using several tools, including,

*X-Ray Diffraction (XRD).* Based on the research of M. Al Qibtiya et al.[60], the grain size characterization of $TiO_2$ can be done using the Scherrer equation (1) of X-Ray Diffraction (XRD), namely:

$$D = \frac{K\lambda}{\beta \cos \theta} \tag{1}$$

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Where $\lambda = 0{,}154056$ nm, $\beta$ is the width at half maximum height, $K = 0{,}9$, which is the dimensionless form factor of the spherical particle, and D is the approximate grain size [59]. Based on the characterization of $TiO_2$ with variations in thickness shown in Figure 3, there are four peaks at the diffraction angles of 25.36°, 38.03°, 48.14°, and 54.96° according to the plane (101), (004), (200), (211), sequentially. The sample's phase structure is anatase with a dominant tetragonal crystal structure in the plane (101). In addition, it was found that the peak intensity in the field (101) increased with increasing thickness. The diffraction peak of the substrate was not detected in the XRD pattern because the substrate glass thickness was too large.

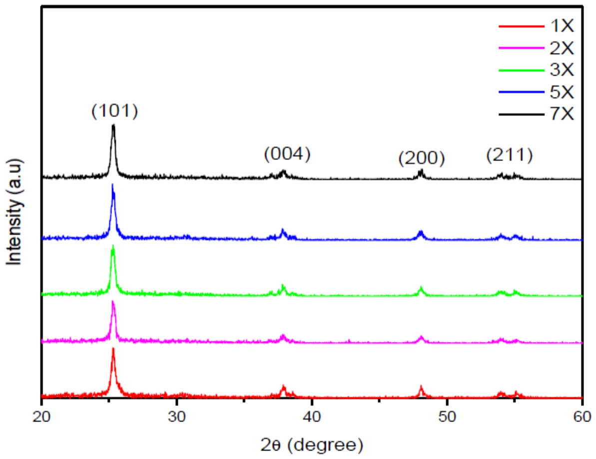


**Figure 3.** XRD spectra of TiO2 thin films of varying thickness [59].

*Scanning Electron Microscope (SEM).* It is used to investigate the morphology of the coating surface on the DSSC. Images were obtained from a JEOL JSM-6360LA apparatus at 20kV at 12,000-220,000 times magnifications [34, 61]. An example of the results of SEM $TiO_2$ characterization with varying thicknesses is shown in Figure 4. The thicker the $TiO_2$, the greater the agglomeration and the more pores.

*UV-Vis Spectrophotometer.* UV-Vis spectrophotometer determines the absorption spectrum by displaying a Wavelength graph against absorption [1]. This measurement is based on the absorbance ability of light [34]. An example can be seen in characterizing a photoelectrode immersed in curcumin dye with various solvents, as shown in Figure 5.

The resulting absorbance spectrum is 300 to 500 nm wavelength range. The highest absorbance intensity was obtained from dye extraction using acetone as a solvent. The suitable solvent increases cell efficiency by increasing the microphase separation, which results in greater amphiphilicity for dye adsorption. Polar aprotic solvents such as acetone, DMF, and DMSO were more effective for dye diffusion, while polar protic ethanol was unsuitable for dye diffusion. In addition, the lower solvent viscosity provides improved mass transport by diffusion. Acetone (0.306 cP) was found to be more effective in this way compared to DMF (0.92 cP) and DMSO (1.996 cP) among polar protic solvents.

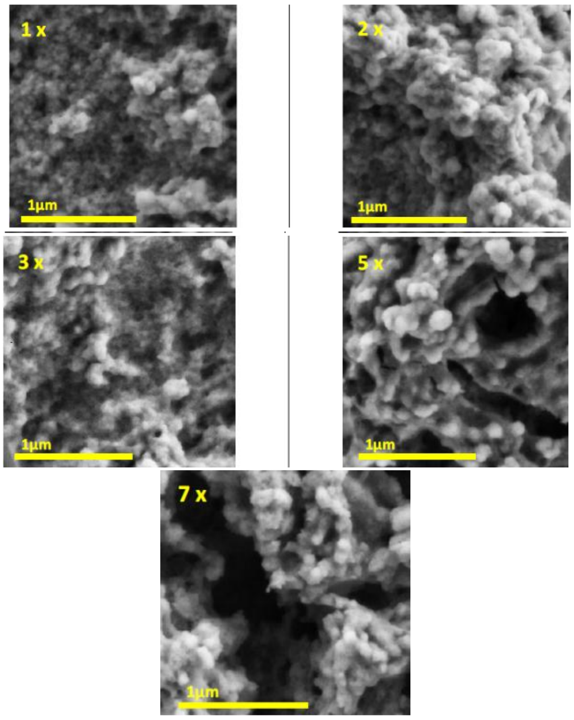


**Figure 4.** The morphology of $TiO_2$ thin films of varying thickness [59].

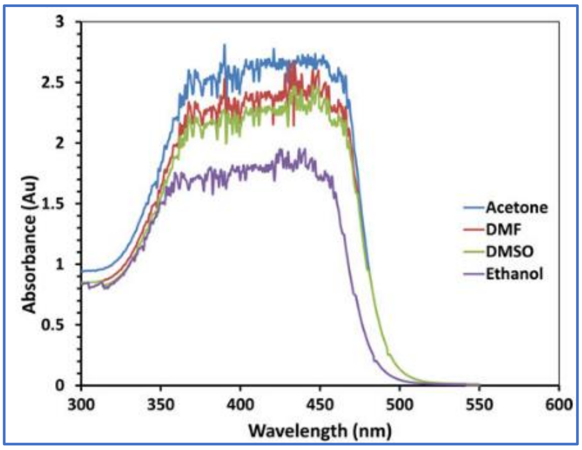


**Figure 5.** Absorbance spectrum of photoelectrode immersed in curcumin dye solution with various solvents [61].

*Cyclic Voltammetry.* This tool is identified as effective for evaluating the HOMO-LUMO energy level of semiconductor materials [62]. Based on the onset, the oxidation potential $E_{ox}$ can be related to HOMO through equation (2), and the potential reduction $E_{red}$ can be related to LUMO through the equation (3),

$$HOMO = -(E_{ox} + 4.4)\ eV \tag{2}$$

$$LUMO = -(E_{red} + 4.4)\ eV \tag{3}$$

and bandgap in equation (4).

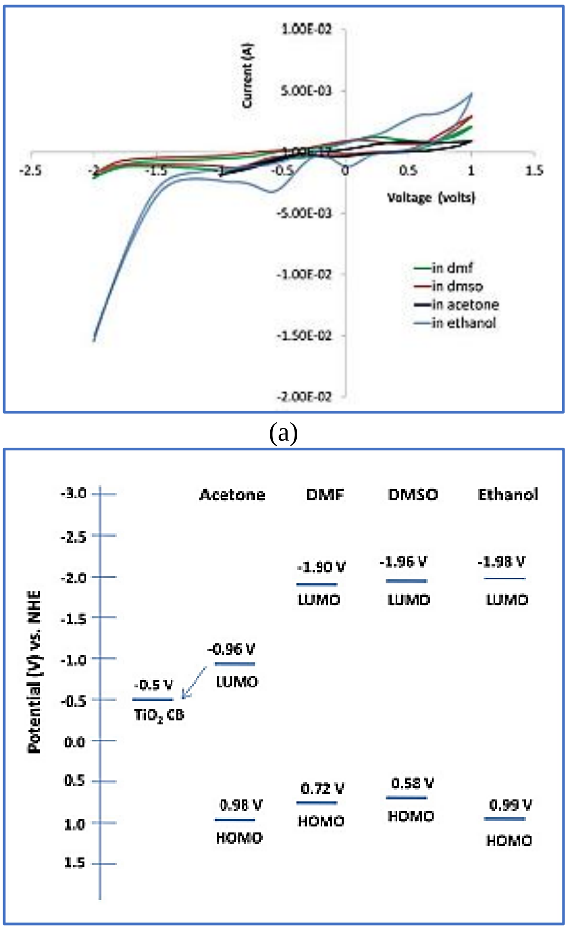
$$E_g\ (eV) = HOMO - LUMO \tag{4}$$

Cyclic voltammogram recorded with Potentiostat/Galvanostat (Autolab Model 30) in different solvents as shown in Figure 6a the position of HOMO-LUMO from ethanol to acetone. To obtain charge separation efficiency, the LUMO of the dye as the site of electron injection must have a more negative potential than the $TiO_2$ conduction band, and HOMO must have a more positive potential than the redox potential (iodide/triiodide system). The narrow HOMO-LUMO gap can increase the current due to energy conversion. In Figure 6b, all solvents produce a more negative LUMO potential than the $TiO_2$ conduction band. However, based on the HOMO-LUMO gap in Table 2, curcumin dye using acetone as a solvent produced the narrowest gap, resulting in maximum energy conversion efficiency.

The results of the characterization determine DSSC performance by generating the following parameters: (i) Short-circuit current density ($J_{sc}$) resulting from irradiation of the DSSC by a standard 1.5 AM solar simulator filter 100 mW.cm$^{-2}$. It shows the ability of the sensitizer to absorb light through a wide area of the solar spectrum and the efficiency of electron injection into the conduction band of the $TiO_2$ semiconductor. In addition, a high value of Jsc is associated with the reduction rate of the oxidized dye molecule [63], (ii) The open-circuit voltage ($V_{oc}$) is the difference in electric potential when the current shows zero value between the $TiO_2$ photoanode and the counter electrode of the cell when irradiated [64]. (iii) Fill Factor (FF) is the compatibility between the voltage at maximum power, the open-circuit voltage, and the current at maximum voltage and short-circuit current determined by equation (5). The energy conversion efficiency ($\eta$) is determined by the ratio between the maximum and light power per unit area, as shown by equation (6).

$$FF = \frac{V_{max} \cdot J_{max}}{V_{OC} \cdot J_{SC}} \tag{5}$$

$$\eta = \frac{V_{OC} \cdot J_{SC}}{P_{in}}\ x\ FF \tag{6}$$



(a)

(b)

**Figure 6.** (a) Cyclic voltammogram results. (b) Energy level diagram of DSSC with Curcumin dye in various solvents [61].

**Table 2.** The position of HOMO-LUMO and bandgap produced by different solvents [61].

| **Solvent** | **$E_{ox}$ (V)** | **$E_{red}$ (V)** | **HOMO (eV)** | **LUMO (eV)** | **Bandgap (eV)** |
|---|---|---|---|---|---|
| Acetone | 0.98 | -0.96 | 5.38 | -3.44 | 1.94 |
| DMF | 0.72 | -1.90 | 5.12 | -2.50 | 2.62 |
| DMSO | 0.58 | -1.96 | 4.98 | -2.44 | 2.54 |
| Ethanol | 0.99 | -1.98 | 5.39 | -2.42 | 2.97 |

## Single and Combination of Dye

The efficiency of DSSC by using photosensitizers from natural materials is a challenge for future research. The absorbance spectrum and low stability can cause it, so the $TiO_2$ semiconductor binds not many dye molecules. Therefore, the study was carried out to increase the absorption spectrum area by combining natural ingredients used as dyes.

The combination of the same pigment with different colors has been carried out by Kwangchit Wongcharee et al. [65]. His research used anthocyanin pigments from rosella (red) and blue pea (blue). The absorbance peaks of rosella are located at 520 nm, and blue pea is found at 580 and 620 nm. Therefore, different anthocyanins and extracted colors caused differences in absorbance characteristics. Meanwhile, combining the two produces a better absorbance spectrum than the blue but not as high as the red color shown in Figure 7.

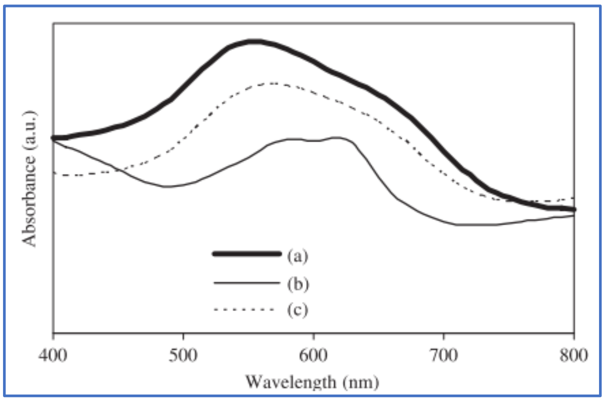


**Figure 7.** Absorbance spectrum of (a) Rosella, (b) Blue Pea, (c) Rosella, and Blue Pea Combination [65].

In the study of Kabir et al. [66], Amaranthusdubius (red) produced an absorbance range of about 400-600 nm and an absorbance peak at 514 nm, and Curcuma longa (turmeric) had an absorbance range of around 350-600 nm with an absorbance peak at 421 nm. While the combination produces an absorbance peak at 420 nm, as shown in Figure 8. The relationship between the bandgap and the absorption wavelength is inverse, where the energy band gap decreases as the absorption wavelength increases.

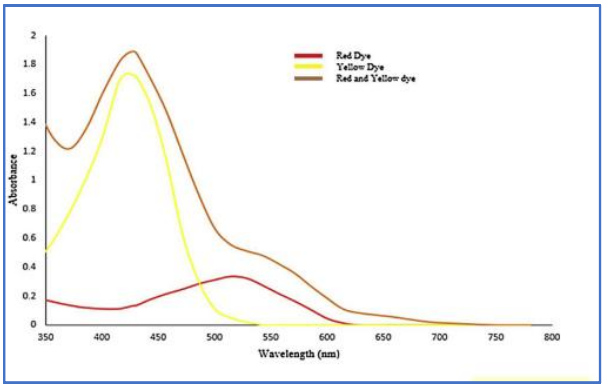


**Figure 8.** Absorbance spectrum of red dye, yellow dye, and a combination of red and yellow dye [66].

The combination of pigments can increase the absorbance spectrum and the excitation energy of electrons in photolytic conversion. Figure 9 shows the absorbance of dye in the 400-700 nm wavelength range. For example, dye from dragon fruit obtained a broad absorbance spectrum at 480-570 nm with a maximum of 540 nm. Dye from the hibiscus obtained the maximum absorbance spectrum at 510 nm. Meanwhile, the dye from the bitter leaf got the maximum absorbance spectrum at 480 nm and 660 nm.

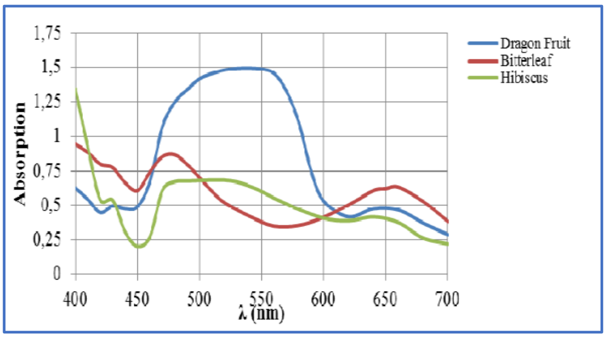


**Figure 9.** Absorbance spectrum of single dye [20].

In addition to optical properties, the performance shown by the solar cell can be in the form of electrical properties shown in Figure 10, which uses a dye derived from Malabar spinach (green) and red spinach (red). Photoelectrochemical activity depends on the morphology of the $TiO_2$ photoelectrode. It can measure the current density and the resulting voltage.

The increase in efficiency due to the combination of pigments is caused by the electronic orbitals of the two dyes not overlapping. It will reduce the transfer of electrons from the two dyes simultaneously. The presence of coadsorption can increase electron injection by suppressing concentration quenching, transfer of electrons or energy between the two types of dye molecules, and preventing charge recombination. The maximum current and voltage density values difference results from the combined synergistic effect. The combination of ligand and hydroxyl accelerates the electron coupling effect in the $TiO_2$ conduction band to increase the electron transfer rate [34].

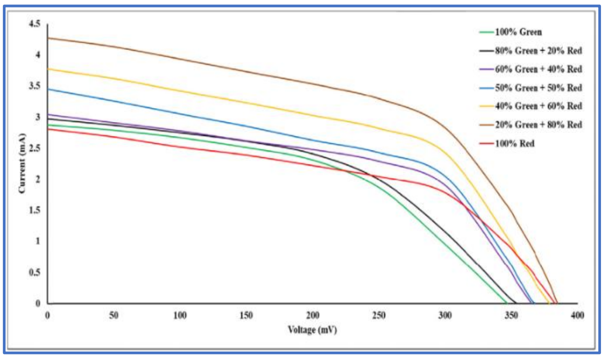


**Figure 10.** I-V Curve of Malabar spinach and red spinach

Based on Table 3, the resulting efficiency of various combinations of pigments does not reach 2%. Therefore, developing DSSC with pigment combinations in the future becomes a challenge.

**Table 3.** Pigment combination of DSSC electrical properties based on previous research

| **Materials** | **$V_{oc}$ (V)** | **$I_{sc}$ (mA)** | **$J_{sc}$ (mA/m$^2$)** | **FF** | **$\eta$ (%)** | **Advantages** | **Deficiency** | **References** |
|---|---|---|---|---|---|---|---|---|
| Spinach and Dragon Fruit | 0.460 | 0.19 | - | 0.0298 | 0.0258 | the $V_{oc}$ combination is more significant than the dragon fruit | Combination efficiency is lower than in spinach leaves | [67] |
| Spinach and Red Cabbage | 0.565 | 0.29 | - | 0.0328 | 0.0544 | The combination $V_{oc}$ is more significant than the purple cabbage | | |
| Spinach and Black Rice | 0.565 | 0.19 | - | 0.0341 | 0.0358 | $I_{sc}$ combination is more prominent than black rice | | |
| Lemon and Spinach | 0.470 | - | 0.055 | - | 0.0300 | - | - | [68] |
| Pomegranate and Beetroot | 0.650 | - | 0.044 | - | 0.0130 | - | - | |
| Turmeric and Red spinach | 0.499 | - | 4.264 | - | 1.078 | - | - | [69] |
| Peltophoroum pterocarpum and Acalypha amentaceous | 0.834 | - | 14.950 | 65.87 | 8.22 | Higher combination efficiency than each dye | Deposition using the doctor blade method | [70] |
| *Moss Chlorophyll* and mangosteen peels | 0.370 | - | 1. 130 | 0.60 | 0.154 | - | - | [71] |
| Dragon Fruit, *Bitterleaf*, and *Hibiscus* | 0.516 | 0.154 | - | - | 1.908 | Higher combination efficiency than each dye | - | [20] |
| Anthocyanin (*Ipomea pescaprea*) and Chlorophyll (*Imperata cylindrica (L.) Beauv, Paspalum conjugatum Berg.*) | 0.450 | - | 1.160 | 52.40 | 0.7600 | Higher combination efficiency than each dye | - | [34] |

## V. Conclusion

DSSC efficiency becomes an important parameter and can be continuous research. It is greatly influenced by synthesizing natural materials used as photosensitizers, photoelectrodes, electrolytes, and counter electrodes. The advantages of a single dye can be developed by combining them so that the absorbance spectrum of the dye will increase, and the resulting current is automatically more extensive.

The utilization of natural pigments in dye-sensitized solar cells (DSSCs) poses challenges in terms of efficiency due to limited absorbance spectra and low stability. To address these issues, researchers have explored the combination of different pigments. Studies have shown that such combinations can broaden the absorbance spectrum, enhance electron excitation, and improve photoelectrochemical activity. However, the current efficiency of DSSCs using pigment combinations remains relatively low. Further research and development are necessary to overcome these challenges and enhance the efficiency of DSSCs incorporating pigment combinations in the future.

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## Declarations

| | | |
|---|---|---|
| **Author contribution** | : | Prima Fitri Rusliani was the first author who participated in the data collection, transcription, and analysis. She also revised the manuscript. Eka Cahya Prima was responsible for the entire research project. He also led the writing of the manuscript. Both authors approved the final manuscript. |
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| **Additional information** | : | No additional information is available for this paper. |