Journal of Engineering, Electrical and Informatics

E- ISSN: 2809-8706
P- ISSN: 2810-0557

(Research/Review Article)

Efficiency Analysis of Dye Sensitized Solar Cells (DSSC) based on natural dyes using single and double layer TiO_2 Photoelectrodes

Nurul Amalia Silviyanti [1]*, Nurrima Puspitasari [2], Endarko [2],

[1]Universitas Abdurachman Saleh; email: nurul_amalia_silvi@unars.ac.id

[2] Institut Teknologi Sepuluh Nopember email: nurul_amalia_silvi@unars.ac.id

Abstract: .Dye sensitized solar cells based on natural dyes have been successfully fabricated using single layer and double layer photoelectrodes of TiO_2. Single layer photoelectrodes have been fabricated with TiO_2 nanoparticles (14 –40 nm). Meanwhile the double layer photoelectrodes have been fabricated with TiO_2 nanoparticles (14 –40 nm) as bottom layer and subnano-particles (120 –140 nm) as top layer. Gel electrolyte based on PEG 1000 has been utilized to increase the lifetime of DSSC. This study was to investigate the characteristics of DSSC that have been fabricated from single and double layer TiO_2 photoelectrodes. The results showed that the double layer photoelectrodes were generally better than the single layer photoelectrodes, with the result efficiency of 0.38% and 0.25%, respectively. The open circuit voltage (Voc), short circuit current (Isc), maximum power (Pmax) and Fill Factor (FF) were measured at 310 mV, 638 μA, 71.5 μW and 36.18%, respectively, for the double layer TiO_2 photoelectrodes. Meanwhile the open circuit voltage (Voc), short circuit current (Isc), maximum power (Pmax), and Fill Factor (FF) were 330 mV, 580 μA, 46.94μW and 24.52%, respectively, were achieved for the single layer TiO_2 photoelectrode.

Keywords: Double Layer; Dye Sensitized Solar Cells; Nanoparticles and Natural Dye; TiO_2.

Received: date
Revised: date
Received: date
Published: date
Current version: date

1. Introduction

The effects of CO2 emissions on the climate and the dwindling supply of fossil fuels have prompted researchers to seek renewable energy sources. Of all renewable energy sources, solar energy is ideal because it is readily available, quiet, and ubiquitous [1] . Solar energy can be converted into electrical energy using solar cells or photovoltaics (PV) [2] .

Currently, PV technology available on the market uses inorganic materials that require expensive production costs and are quite difficult to produce. On the other hand, there is DSSC (dye-sensitized solar cell) technology that can be produced at a relatively low cost [3] . DSSC consists of TCO (transparent conducting oxide) conductive glass, a semiconductor layer, a dye to capture sunlight, a redox electrolyte, and a platinum layer [4] .

In this study we aim to make DSSC from natural materials such as natural dyes from plants. In addition, we also use cheap and more durable materials such as the use of gel electrolytes compared to liquid electrolytes that corrode faster so that the life of DSSC is not long-lasting.

2. Literature Review

DSSC (Dye Sensitized Solar Cell) is a photovoltaic that converts light energy into electrical energy. The concept used in DSSC is similar to the concept of photosynthesis in plants. The parts of the DSSC are the photoelectrode consisting of ITO glass coated with semiconductors and soaked in dye. The part on the counter electrode consists of ITO glass that has been coated with carbon. The photoelectrode and counter electrode are connected and electrolyte is dripped in the middle [5] . When the DSSC is dried in sunlight and connected to electrical equipment, the DSSC can produce electrical energy.

2.1. ITO Glass

ITO (Indium Thin Oxide) glass is glass coated with ITO to make it conductive or in other words, it can conduct electricity [6] . Besides ITO glass, there is also FTO (Flourine Doped Thin Oxide) glass [7] , but in this research we use ITO as induction glass.

2.2 Electrode counter and electrolyte gel

In the manufacture of DSSC, the electrolyte solution serves as a substitute source of electrons for dye electrons excited through the redox process [8] . This electrolyte solution is dripped between the photoelectrode and the counterelectrode. The counter electrode is an ITO/FTO glass coated with activated carbon [9] . Although liquid electrolytes can produce higher efficiency, they have many disadvantages such as being easily spilled, corrosion that reduces the service life of the cell. So we use an electrolyte with a polymer gel. For the counter electrode, a cheap and easily obtained material is used, namely carbon graphite. In this study, we used carbon from a 2B pencil that was finely ground and coated on the ITO glass.

2.4 Dye

DSSC uses dye experience And produce efficiency high . However dye experience often cause problem like channel sufficient synthesis complicated If We want to separate component dye [10] . In addition that , dye experience can found on flowers , leaves And fruit . Because easy found , no poisonous And easy outlined , dye experience become Wrong One object a lot of research used [11] . By Because that , some dye experience often used as a sensitizer such as anthocyanin , curcumin , cyanine , chlorophyll , carotene And others [12] .

Single dyes are responsible for capturing light. The disadvantage of single dyes is that the light captured is limited to a specific wavelength group. Therefore, using multiple dyes simultaneously can broaden the wavelength absorption range to absorb more light, resulting in higher efficiency [13] . In this study, we used a mixture of three natural dyes as a sensitizer.

2.4 Semiconductors

The addition of large particles is used as a layer to scatter the light captured on the photoelectrode where the scattering layer is deposited above the main electrode layer to produce a double layer structure. A large surface area on the TiO_2 photoelectrode is needed to increase photon absorption so that it can produce high currents [14] .

Several studies have attempted to increase the surface area of TiO_2 . However, smaller nanoparticles reduce the light scattering effect, causing light to pass through the photoelectrode without interacting with the dye. Conversely, the use of nanoparticles is needed to reduce the dye capacity loading on the photoelectrode [15] .

To balance these two needs, researchers made a design based on the aggregation of the second structure where the photoelectrode can have both functions so that it can capture more photons. In addition to TiO_2 nanoparticles, TiO_2 nanorods, nanowires, nanotubes, nanosheets and core-shell structures are also used in DSSCs to study their performance [16] . However, they still have performance below TiO_2 nano, so in this study TiO_2 nanoparticle semiconductors were used.

3. Method

3.1 Materials

subnano TiO_2 powder from Merck, HCL 2M 37%, $TiCl_3$, NH_4OH 25%, polyethylene glycol (PEG) 1000, iodine, ethanol, acetic acid, chloroform, carbon, distilled water, 98% alcohol, chlorophyll dye, curcumin and anthocyanin.

3.2 Synthesis of $TiO_{2\ \text{nanoparticles}}$

Synthesis of TiO_2 nanoparticles was obtained using the corestipation method. First, 50 ml of distilled water was mixed with 20 ml of 2M 37% HCl and 20 ml of $TiCl_3$. Stir using a magnetic stirrer for 30 minutes. After mixing, add 50 ml of 25% NH_4OH, stir again for 60 minutes. Cover the mixture, then let it stand at room temperature for 1 day. Rinse the solid formed with alcohol, dry it until it becomes TiO^2 nanoparticle powder [17] .

3.3 Preparation of dye, electrolyte and counter electrode

Prepare a 3-color dye mixture, namely chlorophyll, curcumin, and anthocyanin with a ratio of 1:1:1. The electrolyte gel is made using PEG 1000 dissolved in a chloroform solution mixed with iodine and KI. Stir the mixture with a magnetic stirrer at a temperature of 80º C. The electrode is made by coating ITO glass with granite that is fired using a small flame [18] .

3.4 DSSC Fabrication

The ITO glass substrate was washed thoroughly using alcohol, then coated with TiO_2 nanoparticles in paste form using the doctor blade method. The photoelectrode was heated at 450ºC for 30 minutes and then cooled at room temperature for 5 hours. For the double layer photoelectrode, after the first coating with nanoparticle paste, it was coated again with a layer of TiO_2 subnanoparticle paste using the same method and steps as the first layer. Next, the photoelectrode was soaked in a mixture of 3 dyes at room temperature and in the dark for 24 hours and then cleaned using ethanol. Finally, a gel-shaped polymer electrolyte was dripped between the photoelectrode and the counter electrode [19] .

3.5 DSSC Characterization

The voltage and current measurements generated by the DSSC were carried out under daylight without the UV filter of the AR layer. The performance of the DSSC with an area of 1.5 cm^2 was calculated using the equation:

$$\eta = \frac{P_{max}}{P_{in}} \times 100 \quad (1)$$

$$FF = \frac{V_{max} J_{max}}{V_{oc} J_{sc}} \times 100 \quad (2)$$

Where Jsc is the current (A/m^2), Voc is the voltage, Pin is the power of the incident light, FF is the fill factor, (125W/m^2). FF is the fill factor, η is the efficiency of energy conversion in the DSSC, Jmax (A/m^2) and Vmax (V) are the maximum current and voltage [20] .

4. Results and Discussion

Semiconductor TiO_2 nanoparticle powder and TiO_2 sub-nanoparticle powder have been characterized using X-ray diffraction and MAUD (material analysis using diffraction). The test results are shown in Figure 1, both TiO_2 nanoparticle powder and TiO_2 sub-nanoparticle have 100% anatase phase. The magnitude of the diffraction peak protrusion indicates smaller crystallites, this is evidenced by the size of the nanoparticle crystallite of 14 nm and sub-nanoparticle of 125 nm [21] .

Single-layer photoelectrodes are coated only by TiO_2 nanoparticles, while double-layer photoelectrodes are coated with a layer of nanoparticles and a layer of subnanoparticles in the second layer. In general, small nanoparticles have a larger surface area, providing sufficient space for the dye so that it can absorb more light to increase Jsc.

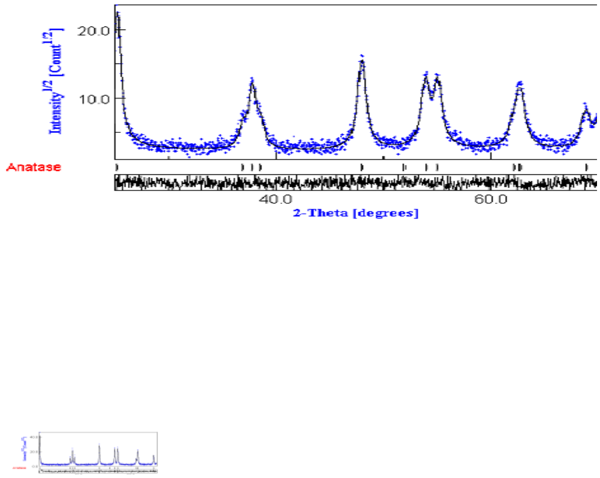

Figure 1. Refinement results from MAUD a) TiO_2 nanoparticles and b) TiO_2 sub-nanoparticles.

However, according to theoretical approaches, the diameter of the scattering particles should be close to half the wavelength of light with a crystallite size of more than 100 nm for better light scattering effect. We use large particles to be able to scatter light [22]

The next problem for double-layer photoelectrodes is the effect of thickness on DSSC characterization. If the photoelectrode uses a thin layer, then the number of TiO_2 particles is not as much as a photoelectrode with a thick layer which can result in the least dye absorption on the photoelectrode, this causes a decrease in the efficiency of photovoltaic performance [23] . Therefore, the ideal thickness for a photoelectrode is between 10 μm - 20 μm]. From this problem, we tried to control the thickness using a thin template with a thickness of 10 μm. After the photoelectrode was heated and cooled, the thickness was checked using a Microsoft computer. The thickness of the single-layer photoelectrode was 13 μm and for the double-layer photoelectrode was 23 μm.

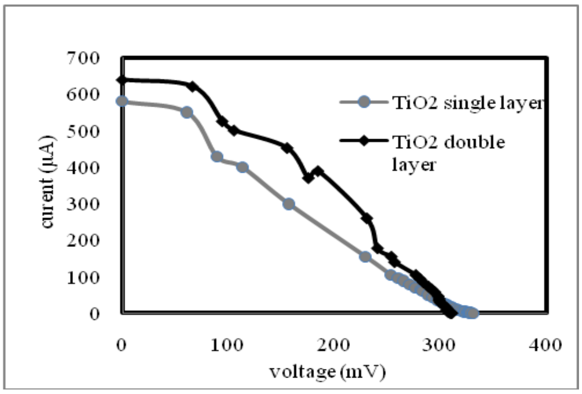

Figure 2. Characteristics of DSSC with single layer and double layer photoelectrodes

The photovoltaic performance of DSSC with single layer photoelectrode and double layer photoelectrode was measured at 125 W/m2 as shown in Figure 2. DSSC with single layer photoelectrode produces Isc (short circuit current) of 580 μm, this value increases for double layer photoelectrode up to 638 μm. On the other hand the open circuit voltage (Voc) value decreases from 350 mV single layer to 310 mV for double layer. In double layer dye absorption has a larger amount due to the presence of nanoparticles which are responsible for the high surface area and high porosity of the presence of sub-nanoparticles which also increases the increase in light scattering effect. Meanwhile the decrease in Voc is due to the higher thickness and larger surface of the double layer photoelectrode. Voc is determined by the difference between the quasi fermi level of TiO2 and the potential of the I-/I3- redox couple in the electrolyte and thus depends on the recombination rate and the position of the TiO2 band edge. In double layer photoelectrodes there are more sites for surface charge trapping on

TiO2, which causes a decrease in Voc. Therefore the double layer efficiency is 0.38% higher than the single layer 0.25%.

The efficiency value in this study is not as high as compared to DSSC in other studies [24] because in this study we used natural dyes and gel-electrolytes. Dyes sensitized from organic dyes have better efficiency performance, because the bond with organic dyes (especially Ruthenium dyes) is stronger than those bound to natural dyes [25] . Thus organic dyes can produce more electrons. Liquid electrolytes can produce higher efficiency values, because the electrolyte's task is to regenerate oxidized and reduced dyes, which can be charged faster than gel electrolytes due to the rapid mobilization of liquid electrolyte particles. However, this work aims to make low-cost and long-lived DSSCs, therefore we use natural dyes and gel-electrolytes.

6. Conclusion

A study has been conducted on the photovoltaic performance of single-layer photoelectrodes and double-layer photoelectrodes. The performance of double-layer photoelectrodes has a higher efficiency of 0.38% than that of single-layer photoelectrodes with 0.25%. Although the Voc from single to double layers decreases due to the higher thickness, the performance is still better because double-layer photoelectrodes have a higher Isc value caused by the larger amount of dye absorption and the increased light scattering effect. The efficiency value is still lower than other studies because we used natural dyes that have poor bonding with TiO2 and slower particle mobilization from the gel electrolyte.

Author Contributions: The following statement should be used "Conceptualization: Nurul Amalia and Nurrisma; Methodology: Nurul Amalia and Nurrisma; Software: Nurul Amalia; Validation: Endarko; Formal analysis: Nurul Amalia; Investigation: Nurul Amalia; Resources: Nurul Amalia; Data curation: Nurul Amalia; Writing—original draft preparation: Nurul Amalia; Writing—review and editing: Nurul Amalia; Visualization: Nurul Amalia and Nurrisma; Supervision: Endarko; Project administration: Nurul Amalia and Nurrisma; Funding acquisition: Nurul Amalia and Nurrisma"

Reference

[1] S. Nurul Amalia Silviyanti and Santoso, "Performance investigation of convex lens as light collector in low cost solar cooker," *J. Phys. Conf. Ser.* , vol. 1842, no. 1, p. 012061, Mar. 2021, doi: 10.1088/1742-6596/1842/1/012061.

[2] E. Tarigan, "Hybrid PV-T Solar Collector using Amorphous Type of Solar Cells for Solar Dryer," in *2020 International Seminar on Intelligent Technology and Its Applications (ISITIA)* , Jul. 2020, pp. 352–356. doi: 10.1109/ISITIA49792.2020.9163789.

[3] N. Hindryawati, IA Hiyahara, H. Saputra, MS Arief, and GP Maniam, "Preparation of Dye-Sensitized Solar Cell (DSSC) Using TiO2 and Mahkota Dewa Fruit (Phaleria Macrocarpa (Scheff) Boerl.) Extract," *J. Renewable Natural Materials* , vol. 10, no. 1, Art. no. 1, Jun. 2021, doi: 10.15294/jbat.v10i1.32378.

[4] H. Patel *et al.* , " *Tagetes erecta* (marigold) flower extract in the different solvents used as a capping agent and sensitizer for TiO2 photoanode based DSSC," *Mater.* , vol. 8, p. 100875, Jul. 2025, doi: 10.1016/j.nxmate.2025.100875.

[5] S. Qamar and S. Erten Ela, "Dye-sensitized solar cells (DSSC): Principles, materials and working mechanism," *Curr. Opinion. Colloid Interface Sci.* , vol. 74, p. 101871, Dec. 2024, doi: 10.1016/j.cocis.2024.101871.

[6] E. Wahyuni, D. Darsikin, and S. Saehana, "FABRICATION OF FLUORINE DOPED-TIN OXIDE (FTO) GLASS USING SPRAY PYROLYSIS TECHNIQUE," *JPFT J. Educator. Fis. Tadulako Online* , vol. 10, no. 2, Art. no. 2, Aug. 2022.

[7] IA Handayani, A. Haris, and DS Widodo, "Synthesis of ZnO/NiO Thin Film on Fluorine-doped Tin Oxide (FTO) by Two Step Electrodeposition as Photoanode of a Solar Cell," *J. Kim. Science And Apps.* , vol. 21, no. 3, pp. 124–130, Jul. 2018, doi: 10.14710/jksa.21.3.124-130.

[8] YH Prasetyo, S. Wahyuningsih, and R. Suryana, "Study of Electrolyte Variation on Dye-Sensitized Solar Cell (DSSC) Performance (Pages 47 to 49)," *J. Fis. Indones.* , vol. 18, no. 53, Art. no. 53, Feb. 2015, doi: 10.22146/jfi.24388.

[9] NM Nursam, "THE EFFECT OF COUNTER ELECTRODE MATERIAL ON DYE-SENSITIZED SOLAR CELL," *Metallurgy* , vol. 34, no. 3, Feb. 2020, doi: 10.14203/metallurgy.v34i3.489.

[10] M. Hosseinnezhad, K. Gharanjig, S. Nasiri, and M. Fathi, "Study of the presence of thioindigo in photosensitizers based on phenothiazine: Synthesis and photovoltaic evaluation in DSSCs," *Synth. Met.* , vol. 312, p. 117885, Jun. 2025, doi: 10.1016/j.synthmet.2025.117885.

[11] A. Daniswara, G. Raydiska, and Y. Timotius, "Dye Sensitized Solar Cell (DSSC) Implementation Strategy in Indonesia," *J. Offshore Oil Prod. Facil. Renew. Energy* , vol. 4, no. 2, Dec. 2020, doi: 10.30588/jo.v4i2.835.

[12] I. Nirmalasari, RA Nugrahani, and B. Budiyanto, "Improving the Efficiency of Dye Sentisized Solar Cell (DSSC) from Mangosteen (Garcinia mangostana L) Peel Anthocyanins Using Papain," *Chim. Nat. Acta* , vol. 10, no. 2, pp. 88–93, Aug. 2022, doi: 10.24198/cna.v10.n2.38011.

[13] N. Puspitasari, SS Nurul Amalia, G. Yudoyono, and Endarko, "Effect of Mixing Dyes and Solvent in Electrolyte Toward Characterization of Dye Sensitized Solar Cell Using Natural Dyes as the Sensitizer," *IOP Conf. Ser. Mater. Sci. Eng.* , vol. 214, no. 1, p. 012022, Jul. 2017, doi: 10.1088/1757-899X/214/1/012022.

[14] NA Pirdaus, N. Ahmad, F. Muhammad-Sukki, and WAAQI Wan-Mohtar, "Effect of different titanium dioxide (TiO2) deposition layers for dye-sensitized solar cell (DSSC) applications," *Electrochimica Acta* , vol. 527, p. 146267, Jul. 2025, doi: 10.1016/j.electacta.2025.146267.

[15] H. Jaafar, H. Jaafar, ZA Ahmad, and MAM Asri, "Effect of TiO2/eggshell composite using sol gel method photoanode for dye-sensitized solar cell applications (DSSC) and comparison using k-nearest neighbors method," *Mater. Today Commun.* , vol. 45, p. 112240, Apr. 2025, doi: 10.1016/j.mtcomm.2025.112240.

[16] A. Ashok *et al.* , "Synergistic effects of Co-Mn co-doping on the structural and optical properties of TiO2 nanospheres: Dual functions for DSSC photoanodes and degradation photocatalyst," *J. Alloys Compd.* , vol. 1005, p. 176024, Nov. 2024, doi: 10.1016/j.jallcom.2024.176024.

[17] KY Astuti, "FORMATION OF TIO2 NANOPARTICLES USING VARIOUS METHODS," *J. Ind. Eng. Pass. Manag. JIEOM* , vol. 1, no. 1, Art. no. 1, Feb. 2019, doi: 10.31602/jieom.v1i1.1313.

[18] S. Chadijah, D. Dahlan, and H. Harmadi, "Making Carbon Counter Electrode for Dye-Sensitized Solar Cell (DSSC) Electrode Application," *J. ILMU Phys. Univ. ANDALAS* , vol. 8, no. 2, pp. 78–86, 2016, doi: 10.25077/jif.8.2.78-86.2016.

[19] M. Nafi and D. Susanti, "Application of TiO2 Semiconductor with Variations in Temperature and Calcination Resistance Time as Dye Sensitized Solar Cell (DSSC) with Dye from Dutch Eggplant (Solanum Betaceum) Fruit Extract," Journal: eArticle, Sepuluh Nopember Institute of Technology, 2013. doi: 10.12962/j23373539.v2i1.2195.

[20] AA Rasyid, DHS Maha, M. Irwanto, and RT Ginting, "ANALYSIS OF EFFICIENCY OF DYE SENSITIZED SOLAR CELL (DSSC) MADE FROM RED DRAGON FRUIT EXTRACT AS DYE COLOR," *RELE Rekayasa Elektr. Dan Energi J. Tek. Elektro* , vol. 8, no. 1, Art. no. 1, Jan. 2025, doi: 10.30596/rele.v8i1.22018.

[21] DR Eddy *et al.* , "Heterophase Polymorph of TiO2 (Anatase, Rutile, Brookite, TiO2 (B)) for Efficient Photocatalyst: Fabrication and Activity," *Nanomaterials* , vol. 13, no. 4, Art. no. 4, Jan. 2023, doi: 10.3390/nano13040704.

[22] H. Kanwal *et al.* , "Enhanced photovoltaic performance dye-sensitized solar cells (DSSCs) employing α-GeO2–TiO2 bilayer and heterojunction photoanodes," *Sol. Energy* , vol. 282, p. 112952, Nov. 2024, doi: 10.1016/j.solener.2024.112952.

[23] WR Aprilla and A. Haris, "Synthesis of TiO2 Semiconductor and Its Application to Dye-Sensitized Solar Cell (DSSC) Using Indigo Carmine Dye," *J. Kim. Science and Appl.* , vol. 19, no. 3, pp. 111–117, Dec. 2016.

[24] U. Mahajan, K. Prajapat, M. Dhonde, K. Sahu, and P. M. Shirage, "Natural dyes for dye-sensitized solar cells (DSSCs): An overview of extraction, characterization and performance," *Nano-Struct. Nano-Objects* , vol. 37, p. 101111, Feb. 2024, doi: 10.1016/j.nanoso.2024.101111.

[25] A. Kumar, A. Chaudhari, S. Kumar, S. Kushwaha, and S. Mandal, "Comparative study of natural and synthetic dyes in DSSCs: An experimental and computational approach," *Phys. B Condens. Matter* , vol. 685, p. 415978, Jul. 2024, doi: 10.1016/j.physb.2024.415978 .