

NOVEL PHOTSENSITIZER FROM RED LOTUS FLOWER EXTRACT FOR NATURAL DYE-SENSITIZED SOLAR CELLS

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Abstract

Natural dye-sensitized solar cells (NDSSCs) convert solar radiation into electrical energy using sensitization of dyes which is obtained from a natural source. In this study, a novel photosensitizer was extracted from the petal of Red Lotus flowers (*Nymphaea pubescens* Willd.) using methanol as a solvent. Various NDSSCs using an extracted dye as a photosensitizer were fabricated and the efficiency of cells was investigated. The petal dye showed a high absorption band in the visible region at 540 nm indicating a good light absorption performance. The PCE of NDSSCs based on the petal dye in methanol was 0.208 - 0.281%. The filling factor (FF), photocurrent density (J_{sc}), and photovoltage (V_{oc}) of NDSSCs were in the range of 0.621 - 0.668, 0.615 - 0.855 mA/cm², and 0.506 - 0.523 V, respectively.

Keywords: Natural Dye-Sensitized Solar Cells; *Nymphaea pubescens* Willd; Photosensitizer; Red Lotus

Introduction

Solar energy is a clean energy source in abundance, which is the most important fundamental renewable energy source by converting solar radiations directly into electrical energy using photovoltaic cells also known as solar cells. In the next generation of solar cells, dye-sensitized solar cells (DSSCs) are the photovoltaic devices that the dye which converts light into electricity is a sensitizer and it is an important key in the light absorption and transformation process, which was the first concept proposed by Gratzel and his co-workers

in the year 1991 (O'Regan and Grätzel, 1991). Usually, the plants are composed of pigments that have been employed as sensitizers in DSSCs such as *Callindra haematophata*, *Luffa cylindra* L., *Amaranthus caudatus* flower, Rose bengal, Thornless Prickly Pear Cactus (*Opuntia ficus-indica*), and *Aloe barbadensis miller* (Genta *et al.*, 2017). Moreover, natural pigments extracted such as chlorophyll and anthocyanins have been widely investigated as sensitizers for DSSCs (Hernández-Martínez *et al.*, 2012). The device's efficiency based on chlorophyll and anthocyanins

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is 0.538% and 0.06%, respectively (Syafinar *et al.*, 2015; Ahliha *et al.*, 2018). The natural dye-sensitized solar cells (NDSSCs) are attractive to the researcher despite the efficiency of the devices is still by a factor of 3-4 lower than synthetic dyes because the natural dyes are normally non-poisonous, can be disposed of easily, and should be cheaper and more environmentally friendly (Hug *et al.*, 2014).

Nymphaea pubescens Willd is a member of the Nymphaeaceae family, which flower petals of the *Nymphaea* genus contain a lot of flavonoids such as anthocyanins, flavonols, and flavones, therefore, lotus flower petals with anthocyanin have also shown red, pink, purple, and blue (Zhu *et al.*, 2012; Selvakumari *et al.*, 2016). Lotus is a floating aquatic rhizomatous plant found in freshwater habitats throughout temperate and tropical Asia such as Vietnam, Indonesia, Malaysia, Cambodia, Laos, Myanmar, Philippines, India, Bangladesh, Pakistan, Sri Lanka, Yunnan, Taiwan, including Thailand (Arguelles, 2019). Udon Thani is a province in the northeast of Thailand, there is a beautiful lake named the Red Lotus Sea or Talay Bua Daeng because it is full of millions of pink lotus flowers. The constituents of *Nymphaea lotus* Linn have been reported, there are amino acids, alkanolic acids, and dipeptide (Sowemimo *et al.*, 2007). Besides that, the constituents of Genus *Nymphaea* have been also reported, the results showed the presence of flavonoids, flavonone, saponins, alkaloids, and tannins (Selvakumari *et al.*, 2016). From our previous work, the phytochemical constituents of Red Lotus flowers were studied, and the result revealed flavonoids, phenolics, and tannins in the petals. Furthermore, they showed antioxidant activity due to the presence of flavonoids and phenolics (Prajudtasri and Kitisiworaphan, 2014).

The natural colorants extracted from some fruits, plants, flowers, and leaves can be used as a sensitizer for DSSC due to their optical ability. These sensitizers show strong light absorption in a wide range of visible regions which is the photophysical property of the photosensitizer (Sharma *et al.*, 2018). From our preliminary result, the Red Lotus dye showed absorption bands in the range of 300 - 600 nm, thus we choose the Red Lotus flower as the plant source for natural sensitizers. Additionally, their key benefits are a simple extraction procedure, low cost, wide availability, and an environmentally friendly nature. Herein, we report the extraction of a new photosensitizer from the Red Lotus flower for NDSSC as well as its physical and photophysical properties. The investigation of the device performance using this extractant as a sensitizer is also reported.

Experimental Section

Materials and measurements

Transparent TiO₂ paste (DSL 18NR-T, Dye Sol Ltd.), scattering TiO₂ paste (WER2-O, Dye Sol Ltd.), fluorine-doped SnO₂ (FTO) conducting glass (1.3 × 2 cm², 8 Ω/sq, TEC8, Pilkington), dihexachloroplatinic (IV) acid, LiI (Alfa aesar), iodine (I₂), tetrapropylammonium iodide (TPAI), 4-*tert*-butylpyridine (TBP), acetonitrile, valeronitrile, acetyl lactone, 2-methoxyethanol were used as received. Methanol (Commercial grade) was freshly distilled and used. Double distilled water was used for solution preparation and washing purposes. FT-IR spectrum has been recorded for identifying the functional groups using Perkin Elmer Spectrum Two FT-IR Spectrometer. The UV-visible spectra and reflection spectra were recorded using a Shimadzu UV-2600 spectrophotometer with the integrating spheres. XRD patterns were collected using a Bruker D8 ADVANCE diffractometer at 40 kV, 40 mA for Cu Kα, (λ = 1.5418 Å) from two theta of 10 to 80° with a step size of 0.02° and scanning rate of 0.2° min⁻¹. Scanning electron microscopy (SEM) image was collected by the JEOL microscope, JSM-7610F model to analyze the surface morphology of TiO₂ film samples. The photovoltaic performance of the DSSCs was evaluated under simulated sunlight (AM 1.5G, 100 mWcm⁻²) using the Keithley model 2400 digital source meter.

Extraction of natural dye sensitizer

Red lotus was collected from Kumphawapi district, Udon Thani province which is in the northeast of Thailand. Firstly, the fresh flowers were separated, and other parts were removed. The petals were air-dried and then ground to give small sizes. Next step, these small sizes of dried petals were extracted with methanol using the ultrasonic extraction method for 1 hour three times. The dye solution was separated from its precipitate by the paper filter and was dried by a rotary vacuum evaporator to afford the dye powder as the purple solid.

Preparation of the dye for photo-physical study

Preparation of the dye in various solvents

The extracted dye powder was dissolved in water, methanol, ethanol, and acetone with a concentration of 0.1%w/v. The photophysical properties of these dye solutions were studied by using a UV-Vis spectrophotometer.

Preparation of the dye adsorbed on TiO₂ film

Transparent TiO₂ paste was screen-printed on a microscope slide glass with cell geometry of $1.0 \times 2.5 \text{ cm}^2$ and then heated at 500°C for 30 min to obtain TiO₂ film coated on a microscope slide glass. The thickness of the TiO₂ film was controlled by the selection of screen mesh size and repetition of printing. In the next step, the warm TiO₂ film (50°C) was immersed into various dye solutions (water, methanol, ethanol, acetone, and hexane as solvent) with different concentrations (0.1, 0.5, and 1.0%w/v) and allowed in the dark at room temperature for 24 h to stain the dye onto the TiO₂ film. Finally, the photophysical property of these dye-adsorbed TiO₂ films was investigated by a UV-Vis spectrophotometer.

DSSC fabrication and measurement

Preparation of dye adsorbed TiO₂ working electrode

A fluorine-doped SnO₂ (FTO) conducting glass was cleaned with dish detergent, then rinsed with DI water, and ethanol, and finally dried in an oven at 100°C. Next step, transparent TiO₂ paste was screen-printed on the cleaned FTO glass with cell geometry of $0.5 \times 0.5 \text{ cm}^2$ and then the obtained transparent TiO₂ film was dried in an oven at 120°C. The thickness of the TiO₂ film was controlled by the selection of screen mesh size and repetition of printing. After that, scattering TiO₂ paste was also screen-printed on the top of the transparent TiO₂ film with the same cell geometry and dried in an oven at 120°C and then finally heated at 500°C for 30 min to achieve the TiO₂ film working electrodes according to the method of N. Prachumrak, *et al.* (Prachumrak, *et al.*, 2017). The warm TiO₂ electrode (50°C) was immersed into various dye solutions with different concentrations, then allowed in the dark at room temperature for 24 h to stain the dye onto the TiO₂ surfaces to obtain the dye adsorbed TiO₂ photoanode.

Preparation of Pt counter electrode

The fluorine-doped tin oxide (FTO) coated glass ($1.3 \times 2 \text{ cm}^2$) was drilled at the right corner of the FTO glass to give a pinhole with a diameter of 0.1 mm and cleaned with dish detergent, then rinsed with DI water, ethanol, and finally dried in an oven at 100°C. Next step, 50 μL of 8 mM H₂PtCl₆ in a mixed solvent of acetyl lactone and 2-methoxyethanol was dropped on the FTO surface and heated at 450°C for 30 min and then cooled down to room temperature to give the Pt counter electrodes.

Device assembly

The dye adsorbed TiO₂ photoanode and Pt counter electrode were assembled into a sealed cell by heating a sealant film (Dye Sol film, 30 mm thickness) gasket as a spacer between the electrodes at 120°C. Finally, the electrolyte solution was filled through the pinhole of the Pt counter electrode by a vacuum backfilling method (Prachumrak *et al.*, 2017). The hole was capped by using hot melt sealing film (Dye Sol film, 30 mm thickness) and a thin glass cover to afford the DSSC devices with an active area of $0.5 \times 0.5 \text{ cm}^2$. The mixed solution of 0.03 M I₂, 0.05 M LiI, 0.6 M tetrapropylammonium iodide (TPAI), and 0.5 M 4-*tert*-butylpyridine (TBP) in a mixed solvent of acetonitrile and valeronitrile (85:15) was used as the electrolyte solution.

Device measurement

The current density-voltage (*J-V*) of the DSSC device was measured by using a Keithley 2400 source meter unit in a 4-terminal sense configuration. The simulating sunlight was provided by Newport sun simulator 96000 equipped with an AM 1.5G filter. To minimize the error of measurements, the irradiation intensity of 100 mW/cm² was approximated with a calibrated BS-520 Si photodiode (Bunkoukeiki Co., Ltd., Japan), which its spectral response was very similar to that of the DSSCs. The fill factor (FF) and the power conversion efficiency (PCE) were calculated from the *J-V* curves by using Equation. (1) and Equation. (2) as following (Hamadianian *et al.*, 2014):

$$FF = \frac{P_{\max}}{J_{\text{sc}} \times V_{\text{oc}}} \quad (1)$$

$$PCE = \frac{P_{\max}}{P_{\text{light}}} = \frac{FF \times J_{\text{sc}} \times V_{\text{oc}}}{P_{\text{light}}} \quad (2)$$

where $P_{\max}$ is the maximum power, J_{sc} is short-circuit current density, V_{oc} is open-circuit voltage, and P_{light} is the incident light power with an irradiation intensity of 100 mW/cm².

Results and Discussions

Extraction and function group elucidation

In this work, we have extracted and characterized the Red Lotus dye and studied its potential use as a sensitizer in DSSCs. There are many techniques to extract the dyes from plants, however, the yield not only depends on the extraction method but also on the solvent used for extraction. The solubility of dyes in a particular solvent depends on the chemical characteristics and polarities of that dyes. Polar solvents are frequently

used for recovering pigments from plants, and the most suitable solvents are water, ethanol, methanol, acetone, and ethyl acetate. The alcoholic solvent was found to be more efficient in the extraction of flavonoids and polyphenols, and the alcoholic extract shows a high flavonoid content (Do *et al.*, 2014). Our preliminary phytochemical screening

test of the Red Lotus petal revealed the presence of flavonoids in alcoholic extract but absence in the aqueous extract (Prajudasri and Kitisiworaphan, 2014). Besides that, the methanol solvent is easier to remove from the solution than the aqueous solvent, so from the above mentioned, we extracted the dye using methanol as the solvent. From the extraction, the dye was obtained as a purple solid with a yield of 18%. We determined the functional groups of the dye extracted by Fourier Transform Infrared (FT-IR) Analysis as shown in Figure 1. The FT-IR spectra of powder and film of titanium dioxide and dye adsorbed titanium dioxide film is also reported.

The FT-IR spectra of the Red Lotus dye (Figure 1a) show characteristics of flavonoids, which are widely used as a sensitizer of DSSCs. The vibration frequencies are $\nu_{\text{O-H}}$ at 3273 cm^{-1} , ν_{CH_2} , ν_{CH_3} at $2938, 2860\text{ cm}^{-1}$, δ_{CH_2} , δ_{CH_3} at $1451, 1348\text{ cm}^{-1}$, $\delta_{\text{C-C}}$ at 1712 cm^{-1} , $\delta_{\text{C=Cbenz}}$ at 1613 cm^{-1} , and $\nu_{\text{C=O}}$ at 1023 cm^{-1} (Heneczowski *et al.*, 2001). The powder and film of titanium dioxide (Figure 1b and c) show three vibrational modes, which are described as $\nu_{\text{O-H}}$ at above 3000 cm^{-1} , $\delta_{\text{O-H}}$ at 1635 cm^{-1} , and $\nu_{\text{Ti-O}}$ at 726 cm^{-1} (Chougala *et al.*, 2017). The dye adsorbed titanium dioxide film (Figure 1d) can observe the characteristic vibrational frequencies of both components, which indicates that the dye can be absorbed into the TiO_2 phase.

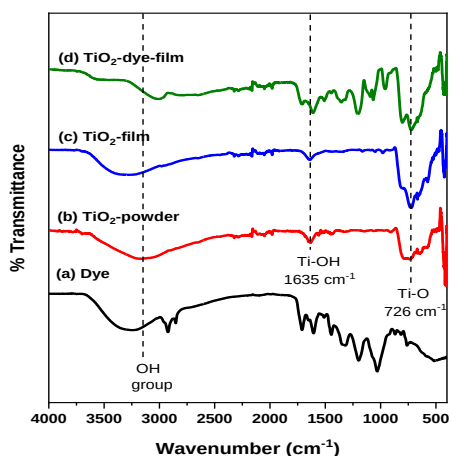


Figure 1. Shows FT-IR spectrum of (a) the dye, (b) titanium dioxide powder, (c) titanium dioxide film, and (d) dye adsorbed titanium dioxide film

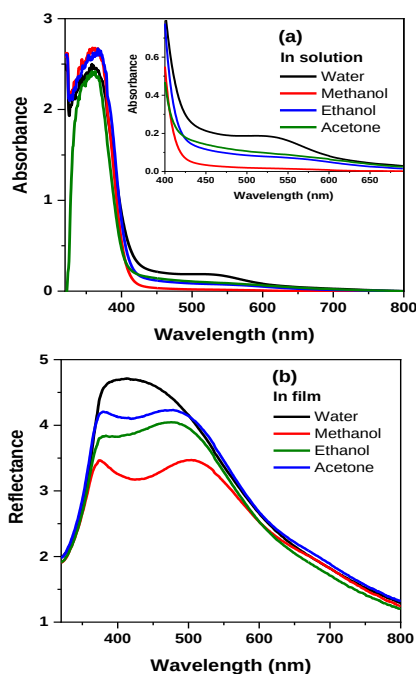


Figure 2. Shows Absorption spectra of (a) Red Lotus dye in a dilute solution with the various solvents and (b) reflection spectra of Red Lotus dye adsorbed on TiO_2 film prepared from various solvents

Photophysical properties of the dye

The effect of solvents on the optical properties of the Red Lotus dye

The absorption spectra of the Red Lotus dye in a dilute solution, which used water, methanol, ethanol, and acetone as the solvent are illustrated in Figure 2a. The petal dye extract showed two absorption bands, which are located at 360 nm in the UV region and 540 nm in the visible region. The peak at the lower wavelength was assigned to $\pi\text{-}\pi^*$ transition of carbonyl chromophores that are conjugated with the aromatic ring and the higher wavelength was assigned to the $n\text{-}\pi^*$ transition of carbonyl chromophores, which ascribes to flavonoids (Sisa *et al.*, 2010). The petal dye extract showed a high absorption band in water and the absorbance intensity decreases in acetone, ethanol, and methanol, respectively. However, the maximum wavelength of the dye solution in these solvents remains the same as shown in a plot inset in Figure 2a. The reflection spectra of Red Lotus dye adsorbed on TiO_2 film prepared from water, methanol, ethanol, and acetone are presented in Figure 2b. All films revealed the broad absorption band in both UV and visible regions. The reflection intensity of a film prepared from the water solution showed the highest at 540 nm and a film prepared from the methanol

solution showed the lowest intensity resulting in the dye film having the highest adsorption intensity when prepared from methanol. Furthermore, the maximum wavelength is shifted to the left called blue-shifted when the dye is diluted in water compared to that in acetone, ethanol, and methanol.

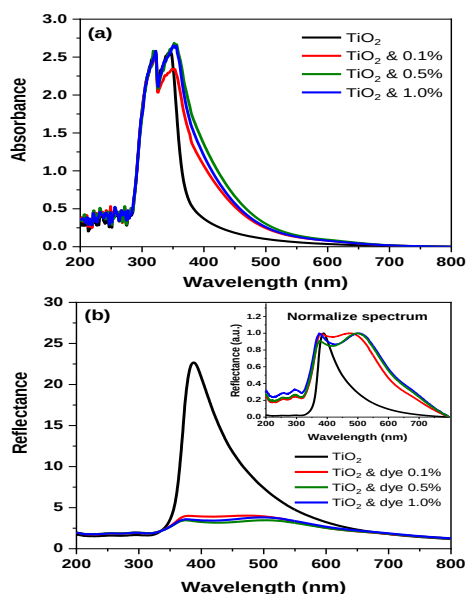


Figure 3. Shows Absorption spectra (a) and reflection spectra (b) of bare TiO_2 and the dye adsorbed on the TiO_2 film with different concentrations. The inset shows the normalized reflection spectra

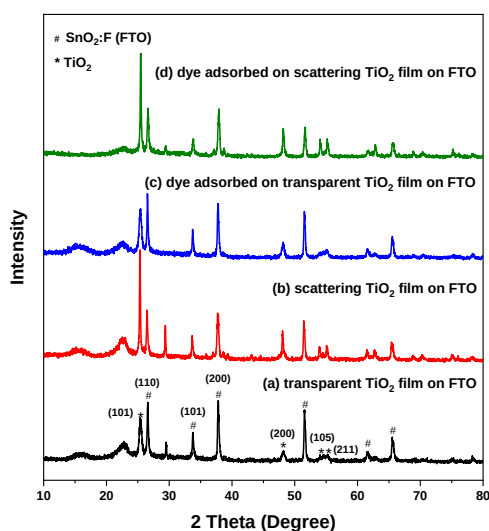


Figure 4. Shows XRD pattern of (a) transparent TiO_2 film/FTO, (b) scattering TiO_2 film/FTO, (c) dye adsorbed on transparent TiO_2 film/FTO, and (d) dye adsorbed on scattering TiO_2 film/FTO

From the result, this intense absorption in the visible region with a peak at 540 nm of dye indicates that it has a good light absorption performance, which is suitable to use as a sensitizer for the harvesting of photons in NDSSC.

Absorption and reflection spectra of the dye adsorbed on TiO_2 film

The absorption spectra of bare TiO_2 , Red Lotus dye extract adsorbed on the TiO_2 film with a concentration of 0.1%, 0.5%, and 1.0% w/v are illustrated in Figure 3a. The result revealed that the visible light was absorbed in the film with a broad absorption band in the range of 400-600 nm, and the peak of the dye in TiO_2 film is not easily visible in the spectrum, nonetheless, a shift in the maximum wavelength is observed when compared to the solution state. The light absorbance of each dye/ TiO_2 film increased with the concentration of the dyes because the change in film density induced the light trapping leading to an increase in light absorption of the films. To study the light scattering effects of the dye adsorbed on TiO_2 films, thus we measured their reflectance as shown in Figure 3b. The reflectance of bare TiO_2 was higher than the others, due to its uniformly TiO_2 particles (Figure 5a) being able to scatter the incident light, on the other hand, the dye in a film can be absorbed the light. Additionally, a plot inset of Figure 3b was the normalized reflectance spectra, all films exhibited the same scattering peak of TiO_2 at 400 nm and the peak of dye shows a shifted peak at 500 nm.

X-ray diffraction analysis

The crystal structures of the TiO_2 films were examined by X-ray diffraction (XRD) experiments as shown in Figure 4. Figure 4a corresponds to the transparent TiO_2 film coated on FTO glass, Figure 4b is the XRD spectra of scattering TiO_2 film/FTO, Figure 4c corresponds to the dye adsorbed on transparent film TiO_2 /FTO and Figure 4d corresponds to the dye adsorbed on scattering TiO_2 film/FTO. XRD patterns of transparent TiO_2 film/FTO glass (Figure 4a) displays three peaks corresponding to the (110), (101), and (200) directions of FTO substrate and the peak (101), (200), (105), and (211) of TiO_2 paste (Ghrai and Bouaicha, 2012). XRD patterns of all films show similar diffraction peaks, which indicates that the TiO_2 phase does not change during the device fabrication process.

Morphologies of the TiO_2 Films

The surface morphology of the TiO_2 layer coated on FTO glass fabricated by screen printing method was analyzed by scanning electron microscope (SEM) as shown in Figure 5. The

particle size from the SEM image was calculated using the ImageJ software, which uses the Analyze Particle tool to determine the diameters of particles. Identifying the particles and calculating their areas process by this command. The results report as the particle area and the particles size were calculated using Equation. (3) as follows (Barreto *et al.*, 2019):

$$d = 2 \sqrt{\frac{A}{\pi}} \quad (3)$$

where d is the diameter of the particle and A is the calculated area.

The average particle size of bare transparent TiO_2 film (Figure 5a), scattering TiO_2 film without dye (Figure 5b), the transparent TiO_2 film with dye (Figure 5c), and scattering TiO_2 film with dye (Figure 5d) were 16.7, 93.9, 20.5, and 93.2 nm, respectively. The bare transparent TiO_2 film and transparent TiO_2 film with an adsorbed layer of dye coated on FTO exhibited numerous uniformly sized with a particle size of 17-20 nm and good aggregation with clear porosity. The particle sizes of scattering TiO_2 film with dye and without dye coated on FTO glasses were bigger than transparent TiO_2 particles. For DSSC, the optical transparency of the TiO_2 Films and the DSSC efficiency increased with decreasing particle size and increasing film homogeneity. It suggests that there is the formation of an electron conduction path in a TiO_2 layer leading to increases in the electron diffusion length (Kawakami *et al.*, 2013). Moreover, the small TiO_2 particle size provides a large surface area, which can increase dye absorption and induce electrolyte diffusion within their pores. On the other hand, the large particle size of TiO_2 layers affects a strong light scattering ability and increases

an optical absorption path (Prachumrak *et al.*, 2017). Therefore, to reduce light loss due to the back-scattering light and increase the light-harvesting in solar cells, the multi-layers devices were fabricated, in which a small particle size of transparent TiO_2 was deposited on the FTO glass and coated with a larger particle size of scattering TiO_2 on the top layer (Jeng *et al.*, 2013). Furthermore, no significant changes were observed in the surface morphology of the films before and after dye sensitization.

Performance of dyes in the device system

To determine the performance of the NDSSCs, the current voltage (J - V) characteristics curve has been evaluated. J - V performance of the cells was measured under a calibrated solar simulator with a 500W Xenon arc lamp and a light intensity of 100 mW/cm^2 at AM 1.5G by the Keithley digital source meter model 2400. From the J - V characteristics curve, short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF), and power conversion efficiency (PCE or η) can be measured. The DSSCs of Red Lotus dye was prepared from 0.1%, 0.5%, and 1.0% w/v of dye in the different solvent, which are methanol, ethanol, water, and acetone. The ruthenium complex (N719) was used as a reference sensitizer in the experiment. The J - V curves of the DSSCs sensitized by the Red Lotus dye and the standard dye N719 are illustrated in Figure 6 and output performances were summarized in Table 1. The J - V curves of the Red Lotus dye-sensitized DSSCs, which were prepared from methanol with the dye concentration of 0.1%, 0.5%, and 1.0% w/v (Figure 6(a)) revealed the curve moves forward by increasing the concentration of dye from 0.1 to 1.0%, which is nearly almost unchanged when increasing the dye concentration from 0.5% to 1.0%. The PCE of N719 which is the control in our fabrication step is 8.574% compared to the results from N. Prachumrak, *et al.* (8.20%) and Nazeeruddin *et al.* (8.4%) (Nazeeruddin *et al.*, 2003; Prachumrak *et al.*, 2017). The PCE of Red Lotus dye cells prepared from 0.1%, 0.5%, and 1.0% w/v of dye in methanol were 0.208, 0.273, and 0.281 %, respectively. It indicates that the performance of the cell depends on the dye concentration, however, the dye concentration of 0.5% w/v is suitable for NDSSC devices with an active area of $0.5 \times 0.5 \text{ cm}^2$. The PCE of NDSSCs prepared from water, ethanol, and acetone were 0.144, 0.155, and 0.196%, respectively. The PCE of methanol cells has higher than all cells because the dye in methanol can be adsorbed into the TiO_2 layer better than water, ethanol, and acetone due to their surface tension, which water has the highest surface tension leads to poor disperse of the dye (Phaechamud and Chitrattha, 2016). According to Table 1, Red Lotus

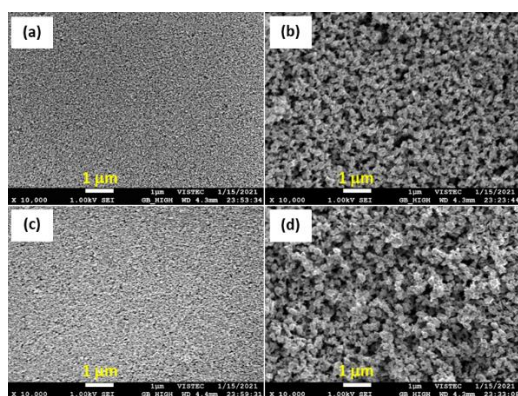


Figure 5. Shows Surface SEM images of (a) transparent TiO_2 film/FTO, (b) scattering TiO_2 film/FTO, (c) transparent TiO_2 film/FTO with dye, and (d) scattering TiO_2 film/FTO with dye

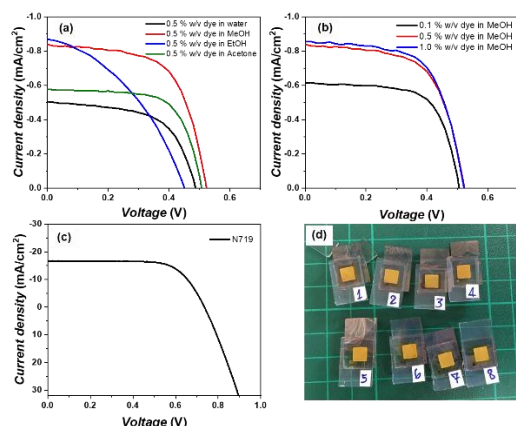


Figure 6. Shows *J-V* curves of the DSSCs sensitized by (a) the Red Lotus dye with different concentrations, (b) the Red Lotus dye prepared from different solvents, (c) N719, and (d) the picture of fabricated NDSSCs.

dye-sensitized DSSC which is prepared from methanol with 1.0% w/v of dye has shown the highest cell parameter ($J_{sc} = 0.855 \text{ mA/cm}^2$, $V_{oc} = 0.522 \text{ V}$, $FF = 0.631$ and $\eta = 0.281\%$). compared to standard dye N719 sensitized DSSC's cell parameter ($J_{sc} = 16.63 \text{ mA/cm}^2$, $V_{oc} = 0.735 \text{ mV}$, $FF = 0.701$ and $\eta = 8.574\%$). Additionally, the prepared cell shows a near FF value compared to standard N719 indicating that the device fabrication process of solar cells is its well-established standard and standardized method. The pictures of prepared NDSSCs as shown in Figure 6(d).

Conclusions

We have successfully extracted red dye from the petal of Red Lotus. In this work, its physical properties and NDSSCs based on this dye were investigated. The dye adsorbed on TiO_2 film can observe the characteristic vibrational frequencies of flavonoids. The Red Lotus dye showed two absorption bands assigned to flavonoids, which are located at 360 nm in the UV region and 540 nm in the visible region. The absorption intensity of the dye showed the lowest in methanol whereas the reflection intensity of the dye adsorbed on TiO_2 film prepared from the methanol solution showed the lowest at 540 nm because the dye dissolves solution can be adsorbed on to TiO_2 layer more than other solvents due to their surface tension leads to the largest amount of dye molecules that adsorbed on TiO_2 film. Therefore, the efficiencies of the NDSSCs depended on the dye concentration and

Table 1. Shows Photovoltaic parameters of the DSSCs.

Photosensitizer (Red Lotus dye)	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	PCE (%)
0.1% w/v in MeOH	0.615	0.506	0.668	0.208
0.5% w/v in MeOH	0.840	0.523	0.621	0.273
1.0% w/v in MeOH	0.855	0.522	0.631	0.281
0.5% w/v in Water	0.504	0.487	0.589	0.144
0.5% w/v in EtOH	0.869	0.451	0.395	0.155
0.5% w/v in Acetone	0.578	0.507	0.671	0.196
N719	16.637	0.735	0.701	8.574

solvent. The efficiency of the cell has limited by the active area. Even though the cell fabricated with 1% w/v of dye has the highest PCE with a value of 0.281 but in terms of the efficiency with the small amount of dye, the 0.5%w/v of dye provides good stability and shows high ability along with its low production cost as the photosensitizer of DSSC cell. It can be concluded that the 0.5% w/v of dye dilute in methanol is suitable for fabricated NDSSC devices with a power conversion efficiency of 0.273%.

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References

- Ahliha, A.H., Nurosyid, F., Supriyanto, A., and Kusumaningsih, T. (2018). Optical properties of anthocyanin dyes on TiO_2 as photosensitizers for application of dye-sensitized solar cell (DSSC). IOP Conference Series: Materials Science and Engineering; Sep 4-5, 2017; Surakarta, Indonesia., p. 1-5. <https://doi.org/10.1088/1757-899X/333/1/012018>
- Arguelles, E., and D, L.R. (2019). Species composition of algal epiphyton of Pink Lotus (*Nymphaea pubescens* Willd) found in Laguna de Bay (Philippines). Walailak J. Sci and Tech., 17(3):237-256. <https://doi.org/10.48048/wjst.2020.5015>
- Barreto, J.C.G., Tita, D.L., and Orlandi, M.O. (2019). Development of an automated method to perform a quantitative study of particle size distribution and the effect of a conductive layer in scanning electron microscopy. Quim. Nova., 42(4):447-452. <https://doi.org/10.21577/0100-4042.20170353>
- Chougala, L.S., Yatnatti, M.S., Lingangoudar, R.K., Kamble, R.R., and Kadadevarmath, J.S. (2017). A simple approach on synthesis of TiO_2 nanoparticles and its application in dye sensitized solar cells. J. Nano-Electron. Phys.,

- 9(4):04005-1-04005-6.
[https://doi.org/10.21272/jnep.9\(4\).04005](https://doi.org/10.21272/jnep.9(4).04005)
- Do, Q.D., Angkawijaya, A.E., Tran-Nguyen, P.L., Huynh L.H., Soetaredjo, F.E., Ismadji, S., and Ju, Y.H. (2014). Effect of extraction solvent on total phenol content, total flavonoid content, and antioxidant activity of *Limnophila aromatic*. *J. Food Drug Anal.*, 22:296-302. <https://doi.org/10.1016/j.jfda.2013.11.001>
- Genta, D., Jara, J., and Villanueva, R. (2017). Dye-sensitized solar cells using aloe vera and cladode of cactus extracts as natural sensitizers. *Chem. Phys. Lett.*, 679:97-101. <https://doi.org/10.1016/j.cplett.2017.04.094>
- Ghraiiri, N., and Bouaicha, M. (2012). Structural, morphological, and optical properties of TiO₂ thin films synthesized by the electro phoretic deposition technique. *Nanoscale Res. Lett.*, 7:1-7. <https://doi.org/10.1186/1556-276X-7-357>
- Hamadani, M., Safaei-Ghomi, J., Hosseinpour, M., Masoomi, R., and Jabbari, V. (2014). Uses of new natural dye photosensitizers in fabrication of high potential dye-sensitized solar cells (DSSCs). *Mater Sci Semicond Process.*, 27:733-739. <https://doi.org/10.1016/j.mssp.2014.08.017>
- Heneczowski, M., Kopacz, M., Nowak, D., and Kuźniar, A. (2001). Infrared spectrum analysis of some flavonoids. *Acta Pol Pharm.*, 58(6):415-420.
- Hernández-Martínez, A.R., Estevez, M., Vargas, S., Quintanilla, F., and Rodríguez, R. (2012). Natural pigment-based dye-sensitized solar cells. *J. Appl. Res. Technol.*, 10(1):38-47. <https://doi.org/10.22201/icat.16656423.2012.10.1.419>
- Hug, H., Bader, M., Mair, P., and Glatzel, T. (2014). Biophotovoltaics: natural pigments in dye-sensitized solar cells. *Appl. Energy.*, 115:216-225. <https://doi.org/10.1016/j.apenergy.2013.10.055>
- Jeng, M.J., Wung, Y.L., Chang, L.B., and Chow, L. (2013). Particle size effects of TiO₂ layers on the solar efficiency of dye-sensitized solar cells. *Int. J. Photoenergy.*, 1-9. <https://doi.org/10.1155/2013/563897>
- Kawakami, R., Yuasa, T., Sato, Y., Mori, Y., Adachi, M., and Yoshikado, S. (2013). Effects of particle size on properties of TiO₂ nanoparticle thin films deposited by electrophoresis. *Key Eng. Mater.*, 566:199-203. <https://doi.org/10.4028/www.scientific.net/KEM.566.199>
- Nazeeruddin, M.K., Humphry-Baker, R., Liska, P., and Grätzel, M. (2003). Investigation of sensitizer adsorption and the influence of protons on current and voltage of a dye-sensitized nanocrystalline TiO₂ solar cell. *J. Phys. Chem.*, 107:8,981-8,987. <https://doi.org/10.1021/jp022656f>
- O'Regan, B., and Grätzel, M. (1991). A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO₂ films. *Nature.*, 353:737-740. <https://doi.org/10.1038/353737a0>
- Phaeachamud, T., and Chitrattha, S. (2016). Pore formation mechanism of porous poly(DL-lactic acid) matrix Membrane. *Mater. Sci. Eng. C.*, 61:744-752. <https://doi.org/10.1016/j.msec.2016.01.014>
- Prachumrak, N., Sudyoadsuk, T., Thangthong, A., Nalaoh, P., Jungsuttiwong, S., Daengngern, R., Namuangruk, S., Pattanasattayavonga, P., and Promarak, V. (2017). Improvement of D- π -a organic dye-based dye-sensitized solar cell performance by simple triphenylamine donor substitutions on the π -linker of the dye. *Mater. Chem. Front.*, 1(6):1,059-1,072. <https://doi.org/10.1039/C6QM00271D>
- Prajudtari, N., and Kitisriworaphan, W. (2014). Preliminary phytochemicals screening and antioxidant activity of crude extracts from *Nymphaea lotus* L. var. pubescens Hook.F.&Thomson. *Pure and Applied Chemistry International Conference 2014 (PACCON2014)*; Jan 8-10, 2014; Khon Kaen, Thailand, p. 364-367.
- Selvakumari, E., Shantha, A., Sreenath Kumar, C., and Purushoth, Prabhu T. (2016). Phytochemistry and pharmacology of the genus *Nymphaea*. *J. Acad. Ind. Res.*, 5(7):98-108.
- Sharma, K., Sharma, V., and Sharma, S.S. (2018). Dye-sensitized solar cells: Fundamentals and current status. *Nanoscale Res. Lett.*, 13(381):1-46. <https://doi.org/10.1186/s11671-018-2760-6>
- Sisa, M., Bonnet, S.L., Ferreira, D., and Van der Westhuizen, J.H. (2010). Photochemistry of flavonoids. *Molecules.*, 15(8):5,196-245. <https://doi.org/10.3390/molecules15085196>
- Sowemimo, A.A., Omobuwajo, O.R., and Adesanya, S.A. (2007). Constituents of *Nymphaea lotus* Linn. *Nig. J. Nat. Prod. and Med.*, 11:1-2. <https://doi.org/10.4314/njnp.v11i1.11890>
- Syafinar, R., Gomes, N., Irwanto, M., Fareq, M., and Irwan, Y.M. (2015). Chlorophyll pigments as nature-based dye for dye-sensitized solar cell (DSSC). *Energy Procedia.*, 79:896-902. <https://doi.org/10.1016/j.egypro.2015.11.584>
- Zhu, M., Zheng, X., Shu, Q., Li, H., Zhong, P., Zhang, H., Xu, Y., Wang, L., and Wang, L. (2012). Relationship between the composition of flavonoids and flower colors variation in tropical Water Lily (*Nymphaea*) cultivars. *PLoS one.*, 7(4):1-11. <https://doi.org/10.1371/journal.pone.0034335>