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Research Article

Optimization of a Mixture of Curcuma Dye Mixture with SiO_2 (Rice Husk Waste) to the Energy Efficiency of TiO_2 -based Solar Cells

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Abstract
Global energy challenges and environmental problems encourage the search for sustainable energy solutions, with TiO_2-based solar cells that are still limited to its efficiency due to low light absorption and charge recombination. This study aims to examine the synergistic effect of curcuma and SiO_2 dye from rice husk waste in improving the energy efficiency of TiO_2 solar cells. The research methodology involves the fabrication of sensitive solar cells with different layer compositions: TiO_2 only, TiO_2 with one layer of SiO_2 (1L-SiO_2), two layers (2L-SiO_2), and three layers (3L-SiO_2). The TiO_2 photoanode is prepared using the screen printing method, followed by loading coloring through immersion in the curcuma coloring solution. The performance of solar cells is evaluated using the current voltage measurement (I-V) and electrochemical impedance spectroscopy (EIS) to analyze efficiency, charge transportation, and recombination processes. The results show that the addition of SiO_2 increases the efficiency of solar cells, with 1L-SiO_2 producing the highest compilation of short circuit (J_{SC}) 0.37 mA/cm², showing an increase in cargo transportation. However, 1L-SiO_2 shows a decrease in performance due to excessive thickness, which leads to an increase in charge recombination and internal resistance. Impedance analysis confirms that 1L-SiO_2 optimizes cargo transportation but also increases recombination resistance, which affects overall efficiency. Adding SiO_2 from rice husk waste increases the efficiency of TiO_2-based solar cells, with curcuma coloring increases light absorption and charge transfer. However, excessive SiO_2 layers reduce performance due to higher recombination and resistance. Further research is needed to optimize the thickness of the layer and dye stability.

Keywords: TiO_2, solar cells, sensitive solar cells, curcuma coloring, SiO_2, rice husk waste

1. INTRODUCTION

The development of sustainable and efficient solar cells is one of the most promising approaches to meet global energy demand while overcoming environmental problems. Solar cells based on titanium dioxide (TiO_2), especially solar-sensitive solar cells (DSSC), have gathered significant attention due to low costs, ease of fabrication, and relatively high efficiency [1]-[4]. However, its efficiency is still limited by factors such as light absorption and charge recombination [5]. Therefore, various strategies have been explored to improve the performance of TiO_2-based solar cells, one of which is the use of natural dyes.

Curcuma, a plant genus that is widely used in treatment and traditional food, contains curcumin, bioactive compounds known for antioxidant and anti-inflammatory properties [6][7]. Recent studies have shown the potential of curcuma-based dyes in improving the ability to harvest solar cell light [8][9]. This natural dyes are environmentally friendly alternatives for synthetic dyes, which are often toxic and expensive [10]. The integration of curcuma coloring in TiO_2-based solar cells can help increase their light absorption and, as a result, their overall energy efficiency [11].

One of the promising ingredients to improve the performance of solar cells is silica (SiO_2) originating from rice husk waste. The husk constellation, abundant agricultural products, is rich in SiO_2, which can be used to improve structural and optical properties of solar cell electrodes [12][13]. The latest progress has shown that SiO_2 can increase the surface area and porosity of TiO_2 electrodes, thereby increasing the absorption of light and the efficiency of electron transportation [14]. Utilization of SiO_2 from rice husk waste not only provides effective materials to improve the performance of solar cells but also offers sustainable solutions for disposal of agricultural waste [15][16]. The combination of curcuma and SiO_2 coloring (from rice husk waste) in TiO_2-based solar cells has the potential to optimize energy efficiency by overcoming limitations associated

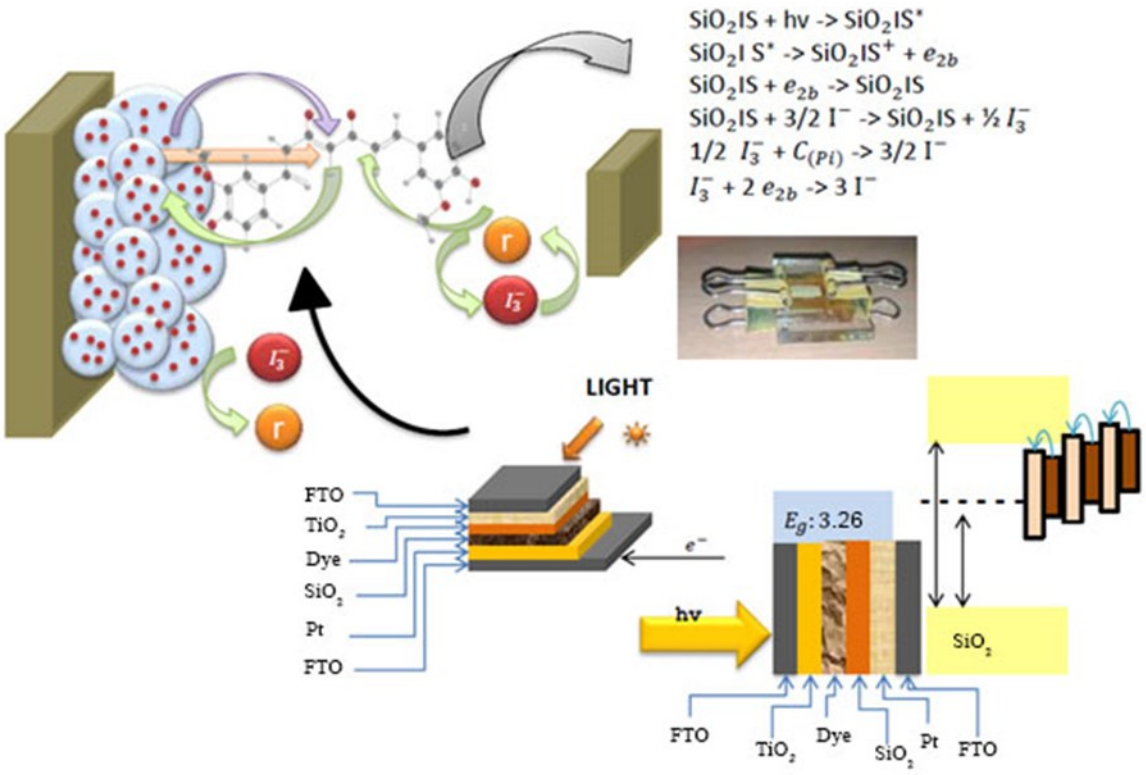


Figure 1. DSSC cell design.

with light absorption, cargo transportation, and material sustainability. This study aims to investigate the synergistic effects of the curcuma coloring mixture with SiO_2 on TiO_2-based solar cell energy efficiency, with a focus on optimizing the composition of the mixture to achieve the highest DSSC performance.

2. MATERIALS AND METHODS

2.1. Material

We use an experimental study to optimize the curcuma coloring mixture with SiO_2 (from rice husk waste) to increase the energy efficiency of TiO_2-based solar cells. The materials used include TiO_2 nanoparticles, curcuma extract, and SiO_2 sourced from rice husk waste. The TiO_2 nanoparticles are bought from Sigma-Aldrich, while curcuma dyes are extracted from the *Curcuma longa* root. Rice husk was collected from a rice factory in Malang, Indonesia. All chemicals and solvents used in experiments are analytical levels, including ethanol and acetone, which is used for washing and preparation.

2.2. Curcuma and SiO_2 Coloring Preparations from Rice Husk

2.2.1. Curcuma Coloring Extraction

Curcuma coloring is extracted from the root of the dry longa curcuma using an ethanol-based maceration process. Dry root (50 g) is crushed into powder and soaked in 500 mL of 96% ethanol for 72 h. The extract is then filtered, and the solvent is evaporated under reduced pressure using a rotary evaporator to get a concentrated coloring solution. This dyes are used in various concentrations to test their efficiency in improving the performance of TIO_2-based solar cells [17][18].

2.2.2. SiO_2 Extraction from Rice Husk

The SiO_2 is extracted from rice husks using a simple alkaline treatment method. Rice husk (100 g) was first washed thoroughly with distilled water to remove dirt. Then heated in the oven at 600 °C for 5 h to remove organic content, followed by soaking in a 2 M NaOH solution for 24 h. After filtering and washing with distilled water, the remaining SiO_2 is dried at 110 °C for 12 h and crushed into fine powder. SiO_2 powder is then characterized using X-ray diffraction (XRD) and scanning electron microscope (SEM) to confirm the

purity and size of the particle, respectively [19][20].

2.3. TiO_2-based Solar Cell Fabrication

The research method used is a laboratory experiment with the independent variable in the form of variations in the thickness of the TiO_2 photoactive layer, which is an integral part of the structure of the photographical material in the DSSC. In the initial stages, the blocking layer is applied to the conductive glass substrate of fluorine -doped tin oxide (FTO) using spin coating techniques to ensure homogeneous and controlled deposition. After that, the TiO_2 layer is deposited using the T-61 Pasta Printing Printing method, with a variety of thickness regulated based on the number of layers, namely as many as 1 layer, 2 and 3 layers. Furthermore, an additional reflective layer deposition above the mesoporous TiO_2 layer uses the same screen-printing method, with the aim of increasing light reflection for more optimal absorption efficiency.

The next process involves additional treatment by soaking photographs into the titanium tetraetoxide acetylacetonate isopropoxide solution that has been dissolved in 2-propanol. After soaking, the photograph is dried in a stable temperature condition of 70 °C for a duration of 30 min to increase the surface characteristics of the material. Loading of natural curcumin in the photograph is done through the immersion method, by soaking it in a solution of curcumin concentrating 0.7 mm for 24 h, to ensure optimal dye adsorption on the TiO_2 surface.

Furthermore, TiO_2-based solar cells are made by preparing TIO_2 photoanode. Transparent conductive oxide (TCO) glass is cleaned with acetone and isopropanol, followed by treatment with ultraviolet (UV) lamps for 30 min. The TiO_2 nanoparticles are scattered in ethanol solution and applied to TCO glass with a doctor's blade method, forming a thin

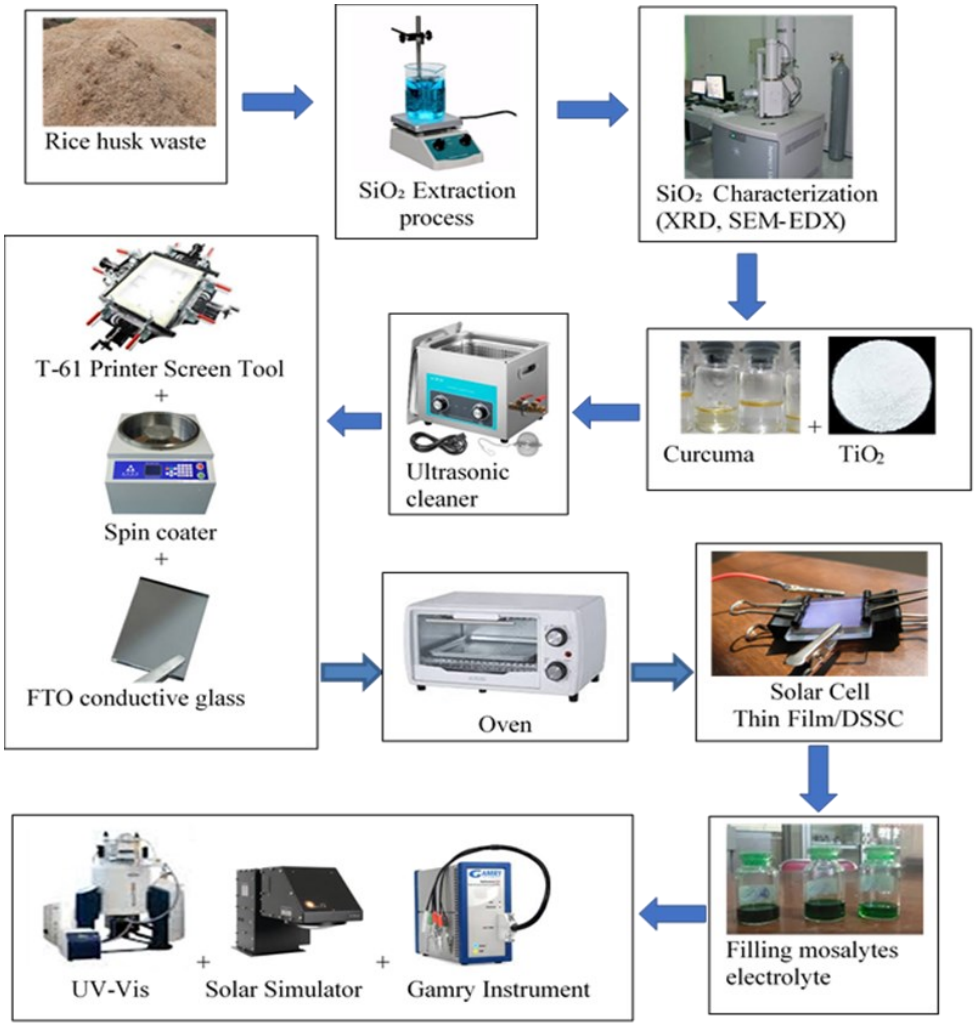


Figure 2. Experimental set up.

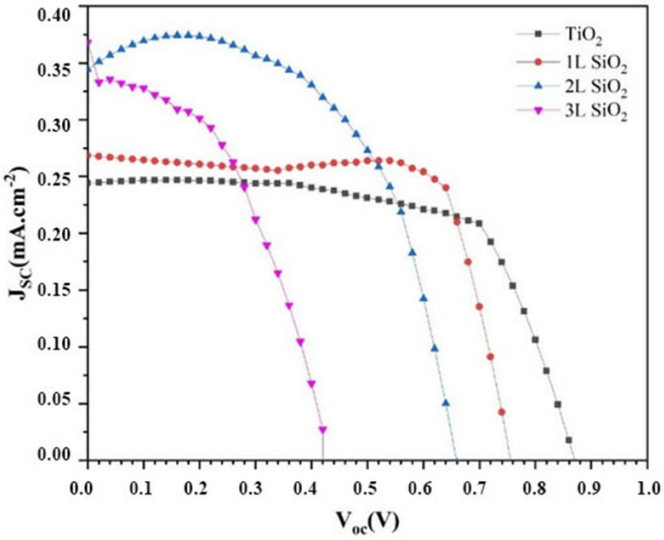


Figure 3. Relationship between J_{SC} and V_{OC} for various materials.

TiO_2 film. After syntrary at 450 °C for 30 min, TiO_2 films are coated with a mixture of curcuma and SiO_2 coloring (in various weight ratios) to evaluate the effects of optimization on energy efficiency. Cells are then assembled with platinum and electrolyte electrolytes/triiodide electrolytes [21][22]. Complete DSSC components, consisting of modified photographs, iodide electrolytes as electron transfer mediums, spacers from 25 µm sulyn material which functions as an insulator and sealing between layers, as well as opponent's electrodes in the form of platinum (Pt) layers. The component series is assembled with a structural scheme described in more detail in Figure 1.

2.4. Characterization of Solar Cell Performance

2.4.1. UV-VIS Spectroscopy

To characterize the optical properties of the curcuma coloring mixture, the UV-Vis absorption spectrum is obtained using the Shimadzu UV-3600 spectrophotometer. The absorption spectrum is recorded in the range of 300–800 nm, and the capacity of light absorption from a mixture of coloring compared to pure TiO_2-based solar cells [23].

2.4.2. Current Voltage Measurement (I-V)

TiO_2-based solar cell energy efficiency is evaluated using the current voltage measurement (I-V). The 2400 Sumber Keithley gauge is used to measure the photocurants in the simulated sunlight (100 mW/cm²) using Xenon lamps. Power conversion efficiency (PCE) of each solar cell is calculated using Equation 1 [24];

$$PCE = \frac{J_{sc}\, x\, V_{oc}\, x\, FF}{P_{in}} \quad (1)$$

where J_{SC} is a short circuit current density, V_{OC} is an open circuit voltage, and FF is a filling factor. This experiment was carried out with variations in mixing curcuma and SiO_2 to obtain optimal solar cell performance. This study uses variations in the number of mixture layers, namely 1 layer (1L-SiO_2), 2 layers (2L-SiO_2), and 3 layers (3L-SiO_2) in DSSC solar cells. Where the average thickness of each layer variation is as follows: 1L-SiO_2 ≈ 1.2±0.1 µm, 2L-SiO_2 ≈ 2.4±0.2 µm, and 3L-SiO_2 ≈ 3.6±0.3 µm. This thickness increases proportionally with the number of layers printed using the screen-printing method.

In the early stages, the blocking layer is applied to the conductive glass substrate that is coated in FTO using the spin coating technique, to ensure a homogeneous and controlled deposit. Furthermore, The TiO_2 layer is deposited using the T-61 Paste Screen Printing Method, with a variety of things that is adjusted based on the number of layers. Additional reflective layers are applied above the mesopori layer TiO_2 using the same screen-printing method, with the aim of increasing light reflection and achieving more optimal absorption efficiency. The next process involves immersion of photographs in the tetraetoxide acetylacetonate

isopropoxide solution which has been dissolved in 2 -propanol. After immersion, the photo is dried at a stable temperature of 70 °C for 30 min to increase the surface characteristics of the material.

2.4.3. Electrochemical Impedance Spectroscopy (EIS)

The capacitance value presented in this study was obtained from the Electrochemical Impedance Spectroscopy (EIS) analysis using the equivalent circuit model approach. Complex impedance spectrum data (nyquist curve) analyzed and fitted using zview software with a simple electrical circuit model (randles circuit), which includes serial resistance elements (RS), charge transfer resistance (RCT), and capacitive elements (CPE or multiple capacitance). The capacitance value (C_1) is calculated based on the fitting curve at low frequency, which reflects the ability of the electrode in storing charges before the charge transfer process takes place. Measurements are carried out in a frequency range of 100 kHz to 0.1 Hz with AC signal amplitude of 10 mV in dark conditions at room temperature. This method allows quantitative evaluation of the electrochemical performance of the photographic interface modified by the variation of the SiO_2 layer. The DSSC performance testing is carried out using a solar simulator integrated with a device for measurement of voltage-voltage characteristics (I-V meter), which aims to determine the efficiency of the DSSC system energy conversion. In addition, the analysis of DSSC internal resistance was also carried out using the EIS technique to identify the characteristics of electrical resistance in the solar cell device. Experimental settings used in this study are shown in Figure 2.

3. RESULTS AND DISCUSSIONS

3.1. SiO_2 Layer Thickness on Solar Cell Performance

Figure 3 shows different characteristics related to the density of short circuit current (J_{SC}) and open circuit voltage (V_{OC}). In TiO_2 as a reference material, the JSC value is relatively stable in the range of 0.25 mA/cm² at low voltage. However, this material shows a sharp decrease in current when the voltage increases above 0.7 V, which indicates that TiO_2 has limitations in maintaining current at a higher voltage [25]. This shows that TiO_2 has a lower charge transfer efficiency compared to other materials tested. Conversely, 1L-SiO_2 material shows an increase in performance compared to pure TiO_2, with a slightly higher JSC value is 0.27 mA/cm². In addition, the V_{OC} value for this material is higher than pure TiO_2, reaching around 0.75 V, before the current starts to decrease significantly. This shows that the addition of a mixture of dye curcuma with SiO_2 increases the efficiency of charge transfer and stability at a higher voltage [26]. This shows that the dye-curcuma mixture with SiO_2 significantly increases the efficiency of charge transfer.

For 2L-SiO_2 material, better performance is recorded than all other treatments. J_{SC} reaches a

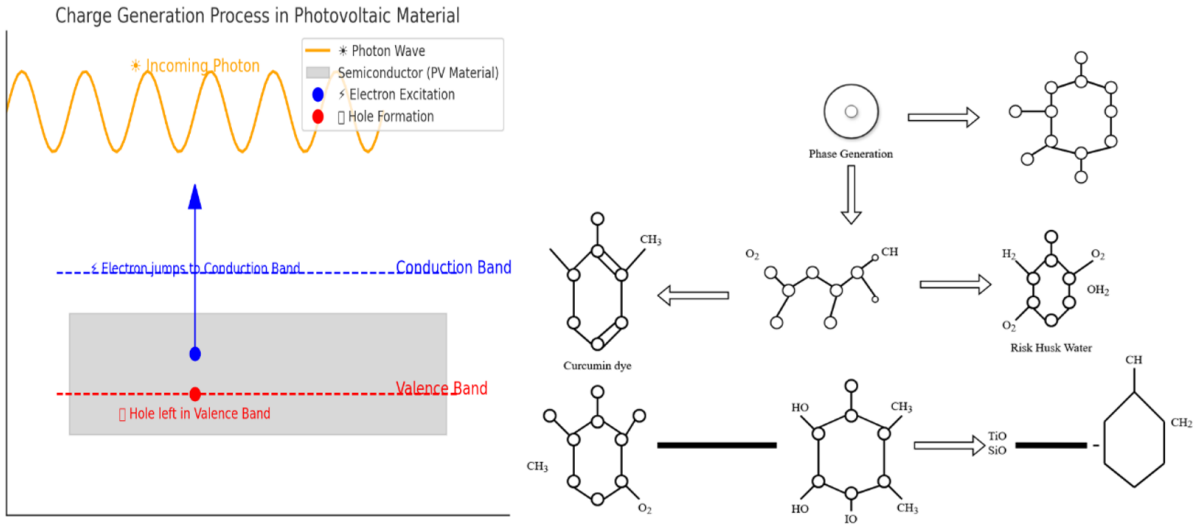


Figure 4. Charge generation in photovoltaic material process.

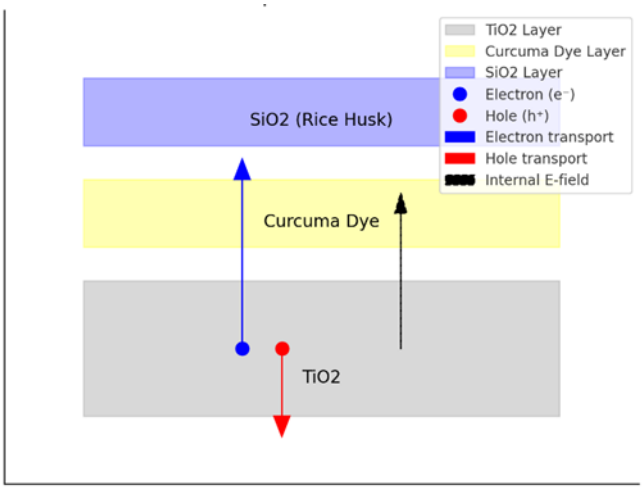


Figure 5. Electron-hole pair formation and transport phenomenon scheme.

maximum value of around 0.37 mA/cm², which is a significant increase compared to TiO_2 and 1L-SiO_2. In addition, this material shows the characteristics of a better V_{OC}, with an open circuit voltage that is quite high before a drastic decrease in current. This indicates that the addition of two layers of SiO_2 produces a more efficient charge transfer and increases carrier charges in the material. However, 1L-SiO_2 material shows less than optimal results compared to 1L-SiO_2. Although the J_{SC} value at low voltage is still quite high (0.32 mA/cm²), a decrease in current occurs faster than 1L-SiO_2 when the voltage increases. A sharp decrease in current after 0.4 V indicates that excessive layer thickness can inhibit charge transfer, increase recombination of electron holes, and reduce the overall efficiency of the device.

The relationship between the number of layers of mixture of coloring curcuma and SiO_2 with the efficiency of charge transfer is a crucial aspect in understanding the performance of photovoltaic material. The efficiency of charge transfer is very dependent on the ability of the material to allow electron flow that is not disturbed by high recombination. TiO_2, as a basic reference material, shows limitations in maintaining an electric current at high voltage, which reflects the efficiency of low charge transportation. However, there is a significant increase in the efficiency of charge transfer in 1L-SiO_2 material, which is indicated by an increase in the density of J_{SC} to 0.27 mA/cm² and a V_{OC} of 0.75 V. This shows that electrons can move more efficiently before a significant decrease in current.

The best photovoltaic performance is found in 2L-SiO_2 material, with a J_{SC} value of 0.37 mA/cm², which shows the more efficient electron hole transportation pathway and lower resistance in charge transfer. This indicates that the addition of two layers of SiO_2 made a significant contribution to increasing the efficiency of charge transfer. However, when the number of layers is increased to three (3L-SiO_2), there is a negative effect in the form of an increase in charge recombination caused by excessive material thickness. This thickness inhibits the movement of the charge, which causes the current to decrease faster after reaching a voltage of around 0.4 V. This finding proves that although the addition of layers can increase charge transfer, there are optimal limits in the number of layers before negative effects, such as higher recombination, begin to reduce the performance of solar cells as a whole. The process of transportation of cargo in photovoltaic material includes four main stages. The first stage is the power generation (Figure 4), where light falls to the surface of the semiconductor such as TiO_2 lifts electrons from the valence band to the conduction band, forming an electron-hole pair. Only photons who have a minimum energy are equivalent to the gap of the ribbon (band gap) material that can trigger this process.

Furthermore, the electron-hole pair is separated by the internal electric field to prevent the initial recombination (Figure 5). In TiO_2-based solar cells modified with dye curcuma and SiO_2 from rice husk waste, TiO_2 acts as the main semiconductor, Curcuma increases light absorption, and SiO_2

stabilizes structure and suppressing the recombination of charge.

The next stage is the charge transportation (Figure 6), where the electron moves to the negative electrode and the hole to the positive electrode through the path with a low resistance. Internal electric fields help separate charges, reduce recombination, and increase the efficiency of charge transfer. However, some charges can experience recombination before reaching the electrode (Figure 7), due to structural defects or atomic irregularities. Material engineering and adding passive layers are needed to suppress this process so that energy conversion remains optimal.

In addition to the charge transfer, the stability of the voltage also plays an important role in determining the performance of photovoltaic material. As the main indicator of voltage stability, V_{OC} reflects the ability of the material to maintain the voltage before a drastic decrease in current. In TiO_2, although the V_{OC} was initially quite good, this material showed a very sharp decrease in current after reaching 0.7 V, which indicated that TiO_2 could not maintain voltage stability at a higher level. Increased voltage stability recorded at 1L-SiO_2, which has a V_{OC} of 0.75 V, provides better voltage endurance than TiO_2 before the current starts to decrease sharply. 1L-SiO_2 shows the best performance in this aspect, with V_{OC} that remains high before the current starts to decrease, showing the ability of this material to maintain a more stable voltage compared to other materials. However, 1L-SiO_2 experienced degradation of voltage stability, because the current began to fall dramatically after reaching 0.4 V, which indicates that the addition of excessive layers increases internal resistance and accelerates the loss of voltage due to the dominance of recombination of electron holes. This finding confirms that although an increase in layer thickness can increase the efficiency of charge transfer and stability of voltage to a certain point, excessive thickness actually reduces the ability of materials to maintain longer voltage.

Photogeneration of cargo carrier in photovoltaic material is also strongly influenced by the number of SiO_2 layers used, because this layer plays a role in influencing light absorption and its conversion into pairs of holes that can be used in the electricity generation process. TiO_2, as a reference material, shows the lowest J_{SC}, which shows that the ability of this material to photogeneration is less optimal. However, with the addition of 1L-SiO_2, photogeneration increases. There was an increase in JSC from 0.25 to 0.27 mA/cm², which means more charge carriers are produced and can contribute to electric current. Peak performance found in 2L-SiO_2, with J_{SC} reaching 0.37 mA/cm², shows that this thickness is an optimal condition to capture light and convert them into holes efficiently. However, when the number of layers increases to 3L-SiO_2, photogeneration is still quite high with J_{SC} around 0.32 mA/cm², but the negative effects begin to appear. Excessive material thickness causes an increase in recombination, reducing the efficiency of cargo carrier transportation, and causing a faster decrease in current compared to 1L-SiO_2. This confirms the balance between material thickness and photogeneration efficiency, where 1L-SiO_2 provides the best combination between light absorption, load transportation, and lack of recombination, while excessive thickness, such as in 1L-SiO_2, actually reduces the effectiveness of

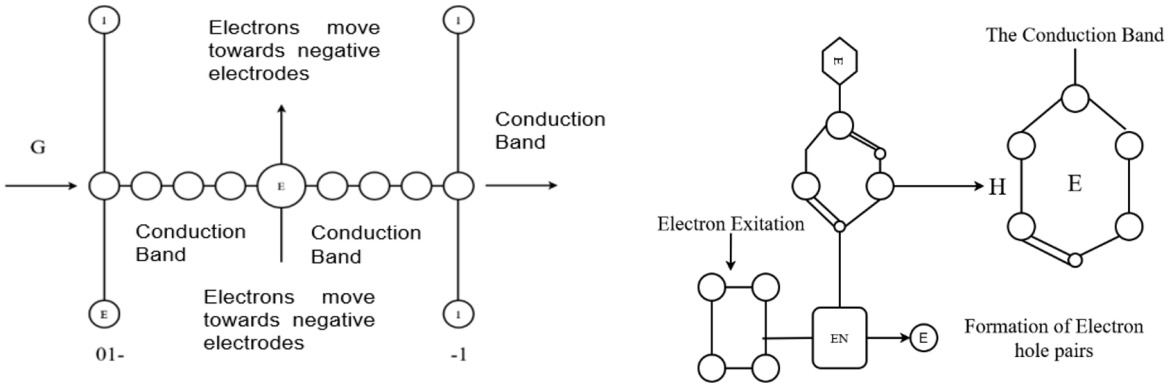


Figure 6. Cost transportation process.

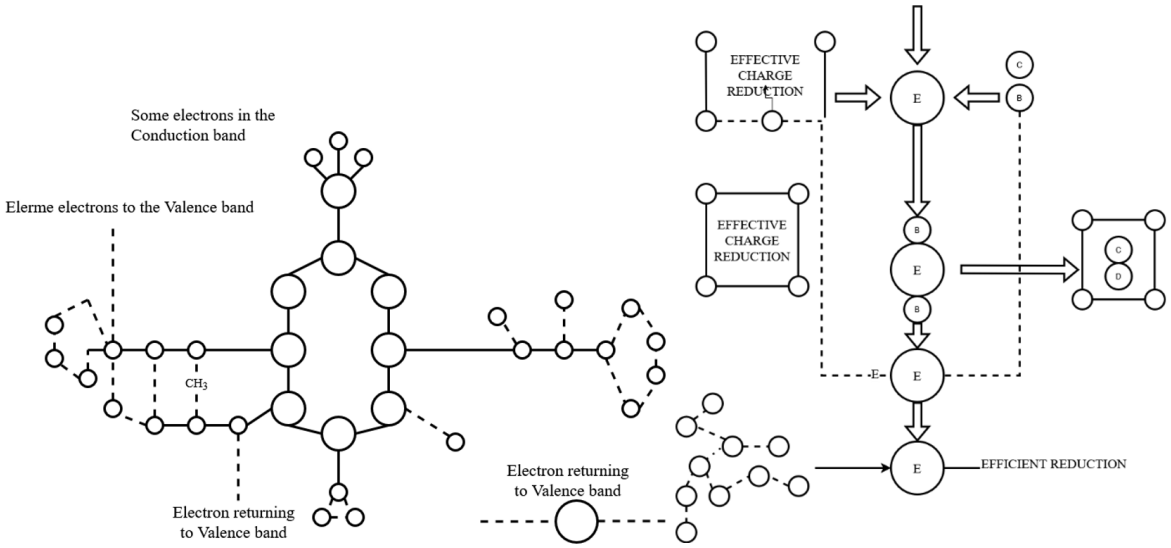


Figure 7. Recombination mechanism process.

energy conversion.

3.2. SiO_2 Layer Thickness on P_{MAX}, I_{SC}, V_{OC}, FF, and Efficiency Parameters (η) Solar Cells

Table 1 shows that the 1L-SiO_2 material has a relatively stable performance, with a high maximum power value (0.0347 mW) and an efficiency of 0.0403%. The V_{OC} recorded is 0.8982 V, which shows the ability of this material in maintaining a good voltage. Filling factor (FF) value of 0.6137 indicates the quality of good filling factors on this device. This characteristic is comparable to TiO_2 material [27].

Conversely, the 2L-SiO_2 material recorded the highest short circuit current (ISC) value compared to other compositions, which is 0.0916 mA, which shows a significant increase in short circuit currents. However, the V_{OC} has decreased to 0.6690 V, which is lower than other compositions. Although the FF remains stable at a value of 0.6156, its efficiency is slightly lower (0.0377%) compared to 1L-SiO_2. This shows that although the current is higher, other parameter factors are not enough to support to increase the overall efficiency of the device [28]. Although 2L-SiO_2 shows the highest J_{SC} value (0.037 mA), the efficiency is even lower than 1L-SiO_2 (0.0377% vs. 0403%). This is caused by an imbalance of parameters, especially a significant decrease in the V_{OC} value to 0.6690 V and an increase in the RCT value to 90,388 Ω·cm². High charge transfer resistance increases the charge recombination, thereby limiting the number of electrons that succeed in reaching the electrode. Although high J_{SC} shows effective photogeneration, increased recombination and resistance inhibits the efficiency of overall power conversion. This explanation is now added to strengthen the interpretation of experimental data. Table 1 shows the characteristics of various TiO_2-based solar material materials.

For 3L-SiO_2 material, although the V_{OC} value remains equal to 1L-SiO_2 (0.8982 V), the maximum power (P_{MAX}) is lower, which is 0.03476 mW. Although the short circuit current (I_{SC}) is equal to 1L-SiO_2, the lower V_{MAX} value (0.54 V) shows a decrease in performance on the optimal operational voltage side. The efficiency of this material (0.0348%) is also lower than 1L-SiO_2, indicating that the performance of this material is weaker [28]. Meanwhile, pure TiO_2 material shows similar results with 1L-SiO_2, which shows that the addition of 1L-SiO_2 does not provide a significant increase to the characteristics of I-V compared to pure TiO_2.

The highest maximum synchronization I_{SC} is recorded in 2L-SiO_2 with a value of 0.0916 mA, while the I_{SC} value at 1L-SiO_2 is relatively lower and parallel to pure TiO_2. This phenomenon can be explained through optical interactions and electron transportation in material. The SiO_2 layer functions as an anti-reflective layer that reduces the reflection of light from the surface of the solar cells, thereby increasing the amount of light absorbed by the active material (TiO_2). With a higher photon absorption, more pairs of holes are formed, which

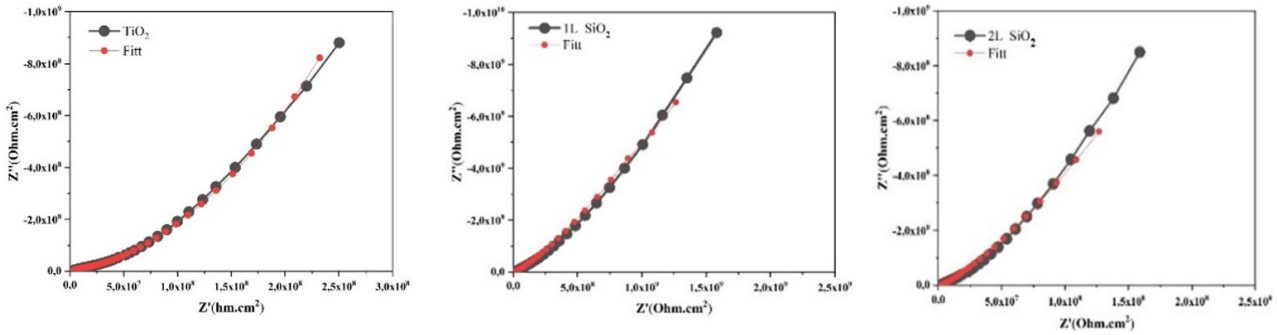
ultimately increase the I_{SC} value. However, when the thickness of the SiO_2 layer exceeds the optimal limit, this effect begins to reach the point of saturation, and at some point, the layer that is too thick actually functions as a barrier for electron transportation, which causes an increase in recombination of holes. This explains why I_{SC} reaches its peak at 2L-SiO_2, before finally stagnant or decreases at 3L-SiO_2.

The V_{OC} is influenced by the quality of the P-N intersection, the level of recombination of holes, as well as the characteristics of the energy barrier formed due to additional layers. The experimental results showed that the highest V_{OC} was recorded in TiO_2 and 1L-SiO_2 with a value of 0.8982 V, whereas in 2L-SiO_2, the V_{OC} dropped significantly to 0.6690 V. The decrease in the V_{OC} was most likely due to an increase in carrier recombination due to excessive layer thickness. At 1L-SiO_2, the SiO_2 layer is still thin enough so that it does not inhibit electron transportation significantly and can even increase energy resistance, which reduces recombination. However, at 1L-SiO_2, a greater layer thickness increases the likelihood of carrier recombination before reaching the electrode, which causes a decrease in the V_{OC}. When the thickness of the layer reaches 3L-SiO_2, the V_{OC} returns to 0.8982 V, shows that electron transportation in the layer may have reached the balance point, although the negative impact on maximum power (P_{MAX}) still exists.

The highest P_{MAX} value occurs at TiO_2 with a value of 0.04033 mW, while at 2L-SiO_2, P_{MAX} decreases slightly to 0.0377 mW, and at 1L-SiO_2, P_{MAX} dropped further to 0.03476 mW. This decrease in P_{MAX} is caused by the effect of the thickness of the SiO_2 layer on other parameters, especially V_{OC} and the efficiency of cargo transportation. Although the I_{SC} at 1L-SiO_2 increases, a significant decrease in the V_{OC} causes the maximum power not to increase proportionally. In 1L-SiO_2, although the V_{OC} is again increasing, the effect of increasing internal resistance and the possibility of the effect of capacitance due to greater layer thickness resulting in a decrease in P_{MAX}. This shows that there is an optimal limit in the thickness of the SiO_2 layer, where a layer that is too thin does not provide sufficient optical benefits, while the layer that is too thick actually reduces the

Table 1. Characteristics of I-V various compositions of TiO_2 material.

Sample	Characteristics I-V						
	Pmax (mW)	Isc (mA)	Voc (V)	FF	Imax (mA)	Vmax (V)	h (%)
TiO	0.040334059	0.07317087	0.898216392	0.613695208	0.05307113	0.76	0.000403341
1L-SiO_2	0.034763029	0.07317087	0.898216392	0.613695208	0.05307113	0.76	0.000403341
2L-SiO_2	0.037722423	0.09159547	0.669021152	0.615581754	0.08573278	0.44	0.000377224
3L-SiO_2	0.034763062	0.07317087	0.898216392	0.613695208	0.06437604	0.54	0.000347631



a. **b.** **c.**

Figure 8. Material complex impedance curve of (a) TiO_2, (b) 1L- SiO_2, and (c) 2L- SiO_2.

efficiency of cargo transportation in the material.

The FF value is relatively stable throughout the composition, ranging from 0.6137 to 0.6156. This stability indicates that the characteristics of the intersection diode in solar cells are not significantly affected by the thickness of the SiO_2 layer. The stable FF value indicates that the series resistance and shunt resistance in the system remain constant even though there are variations in the thickness of the SiO_2 layer. Low series resistance allows efficient charge transfer, while low shunt resistance prevents unwanted current leakage. Therefore, although other parameters such as V_{OC} and I_{SC} experience significant changes with an increase in the thickness of the SiO_2 layer, the FF value remains stable because the internal resistance of the device does not experience significant changes.

The highest efficiency was recorded at 1L-SiO_2 with a value of 0.0403%, while the efficiency at 2L-SiO_2 dropped to 0.0377%, and lower at 3L-SiO_2, which was 0.0348%. Although 1L-SiO_2 shows a high I_{SC}, a significant decrease in the V_{OC} causes overall efficiency to decrease. In 1L-SiO_2, although the V_{OC} increases again, the P_{MAX} remains low, which indicates that its efficiency is still lower. This phenomenon indicates that optimal efficiency occurs in layers thickness that is not too thin or too thick. A layer that is too thin cannot provide sufficient optical effects to increase light absorption, while a layer that is too thick increases resistance and recombination of carriers, thereby reducing the number of electrons that contribute to electric current. Therefore, the selection of additional layers thickness such as SiO_2 is very crucial in increasing the efficiency of TiO_2-based solar cells. The efficiency of solar cells in this study is indeed lower than DSSC -based synthetic dyes such as N719 (~ 7%). However, this value is still in the range of previous reports for natural dyes (0.1% –0.7%) [29]. It is necessary to optimize further on the structure of the electrode and the dyeing condition

3.3 SiO_2 Layer Variation on Resistance and Capacitance of Solar Cells

Figure 5 shows the complex impedance curve for TiO_2, 1L-SiO_2, and 2L-SiO_2 material variations. This curve analysis allows the evaluation of the effects of variations in a mixture of dyes with SiO_2 on resistance and capacitance in solar cells.

Figure 8 shows that the variation of the TiO_2 material produces a larger impedance arches, which indicates a high charge transfer resistance (RCT) of 12,486 Ω · cm², which has an impact on the efficiency of the load transfer that is less than optimal [29]. The first capacitance (C1) of 5.86 F shows a good charge storage capacity, although it can still be optimized, while the series resistance (RS) recorded at 25.10 Ω·cm² is still within an acceptable limit for the photovoltaic application, although not ideal. Overall, although TiO_2 is able to maintain a good voltage, the high charge resistance of charge inhibits the efficiency of the electron hole transfer, which ultimately has a negative impact on the overall performance of solar cells.

Conversely, the 1L-SiO_2 material shows a smaller impedance curve compared to TiO_2, which indicates a decrease in charge transfer resistance with a lower RCT value, which However, the first capacitance is reduced to 1.07 F, indicating a lower charge storage capacity compared to TiO_2, which has the potential to affect the stability of

performance in the long run. A significant increase in the series resistance to 96.91 Ω·cm² can inhibit the flow of charge and reduce the efficiency of output power. Therefore, although the efficiency of charge transfer increases with a decrease in RCT, increased series resistance is the main obstacle in improving the overall performance of solar cells [30].

The 1L-SiO_2 material shows a different pattern, where the impedance arches are smaller at first, but increase sharply in high resistance. The RCT value increases dramatically to 90,388 Ω·cm², much higher than TiO_2 and 1L-SiO_2, which shows an increase in charge transfer resistance that can increase the level of charge recombination. However, capacitance increased to 3.68 F, which allows this material to store more charges than 1L-SiO_2, although it is still lower than TiO_2. The advantage of 1L-SiO_2 lies in a significant decrease in the series resistance recorded at 16.78 Ω·cm², much lower than TiO_2 and 1L-SiO_2, which shows that the charge transfer in electric paths is more efficient. However, the high RCT value results in the transfer of electron holes that are less efficient and increase the possibility of charge recombination, which can inhibit the efficiency of solar cells. Thus, although 1L-SiO_2 shows the advantage in terms of lower series resistance, a significant increase in charge transfer resistance can inhibit the efficiency of charge transfer and reduce the overall performance of the device.

In the TiO_2 material, the curvature of the large impedance in the nyquist curve shows a high RCT, with a value of 12,486 Ω·cm². This resistance is a major factor in inhibition of charge movements, which leads to low charge transfer efficiency, so that it has a negative impact on the overall performance of the photovoltaic device. Although this material can maintain the voltage properly, limitations in the transfer of charge reduce their efficiency, especially for applications that require high speed in electron transfer. In terms of capacitance, the C1 value of 5.86 F shows a fairly good charge storage capacity, which contributes to the stability of the system, although there is still potential for further optimization. On the other hand, series resistance (RS) of 25.10 Ω·CM² is within reasonable limits, but this value is not low enough to support maximum charge transfer efficiency.

When one layer of SiO_2 (1L-SiO_2) is added, the RCT value decreases to 10.501 Ω·cm², which shows an increase in the efficiency of charge transfer, because electrons can move more easily compared to pure TiO_2. However, the decrease in RCT is accompanied by a decrease in the first capacitance (C1), which decreased to 1.07 F. This shows that although the efficiency of the charge transfer increases, the ability of the material in storing charges decreases. As a result, although the load transfer becomes more efficient, the capacity of charge storage can be a long -term challenge. In addition, series resistance increases significantly to 96.91 Ω·cm², which can limit the flow of charge and reduce the efficiency of the device output power. Therefore, despite the decline in RCT in 1L-SiO_2 increases the efficiency of charge transfer, increased series resistance and decreased capacitance must be taken into account to ensure optimal performance [31].

When the material is further modified with the addition of two layers of SiO_2 (2L-SiO_2), the impedance pattern becomes more complex, with a nyquist curve that was initially smaller but showed a sharp increase in higher resistance values. The most significant increase is in RCT which reaches 90,388 Ω·cm², which shows that the charge resistance is greater. This increases the likelihood of recombination of charges, which can reduce the efficiency of overall energy conversion. However, in contrast to 1L-SiO_2, capacitance at 1L-SiO_2 increased to 3.68 F, which shows that the charge capacity is better than 1L-SiO_2, although it is still lower than pure TiO_2. The main advantage of the 2L-SiO_2 lies in a significant decrease in the series resistance which now reaches 16.78 Ω·cm², which shows a more efficient charge transfer pathway, so as to increase the output power of the device [32]. Although the series resistance decreases and capacitance increases, the high RCT value remains the main resistance because it can increase the recombination.

4. CONCLUSIONS

The thickness of the SiO_2 layer has a significant effect on the performance of TiO_2-based solar cells. The addition of one layer of SiO_2 (1L-SiO_2) has

succeeded in increasing the J_{SC} and V_{OC} compared to pure TiO_2, which shows an increase in the efficiency of charge transfer. Meanwhile, the addition of two layers of SiO_2 (2L-SiO_2) gave the best performance, reflected in the highest J_{SC} value of 0.37 MA/cm² and optimal charge transfer efficiency. However, the addition of three layers of SiO_2 (3L-SiO_2) actually resulted in a decrease in overall performance, caused by an increase in charge transfer resistance and recombination of electron holes, which reduces the efficiency of the device. Based on parameter I-V analysis, layer 1L-SiO_2 shows the highest efficiency of 0.0403% and the best maximum power. The addition of two layers of SiO_2 (2L-SiO_2) produces a higher J_{SC} value than 1L-SiO_2, but the decline in the V_{OC} value causes the overall efficiency to be lower. In layer three (3L-SiO_2), although the V_{OC} increases again, efficiency remains decreased due to an increase in internal resistance. The FF shows stability throughout the composition of the SiO_2 layer, which indicates that internal resistance is not significantly affected by the variation of the thickness of the SiO_2 layer. The results of complex impedance analysis indicate that pure TiO_2 has the highest RCT of 12,486 Ω·cm², which inhibits the efficiency of cargo transportation in material. The addition of 1L-SiO_2 reduces the RCT value to 10.501 Ω·cm², which increases the efficiency of charge transfer, although the series resistance (RS) increases. At 1L-SiO_2, although the hospital value decreased to 16.78 Ω·cm², the RCT value increased dramatically to 90.388 Ω·cm², which contributed to an increase in the recombination of electron holes and reduced the efficiency of energy conversion. The addition of SiO_2 layers increases the efficiency of charge transfer to reach the optimal point at 1L-SiO_2, but excessive layer thickness can reduce efficiency due to increased internal resistance and greater charge recombination.

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Conflicts of Interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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