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Simulation of Dye-Sensitized Solar Cells (DSSC) Performance for Various Local Natural Dye Photosensitizers

Simulation of Dye-Sensitized Solar Cells (DSSC) Performance for Various Local Natural Dye Photosensitizers

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Abstract. Dye is a photosensitizer which is one of the key elements in developing high performance dye-sensitized solar cells (DSSC). However, the use of natural dyes as photosensitizers in DSSC, until now still produces much lower device efficiency compared to those from complex metal dyes or organic synthesis dyes. Therefore, research is still needed to find the efficiency of DSSC using the best variety of natural dyes. In this research, the characteristics of the dye-sensitized solar cell (DSSC) has been simulated using MATLAB based on TiO_2 by modifying the internal parameters ($\boldsymbol{\Phi}, \boldsymbol{\tau}, \boldsymbol{\alpha}, \mathbf{m}, \mathbf{T}$), external, and previous DSSC research data. The simulation has been performed to determine the performance of natural dye made locally (coffee, turmeric, cocktail (coffee and turmeric), phyllanthus reticulatus poir, piper crocatum, and melaleuca leucadendra), in terms of the change due to the intensity of solar radiation and temperature by displaying the I-V and P-V curve characteristics. The simulation has produced the highest DSSC performance by using natural dye from melaleuca leucadendra with a maximum voltage, current density, and power of 0.7882 Volt, 0.0032 A/cm^2, and 0.0015 W, respectively, using a cell area of 1.5 cm x 1.5 cm. The DSSC performance also produced a higher performance when measured at 12.00 o'clock in the afternoon with a maximum power of 0.0013 W. Therefore, some of these natural dyes have indicated the high potential of becoming low-cost photosensitizer, which is available abundantly and environmentally friendly.

Keywords: Natural local dye, solar radiation, DSSC working temperature, I-V, P-V

1. Introduction

Photovoltaic devices have been dominated by silicon-based solid stated junction devices [1,2]. The first successfully developed solar cell technology was capable of producing solar cells with high efficiency. However, the big problem faced was the expensive cost of the development of crystalline silicon and the complexity of the fabrication process, making solar cell panels produced become less effective as an alternative energy. As time went on, the dominant use of these devices began to change with the discovery of the third-generation solar cells. These solar cells have been considered capable of providing ~~a~~ technically and economically reliable alternative concept as a substitute for the first generation solar cells [3]. This device was being referred to as a dye-sensitized solar cell (DSSC).

Dye-sensitized solar cells are photoelectrochemical devices that convert visible light into electrical energy based on semiconductor sensitization with band gap energy [4]. Dye-sensitized solar cells (DSSC) consist of semiconductor materials, dye molecules, electrolytes containing iodide/triiodide (I^-/I^{3-}), and counter electrodes that act as catalysts for electron regeneration, and TiO_2 as photoanode [3]. Dye is a photosensitizer which is the key to developing high-performance-sensitized solar cells [5-8].

In the DSSC application, this pigment was divided into three groups, namely organic natural dye, organic dye synthesis, and metal dye complex [9]. The dye metal complex is a transition metal component of organic compounds that has 13% efficiency characteristics, is not environmentally friendly, hazardous waste, expensive, multi-stage synthesis, donors (inorganic), and acceptors (organic). Meanwhile, the organic dye materials are synthetic organic compounds that have 9.5% efficiency characteristics, are less environmentally friendly, are relatively cheaper, and develop donor junction acceptors. On the other hand, the natural dye is an organic compound made from nature which has efficiency characteristics of 0.70%, is environmentally friendly, is abundant in nature, and extraction (isolation of compounds from secondary metabolites) [10,11].

In previous research, Syafinar [7] has taken a measurement of the absorbance coefficient from various natural dyes using ultrasonic extraction method by setting the parameter at temperature of 30 °C during 30 minutes in the frequency of 37 Hz. The result showed the combination of purple cabbage and blueberry as the cocktail dye had a good potential for development DSSC in the future. Tayyan [12] has shown the simulation with an accurate approach for calculating internal parameters ($\mathbf{\Phi}, \boldsymbol{\tau}, \boldsymbol{\alpha}, \mathbf{m}, \mathbf{T}$) from dye-sensitized solar cells (DSSC). This approach is based on differential electron diffusion model and the value of short circuit current density (J_{sc}) and open circuit voltage (V_{oc}). The analysis of these parameters is to study the effect temperature and thickness on photoanode. Cahya et al. [10] have done an experimental research. His research focused on anthocyanin, carotenoid, and chlorophyll natural dye with immersion method during two weeks on condition neutral and acid in dark room. The result had high-efficiency DSSC 0.76% by using a combination of anthocyanin and chlorophyll photosensitizer on the acid environment.

All this time, several works of research focused on finding the best natural dye to be used on DSSC. However, it needs a long time and high cost if we use experiment method. Besides,still, the research simulation has not yet found the best natural dye. Therefore,, this research investigated the problem of DSSC efficiency with a variety of natural dyes compared to other types of dye. This study was to find a natural dye that has high-efficiency for DSSC applications. Thus, it has less time efficiency for direct experiments. Therefore, a simulation was required before DSSC fabrication was started. This simulation can be used as a reference for further experiments.

2. Methods

This simulation was performed to obtain the performance of DSSC by using various natural dyes, to determine the effect of work temperature, and to determine the effect of solar light intensity in Indonesia at 08.00 to 17.00 on DSSC performance. The results of the research were some graphs of the relationship between current density and voltage (J-V), and the maximum power relations vs. voltage (P-V) produced by DSSC. The I-V and P-V curves were obtained through simulation. The simulation activity was carried out on the characteristics of natural dye by initially collecting parameters to material's model follows flowchart in Figure 1. The parameters input are listed in Table 1.

Table 1. Input Parameters

Parameters	Value	Information	References
k	1.381×10^{-23} J/K	Boltzmann constant	
q	1.602×10^{-19} C	Electron charge	
L	2.2361×10^{-3} cm	Length of electron diffusion	[12]
d	5×10^{-4} cm	Length of TiO_2	
α	Coffee (2.41), Tumeric (2.26), Phylantus Reticulatus Poir (3.46), Piper Crocatum (3.82), Melaleuca Leucandendra (4.47), cocktail dye (2.41)	Absorption coefficient	[4] [13]
m	4.5	Ideal factor	[14] ; [15] ; [16]
D	2.3×10^{-5} cm^2/s	Diffusion coefficient	[12]
n_0	10^{16}electron/cm^2	Electron concentration	[14] ; [15]
t	0.01 s	Lifetime	[14] ; [15]
ϕ	1×10^{17} cm^{-2}s^{-1}	Sunlight intensity	[14] ; [15] ; [17]
T	300 K	Temperature	[16]

The simulation activity was done with the input of DSSC equation in m-file. Before we did our simulation, we verified our m-file with Tayyan research [12]. This activity was to produce the validity of m-file. The equations related to the system model are as follows [12]:

$$J_{SC} = \frac{q\Phi L\alpha}{1-L^2\alpha^2}\left[-L\alpha + tanh\left(\frac{d}{L}\right) + \frac{L\alpha \exp(-da)}{cosh\left(\frac{d}{L}\right)}\right] \tag{1}$$

$$V_{OC} = \frac{kTm}{q} In\left[\frac{LJ_{SC}}{qDn_o tanh\left(\frac{d}{L}\right)} + 1\right] \tag{2}$$

$$J = J_{SC} - \frac{qDn_o}{L}\tanh\left(\frac{d}{L}\right)\left[exp\left(\frac{qV}{kTm}\right) - 1\right] \tag{3}$$

where J_{sc} is short-circuited current density, V_{oc} is open circuit voltage, J is current density, and V is voltage produced by DSSC.

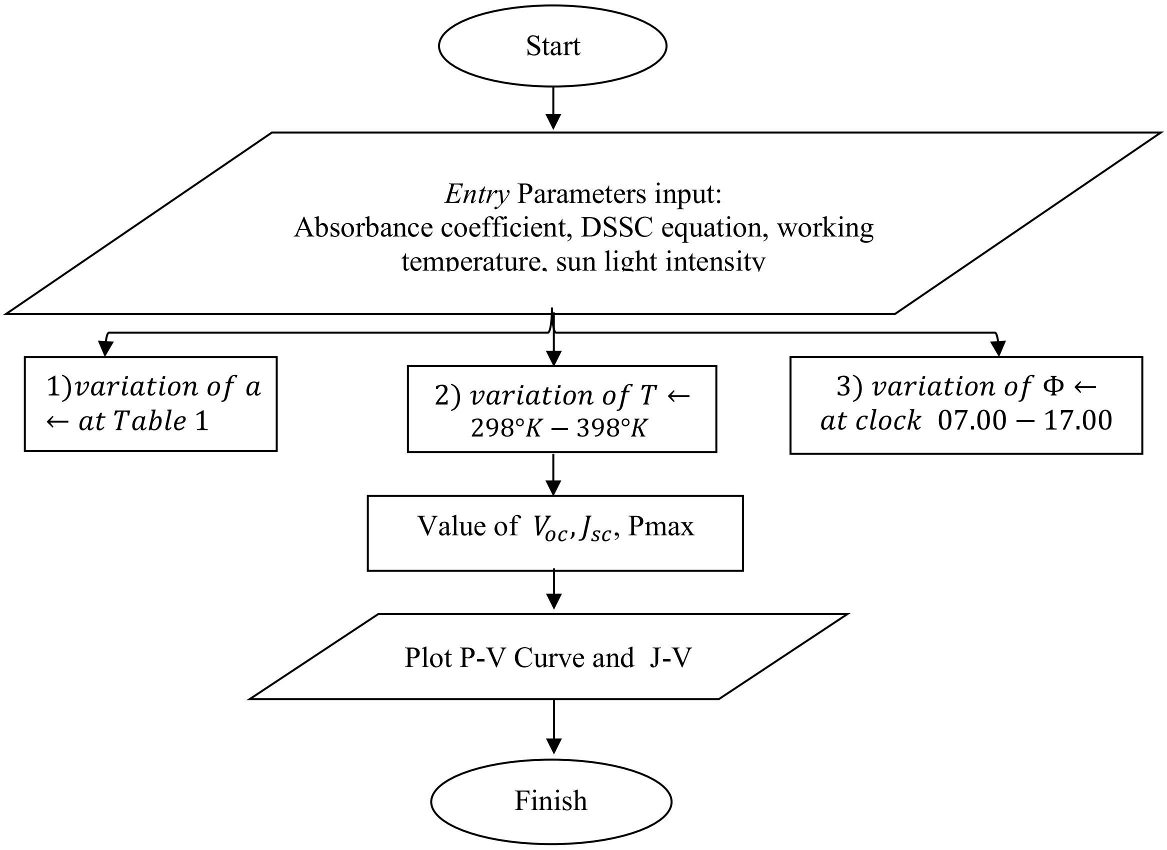

Figure 1. Flowchart of the Simulation Process

3. Results and Discussion

The gap between the conduction band and the valence band is called bandgap energy. This bandgap energy is used to analyze the performance of DSSC related to solar energy or wavelength of sunlight absorbed by the natural dye in DSSC. Based on the references on [4,13] we get the value of the wavelength of sunlight absorbed by the natural dye. Then, the calculation of energy absorbed by natural dye used Equation 5. From the calculation results, the relationship between wavelength and photon energy absorbed by the natural dye is presented in Table 2.

$$E = \frac{h.c}{\lambda} \tag{5}$$

Table 2. Wavelength and Natural Dye's Photon Energy

Variation of Dye	Wavelength (nm)	Photon Energy (eV)
Phyllanthus Reticulatus Poir	350	3.55
Piper Crocatum	410	3.03
Coffee	450	2.76
Tumeric	480	2.58
Melaleuca Leucadendra	520	2.39
Cocktail (Coffee+ turmeric)	450	2.76

Based on Table 2, it can be concluded that the larger the wavelength of the sunlight absorbed by the natural dye, the smaller the absorbed energy. [4]. In another word, a natural dye that absorbs the large wavelengths has small bandgap energy. This is suitable with the equation (5) which states that the wavelength is inversely proportional to the photon's energy. The lowest bandgap energy of Melaleuca Leucadendra which was equal to 2.39 eV, was very suitable with the bandgap energy of TiO2 semiconductors used as a photoelectrode DSSC in this research. The larger bandgap between the dye energy gap and the large bandgap TiO_2 energy helps electrons to move rapidly from the valence band to the conduction band and only requires less energy for electron recombination and increases DSSC efficiency [4].

The first simulation at this research was examining the performance of DSSC by using various natural dyes locally made. The natural dye candidates were made of local ingredients such as coffee, turmeric, cocktail (coffee and turmeric), phyllanthus reticulatus poir, piper crocatum, and melaleuca leucadendra. All parameters of input are listed in Tabel 1. From the simulation's results with the use of equation (1), (2) and equation (3), we got the performance of DSSC by using some natural dye candidates that obtained the maximum voltage, current density, and power presented in Table 3.

Table 3. DSSC Performance Based on Various Local Natural Dye

Variation of Dyes	**Absorbance Coefficient**	V_{oc} **(Volt)**	J_{sc} **mA/cm²**	P_{max}
Coffee (b)	2.41 [4]	0.7220	0.0018	7.6×10^{-4}
Tumeric (a)	2.26 [4]	0.7150	0.0017	7.1×10^{-4}
Cocktail (coffee + tumeric) (c)	2.41 [4]	0.7220	0.0018	7.6×10^{-4}
Phyllanthus Reticulatus Poir (d)	3.46 [13]	0.7613	0.0025	0.0012
Piper Crocatum (e)	3.82 [13]	0.7710	0.0027	0.0013
Melaleuca Leucadendra (f)	4.47 [13]	0.7882	0.0032	0.0015

From Tabel 3, we can see that melaleuca leucadendra (f) has high V_{oc}, J_{sc}, and power than the other natural dyed. It causes the absorbance coefficient of melaleuca leucadendra (f) higher than the absorbance coefficient of the other natural dyes. The absorbance coefficient of natural dye is how much of a dye's ability to absorb the sunlight. The J-V and P-V curves are displayed in Figure 2 and Figure 3.

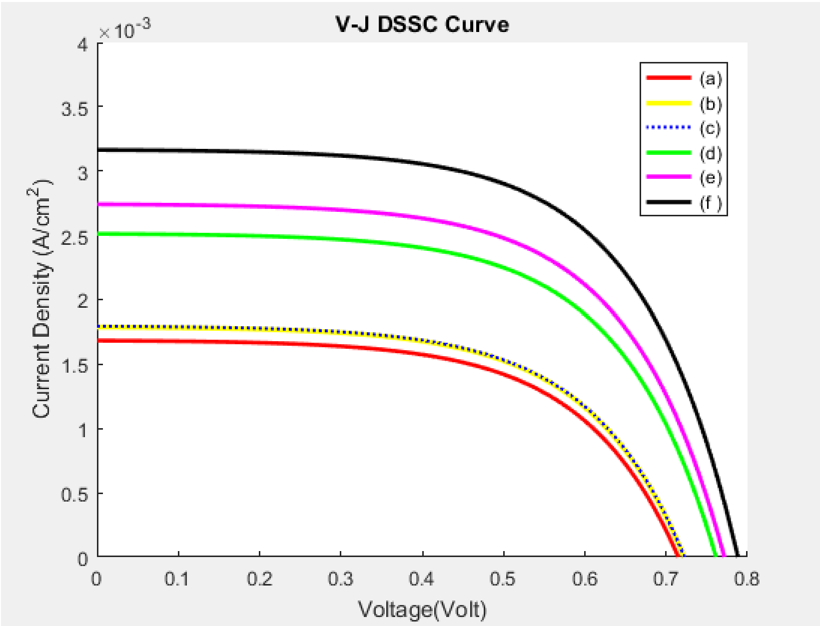

Figure 2. J-V Curve on Various Local Natural Dyes, (a) Tumeric, (b) Coffee, (c) Cocktail Dye (Coffee + Tumeric), (d) Phyllanthus Reticulatus Poir, (e) Piper Crocatum, (f) Melaleuca Leucadendra

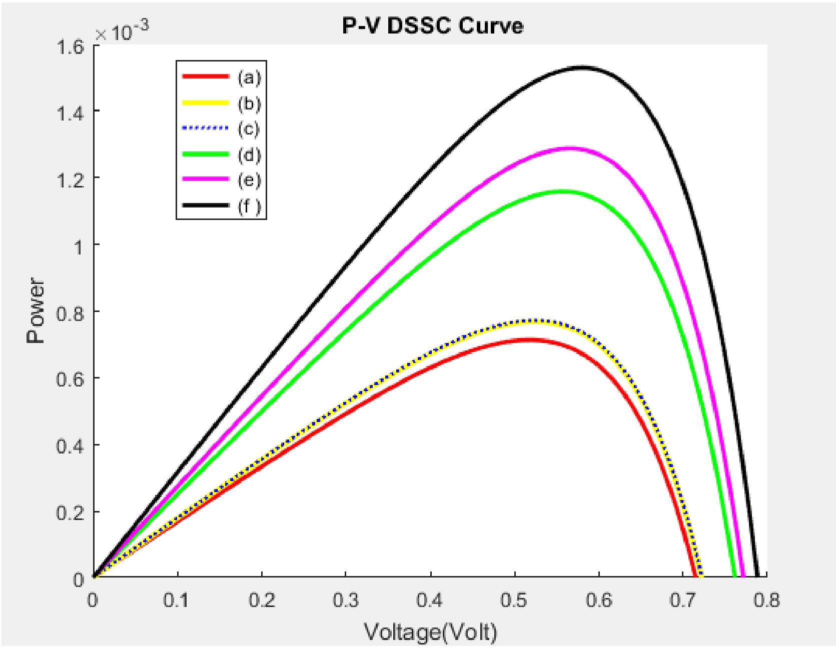

Figure 3. P-V Curve on Various Local Natural Dyes, (a) Tumeric, (b) Coffee, (c) Cocktail Dye (Coffee + Tumeric), (d) Phyllanthus Reticulatus Poir, (e) Piper Crocatum, (f) Melaleuca Leucadendra.

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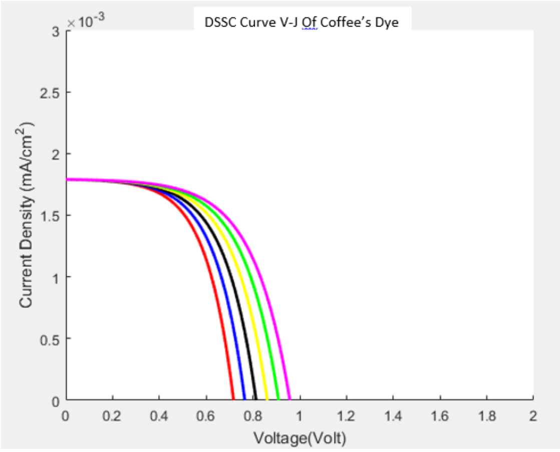

Figure 4. The Effect of Work Temperature Variation Based on Coffee

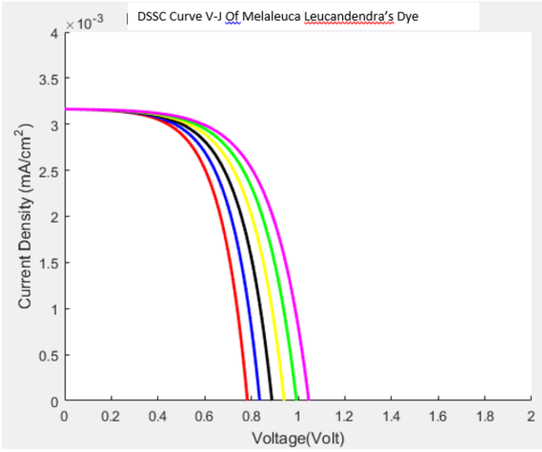

Figure 7. The Effect of Work Temperature Variation Based on Melaleuca Leucadendra

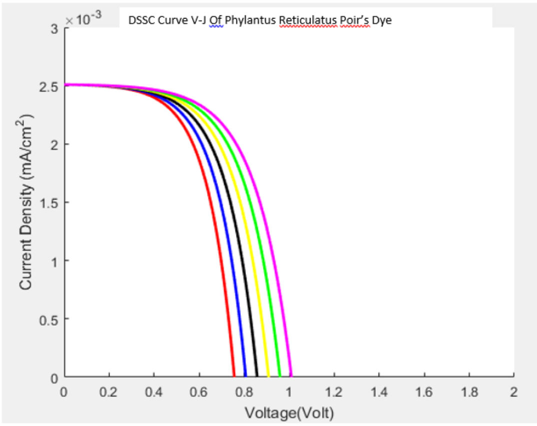

Figure 5. The Effect of Work Temperature Variation Based on Phyllantus Reticulatus

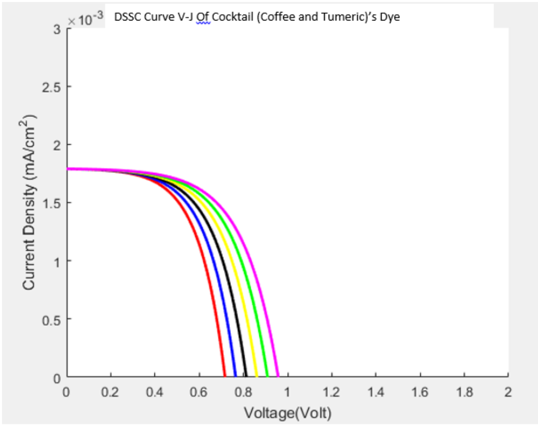

Figure 8. The Effect of Work Temperature Variation Based on Cocktail Dye

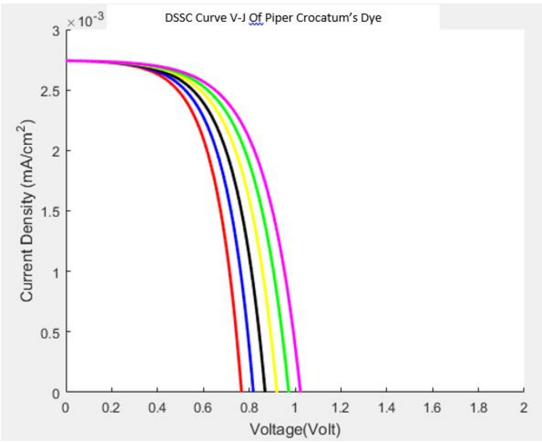

Figure 6. The Effect of Work Temperature Variation Based on Piper Crocatum

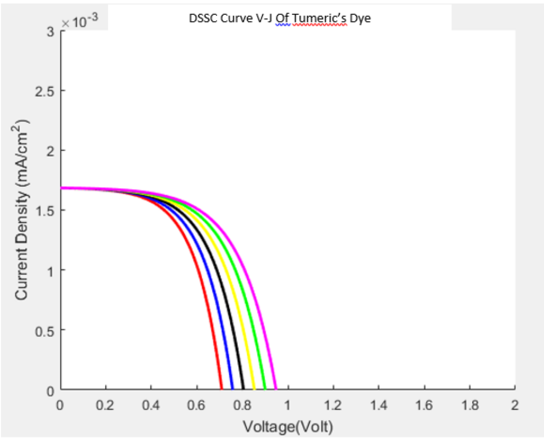

Figure 9. The Effect of Work Temperature Variation Based on Tumeric Dye

Figure 2 and Figure 3 show that melaleuca leucadendra is one of natural dyes that have the best performance of DSSC. The greatest absorbance coefficient value of melaleuca leucadendra, the highest voltage, and electric current will be produced. This is because when the absorbance value is large, the natural dye will absorb the light with a large wavelength. If the wavelength absorbed becomes larger, then the energy of the photon used to excite the electron to the conduction band requires less energy. One way to improve the performance of DSSC is to mix some natural dyes into one so that it can increase the absorbance coefficient of the dye [4,10]. The results of this study were by equations (1), (2) and (3) which stated that the absorbance coefficient of the dye was directly proportional to the magnitude of the voltage and electric current produced. This simulation is suitable with Syafinar [7] finding that high absorbance coefficient of the dye can be one of the alternatives at the development of DSSC.

The simulation results performance of DSSC at second activity research used equation (1), (2), and equation (3) for the various local natural dyes to indicate that temperature changes affect the magnitude of the voltage (Voc) and maximal power. The range of temperature used in this research was $298\ K$ until $398\ K$. Based on the simulation results, the effect of work temperature on the performance of various candidates for natural dye has been obtained.

The results of the second activity simulation are shown in Figure 4,5, 6, 7, 8, and 9. From that figure, we can see that the working temperature of DSSC affected the amount of voltage produced. It was because the hightemperature of the resistant of the cell was low. Therefore, it caused voltage high but the current density constant. This phenomenon is suitable with equation (3) that voltage was perpendicular with temperature. If the temperature was high the voltage was also high. This phenomenon is also suitable with equation (2); the current density is undependent on temperature. This research is in line with Tayyan [12] reporting that the change of temperature makes the change of the performance of DSSC.

The change of the sunlight intensity also gives effect to the performance of DSSC. To find the impact, we used equation (2) and equation (3) by making all parameters in Table.1 except the value of the sunlight intensity. The range of the sunlight intensity would be simulated at clock 8 am until 5 pm. For natural dye, we used melaleuca leucadendra that has high absorbance coefficient. The simulation results of variations in the intensity changes produced voltage, current, and power as presented in Table 4.

Table 4. The Effect of Light Intensity Variations at Performance of DSSC on Melaleuca Leucadendra

Clock	Sunlight Intensity W/m^2 [17]	V_{oc} (Volt)	J_{sc} A/cm^2	P_{max}
8.00	274	0.3007	1.96×10^{-5}	2.47×10^{-6}
9.00	486.3	0.3635	3.481×10^{-5}	5.57×10^{-6}
10.00	668.8	0.3994	4.796×10^{-5}	8.9×10^{-6}
11.00	800	0.4194	5.27×10^{-5}	1.152×10^{-5}
12.00	867.8	0.4287	6.2128×10^{-5}	1.28×10^{-5}
13.00	866.4	0.4285	6.202×10^{-5}	1.2×10^{-5}
14.00	797.3	0.4191	5.7×10^{-5}	1.14×10^{-5}
15.00	664	0.3984	4.75×10^{-5}	8.873×10^{-6}
16.00	479.9	0.3619	3.43×10^{-5}	5.59×10^{-6}
17.00	267	0.2979	1.91×10^{-5}	2.38×10^{-6}

From Table 4, it can be seen that the highest sunlight intensity occurred at 12.00 am. The high intensity produced high voltage, current density, and power. It was further observed that after 12.00 am, the performance of DSSC was decreasing due to the decrease in the sunlight intensity. In Figure 10 and Figure 11, we can see the V-J and P-V curves. Several researchers have studied a similar way to simulate several parameters on the performance of DSSC. One may give us several internal parameters on the DSSC based on the samples using Shockley's equation as reported previously [18].

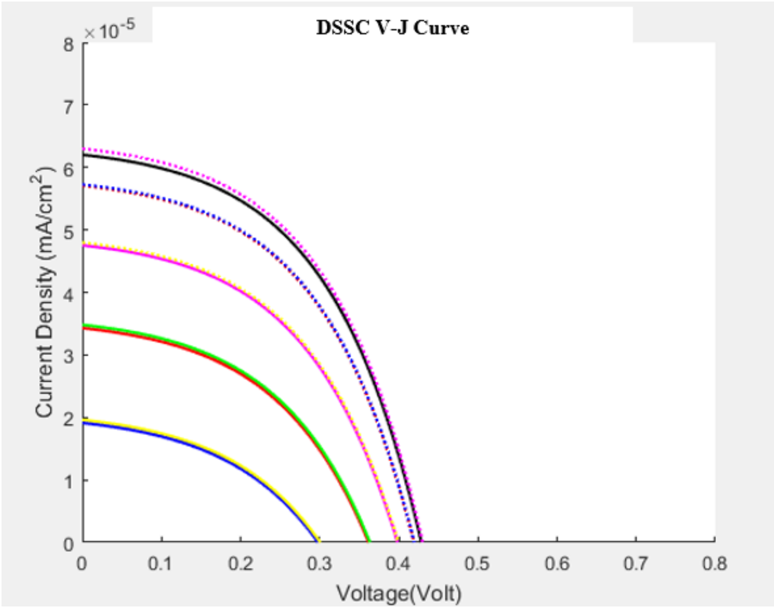

Figure 10. V-J Curve of the Intensity Light Radiation at DSSC Performance Melaleuca Leucadendra.

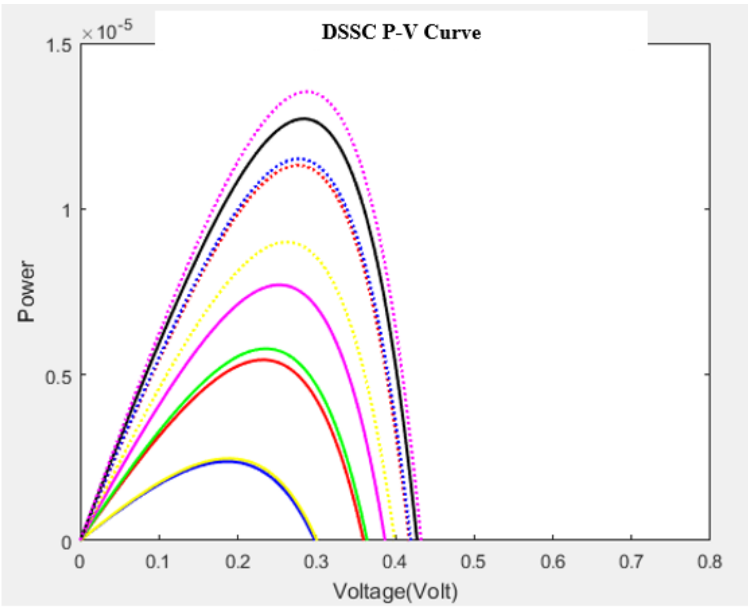

Figure 11. P-V Curve of the Intensity Light Radiation at DSSC Performance Melaleuca Leucadendra

4. Conclusion
We concluded that one of several factors which influence the performance of DSSC is the type of natural dye locally made. Every natural dye made from local has a different absorbance coefficient value. From the simulation's result, it is known that the value of the coefficient absorbance's dye affected the output current, voltage, and power produced. Natural dye material which had the largest absorbance coefficient is eucalyptus flower (Melaleuca Leucadendra) that produced a voltage of 0.7882 volts the electric current density was 0.0032 A/cm^2, and the maximum power was 0.0015 W. Another factor that influences DSSC performance is the change in the working temperature of DSSC. The simulation results showed that the greater the working temperature of the DSSC the greater the voltage generated. This could be seen at a working temperature of 398 K in the melaleuca leucadendra dye that produced the highest voltage. Meanwhile, the other factors that influence DSSC performance are the large changes in the intensity of sunlight radiation. The simulation results showed that the greater the intensity of solar radiation, the resulted current and the voltage increased as well. Besides, It can be seen that at 12.00 WIB, the greatest light intensity (867.8 W/m^2) was produced, resulted in a voltage of 0.4285 V in the dye of eucalyptus flowers (Melaleuca leucadendra).

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