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Electrical and Optical Improvement of Gambier Dye Modification to Enhance DSSC Performance

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Abstract

DSSCs, or dye-sensitized solar cells, are a more affordable alternative than silicon-based photovoltaics. This study aims to optimize important parts to increase DSSC efficiency. The photoanode material is titanium dioxide (TiO_2) nanoparticles, which are utilized because of their large surface area and effective electron transport. Advanced fabrication and surface treatments enhance the stability and light-harvesting performance of TiO_2 films. New natural and metal-organic dyes' absorption, attachment strength, and charge transfer features are created and analyzed. The relationship between dyes and the TiO_2 surface is modified to increase electron injection efficiency. The electrolyte composition is improved to improve ionic conductivity and reduce recombination losses. Power conversion efficiency (PCE), short-circuit current density (Jsc), open-circuit voltage (Voc), and fill factor (FF) are among the performance parameters that are examined. Based on the experimental data, the fabricated DSSC using the pure ruthenium dye possessed the highest level of power conversion efficiency (PCE) is 1.25%, fill factor (FF) is 45.97%, short-circuit current density (Jsc) is 3.98 mA/cm2 and open-circuit voltage (Voc) is 0.85 V. The modified dyes performed better than the pure gambier dye, which only obtained a PCE of 0.43% with a PCE of 1.09%, Jsc: 3.56 mA/cm2, Voc: 0.74 V, FF: 51.13%. The combination of two dyes enhanced the dye loading and electron transfer due to the fact that the agglomeration was less and nanoparticle coverage became homogenous as evident by the FESEM images. The increased UV-Vis and IPCE absorption spectra of the combination dye in the 400 to 700 nm range were also evidenced by the UV-Vis and IPCE data. These findings indicate that, even though such natural dyes as gambier can save money and save the environment without causing significant changes in performance, synthetics such as ruthenium are more efficient. Significant potential strategies toward environmentally benign, rather efficient DSSCs with large-scale industrial potential are evidenced by the successful combination of natural and synthetic sensitizers.

1. Introduction

Renewable energy is derived from naturally replenished, virtually inexhaustible sources over human timescales. Unlike finite fossil fuels, contribute to environmental degradation, renewable energy sources offer a sustainable and cleaner alternative to meet our energy needs [1,2,3,4,5]. At this point, solar energy is harnessed from the sun's radiation using photovoltaic cells to generate electricity or through solar thermal systems to produce heat. It is abundant, widely distributed, and inexhaustible, making it one of the most promising renewable energy sources [1,3,4,6].

DSSCs typically consist of several layers that work together to convert sunlight into electricity such as a photoanode, a counter electrode, a photosensitizer or dye, and an electrolyte [2,7,8,9]. The photoanode is a thin layer of semiconductor material, usually nanoparticles, coated onto the Fluorine-doped Tin Oxide (FTO) layer. It absorbs photons from sunlight and generates electron-hole pairs, initiating the photoelectrochemical process [2,5,6,7,8]. The counter electrode is typically made of a conductive material, such as platinum-coated glass or carbon, and is placed opposite the photoanode. Its catalysis the reduction of the redox couples in the electrolyte, completing the circuit and allowing the flow of electrons back to the photoanode [5,6,8]. The dye in DSSCs play crucial role in absorbing sunlight and initiating the photoelectrochemical process that generates electrical current [10]. The dye molecules in DSSCs serve as light-absorbing agents, capturing photons from sunlight and converting them into electrically excitable states. When a dye molecule absorbs a photon, an electron in the dye molecule is excited from its ground state to a higher energy level. This excited electron is then injected into the semiconductor material's conduction band typically TiO_2 of the photoanode [8,11,12,13,14,15].

In dye-sensitized solar cells, a natural dye is introduced as a sensitizer. While metal free dyes including coumarin, cyanine and merocyanine dyes, derivatives, and porphyrin dyes have been employed as sensitizers, they have not been able to compete with ruthenium dyes regarding solar conversion efficiency [6]. A natural substance called "gambier" is made by pressing the leaves and branches of the gambier plant. Approximately 17,000 tones of gambier's were produced in West Sumatra Province, Indonesia, which accounts for 80% of the global gambier supply [17]. Although there are many chances to use natural dyes in dye sensitized solar cells (DSSC), their efficiency is still poor [19]. For synthetic dyes, including ruthenium and N719, are more efficient than natural dyes, they are more costly and need specific handling [10].

In recent times, a variety of researchers have created sensitizers using organic dyes found in flowers, forests, fruits, and leaves. These dyes are common and reasonably priced, containing pigments like flavonoids, proanthocyanidins, carotenoids, and tannins. Anthocyanins from Sapan linn wood was used, and according to Nasyori et al., it increased efficiency (0.196%), as well as that of mango (0.43%), rosella (0.37%), pawpaw leaf (0.2%), blue pea flower (0.15%), and flame tree flower (0.2%). Even at this point there is still a problem with their low efficiency because several attempts have been made to enhance them, including mixing in other ingredients, adjusting the concentration, and altering the macerating method [9].

For this research, the natural dye material that will be used is gambier. Gambier, derived from the leaves of *Uncaria* Gambier, is being explored as a sensitizing agent in Dye-Sensitized Solar Cells (DSSCs). Gambier contains polyphenolic compounds, such as catechins and tannins, which have been found to exhibit light-absorbing properties [16,17]. These compounds can absorb photons in the visible spectrum, making gambier a potential candidate for harvesting solar energy in DSSCs [18]. Natural and synthetic dyes are often combined in dye-sensitized solar cells (DSSCs) to overcome their weaknesses [19,20,21,22]. Although natural dyes are economical and environmentally friendly, they have slower electron dynamics, a smaller absorption spectrum, and lower efficiency, all of which can result in increased charge recombination and reduced solar performance [23,24,25,26]. The synthetic dye material that will be used is ruthenium. Ruthenium is more efficient than organic dyes, but it is expensive and requires particular care [5]. Regarding this challenge, this research will create gambier extracts, create a new dye, and modify the processing procedure using the mixing method [27,28,29,30]. From what has been discovered, the gambier extracts might be used as a sensitizer with success, so the researchers explored using both solvents to increase the DSSCs' performance. The outcomes will then be examined by using UV-visible (UV-Vis) spectrophotometers to analysis the pigment of sensitizer, field emission scanning electron microscope (FESEM) for the surface morphology, incident photon-to-current efficiency machine IPCE and IV measurement to calculate the solar efficiency using solar simulator.

2. Methodology

The process of creating and analyzing dye-sensitized TiO_2 films involves many crucial stages. To guarantee consistency and maximum adherence, substrate preparation first entails cleaning and preparing the substrate surface. The next step is to prepare the TiO_2 solution, which involves dissolving the precursor components in an appropriate solvent to produce a homogenous solution. Afterwards, this solution is used to the spray pyrolysis technique of TiO_2 deposition, where it is sprayed onto the substrate and undergoes thermal breakdown to produce a TiO_2 layer, the quality of which is determined by the deposition parameters. The deposited films are then exposed to high temperatures which is 450°C for an hour during the annealing process, which improves their structural integrity and crystallinity. Optimizing light absorption and charge transfer qualities is the goal of dye modification, which is accomplished by combining dyes with complimentary absorption spectra. In conclusion, a thorough evaluation and optimization of the TiO_2 films for applications like dye-sensitized solar cells (DSSCs) and photocatalysis is ensured by comprehensive characterization using techniques like Incident-Photon-to-Current Efficiency (IPCE) and current-voltage (IV) measurements to measure the efficiency of the DSSC, UV-Vis spectroscopy for optical properties and field emission scanning electron microscopy (FESEM) for surface morphology. The methodical creation and comprehension of dye-sensitized TiO_2 films for effective energy conversion and catalytic applications are ensured by this comprehensive methodology.

2.1 Substrate Preparation

The preparation of the Fluorine Tin oxide-coated glass substrate (FTO) substrate follows a systematic cleaning process. These measures were done by undertaking research on other journal and carrying out lab to experience which are the most effective measures in this study. First step is put the FTO in a beaker with deionized (DI) water and then put it in the ultrasonic cleaning (UC) machine to cut off any loose impurities which is five minutes. Then place it again inside the UC machine and plug it in ten minutes and introduce ethanol instead of the DI water to assist in dissolving organic contaminants. Substitute the ethanol with acetone which is a stronger solvent and add it to the mixture in the UC machine, wait ten more minutes. Wash out any remaining acetone and impurities using DI water and then wet again using acetone and then placing it in the UC machine for 5 mins. To dispose the solution safely and the most appropriate manner of disposal, pour the solution in the most appropriate bottle. Wipe the FTO with a piece of tissue to remove the remaining liquid. Finally, cover up the FTO by taping with Nitto tape to protect specific areas to be used in the subsequent processes.

2.2 TiO_2 Solution Preparation

To prepare TiO_2 solution, you need to weigh 0.15 g of commercial titanium dioxide powder P25 and add into the same mortar, once you have weighed 0.15 g of TTIP (titanium (IV) isopropoxide). To achieve a homogeneous mixture, the TTIP and P25 should be well ground. After acquiring a homogenous mixture, add 30 milliliters of ethanol to the mortar and grind once more till all the particles dissolve and the homogeneous mixture thus obtained is equal. Empty this mixture into a clean beaker. To stabilize the titanium precursor and to improve the dispersion of the particles, the next step is to add 5.5 ml of acetic acid to the beaker. After that 5 drops of a surfactant known as Triton X100, is added to the solution to spread the solution and minimize surface tension. Place the outlined beaker over a hot plate to enhance the dissolve of the individual components as well as mix them well within a time frame of 5-10min. This step will make sure that solution is prepared in the next step and while all reagents to be used is in the right position. Put this in beaker and mix first and then, put it in ultrasonic cleaning (UC) gun, particularly 1/2 an hour. To make sure that there is a homogenous combining mixture of the solution, the ultrasonic waves make sure that during this mixing process they dissolve the remaining pieces through molecular dispersion at a lower level as well. Finally, achieve it by using the spray pyrolysis method. By so doing, the solution is sprayed in a hot surface where the solvent is evaporated and the solute to dissolve chemically, thus leaving a thin and homogeneous layers of titanium dioxide.

2.3 TiO_2 Deposition Using Spray Pyrolysis Method

Spray pyrolysis is flexible and can also be cheap for depositing thin films of diverse material like Titanium dioxide (TiO_2). In this method, the substrate is first coached with an initial solution and when hit by a heater the droplets split, or pyrolyze to form a thin film. The fume might be produced or sprays during the procedure; therefore, the fume hood or spray chamber should have proper ventilation. Unfortunately, an inadequate discharge system would expose the operator to harm and assure that toxic gases continue to rise upwards. After that, connect the carrier gas or compressed air supply to the spray nozzle or ultrasonic nebulizer. The precursor solution is aided by the carrier gas, which is, in most cases nitrogen or air, to atomize into small droplets to effect uniform deposition. Controlling the flow rate of the gas should allow a stabilization of the spray pattern utilizing a consistent flow rate. Once the spray system is setup then place the substrate on a hot plate or a furnace and heat it to a temperature of 150°C. Before the precursor droplets encounter the substrate, this range ensures optimal pyrolytic process needed in the creation of superior TiO_2 layer. Uniform film characteristics and provides complete coverage and uniformity require a steady and constant temperature.

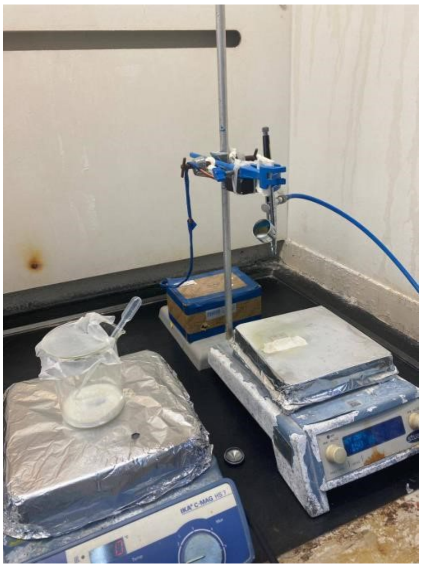

Fig. 1 *Spray pyrolysis that has been setup*

2.4 Annealing Method

An effective method for improving the overall characteristics, phase purity, and crystallinity of materials like TiO_2 sheets is annealing. The procedure is heating the material to an appropriate temperature, holding it there for a predetermined amount of time, and then cooling it down often in a controlled way. Make sure the TiO_2 coated substrate is securely attached and place it in a clean crucible or on an appropriate holder that can endure high temperatures to start the annealing process. Since impurities might change the characteristics of the TiO_2 layer, make sure the furnace is completely clean and clear of anything that can interfere with the annealing process. Choose the appropriate annealing temperature on the furnace, which usually ranges from 400°C to 600°C, based on whether you want to improve the phase purity and crystallinity of TiO_2 in the anatase or rutile forms. For this research, the high temperature is 450°C for an hour. To prevent thermal shock and guarantee consistent cooling, once the furnace reaches the appropriate temperature and the substrate has been annealed for the desired amount of time, gently cool the furnace to the surrounding temperature. Take care to remove the substrate from the furnace without contaminating it or causing damage. Look for any colour, texture, or integrity changes on the TiO_2 film since they might be signs of a successful annealing process. The effectiveness of the annealing procedure should be reflected in the increased crystallinity and improved optical and electrical characteristics of properly annealed TiO_2 films.

Fig. 2 *TiO_2 coated substrate in the furnace to anneal*

2.5 Modification of Dye

The dye technique improvement used in DSSCs is to mix synthetic dye with natural dye to maximize the potentials of both types of dyes and deliver the best performance. The dyes, which have been made from plants, are natural, readily accessible, affordable and eco-friendly. Natural dye has lower resistance even though their light absorption is high. They are generally less efficient. However, higher efficiency and stability is obtained with the use of synthetic dyes such as ruthenium complex-based dyes which have high cost and intricate synthesis procedures. The synthetic dye provides good electron transfer and stability and when combined with the natural dye it can extend the region of absorption thus giving more photons being absorbed in some areas [6,17,18,19]. The modification process involves extracting gambier dye and combining it with ruthenium dye. The optimized dye composition is evaluated using UV-Vis spectroscopy, FESEM, IPCE, and I-V analysis. An overview flow of the modification of dye is shown in Fig. 4. The following is the procedure of enhancing dye performance in DSSC applying the combination method there are several methods. First, two dyes are chosen which are inorganic and organic with different energy states, and different parts of the spectrum they can absorb. Ruthenium dye shall be categorized as synthetic dyes while gambier dyes shall as the natural dye. This makes it possible to achieve better colour results for the dye combination may absorb lighter and the range of light to which it is susceptible to be narrower. A balanced mixture is then prepared by mixing 2ml of the natural dye and 2 mL of a synthetic dye. In the preparation of the mixed dye solution, a substrate coated with a layer of TiO_2 is then placed in the dye mixture. Subsequently, the dye molecules can anchor themselves at the surface of TiO_2.

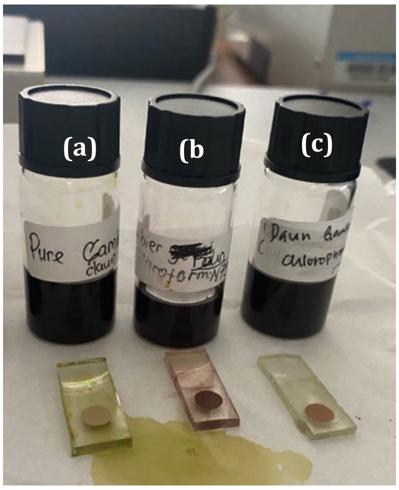

Fig. 3 *Enhancement of dyes which are (a) Pure gambier dye; (b) Pure ruthenium dye; (c) Combination of gambier and ruthenium dye*

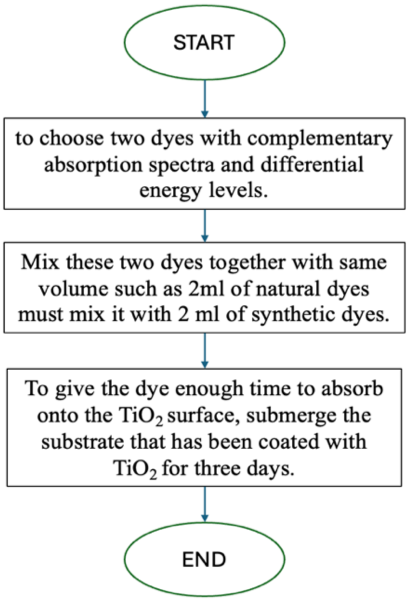

Fig. 4 *Flowchart of modification of dye*

2.6 Characterization

To characterize dye-sensitized TiO_2 films in order to comprehend their optical, electrical, and structural characteristics there are many methods are frequently employed, including current-voltage (I-V) measurements, field emission scanning electron microscopy (FESEM), UV-Vis spectroscopy, and incident photon-to-current efficiency (IPCE). Field emission scanning electron microscopy (FESEM) is used to study surface morphology and nanostructure. The effectiveness of a solar cell or optoelectronic device in converting incoming photons into electrical current at various light wavelengths, UV-Vis spectroscopy is used to analyze optical absorption and determine band gaps; and current-voltage (IV) measurements are used to evaluate electronic properties and overall performance in applications such as dye-sensitized solar cells (DSSCs).

3. Results and Discussion

TiO_2 films sensitized with pure TiO_2, ruthenium dye, gambier dye, or a combination of the two are used in this chapter to study dye-sensitized solar cells (DSSCs). It studies the relationship between efficiency and dye structure, light absorption, and photovoltaic performance. The findings of FESEM research, pure TiO_2 has a uniformly dense structure, but gambier dye produces a porous network and ruthenium dye contributes roughness and clumping. These effects are balanced by the combined dyeing. Different absorption profiles are shown by UV-Vis spectroscopy: ruthenium absorbs from 400–600 nm, gambier dye mostly absorbs from 350–550 nm, and the combined dye increases the absorption range. According to optoelectronic measurements, ruthenium dye has the highest efficiency (1.25%), followed by gambier dye, which is less effective but more sustainable, and the combination of both dye (1.09%). The chapter concludes with a recommendation that DSSC performance can be maximized by combining natural and synthetic dyes, possibly leading to more economical and efficient solar cells.

3.1 Field Emission Scanning Electron Microscopy (FESEM)

A major alteration in this research was to change the dye used in the dye-sensitized solar cells (DSSCs) by mixing two different sensitizers, being a natural dye of gambier and a synthetic dye of ruthenium complexes. The reason behind such a modification was to combine the individual power of both dyes. Gambier dye is environmentally friendly, cheap and available in abundance, but ruthenium dye has excellent photoelectrochemical activity because of its wide visible spectrum absorption, light-harvesting ability and efficient injection of electrons into the TiO_2 conduction band. Nevertheless, natural dyes such as gambier usually experience problems of poor surface adsorption to TiO_2, low absorption coefficients and stability in the presence of light, all of which restricts their efficiency as single sensitizers. Ruthenium dyes on the other hand are highly efficient, but expensive and could raise sustainability issues [3,6,9,17,18,19].

As TiO_2 films change with various dyes, the morphological evolution can be seen in the FESEM images. The research included four samples which are pure TiO_2, pure gambier dye, pure ruthenium dye, and a mixture of two dyes. Several morphological characteristics, especially among these samples, fully influence key DSSC functions as charge recombination, electron transport, and light harvesting. Important information about the material's properties and how they affect DSSC performance is provided through the FESEM data. Since it offers a high surface area for dye absorption, the pure TiO_2 film in Fig. 2(a) shows a homogeneous structure with many nanoparticles tightly packed together and few gaps or agglomerations. This makes it suitable for DSSC. This arrangement makes efficient light gathering and electron injection possible, given the fact that pure TiO_2 only has limited range absorption. Dye is used to enhance performance.

Fig. 2(b) shows a compact structure, most likely for the TiO_2 layer, connected to pure ruthenium dye. Ruthenium dyes efficiently absorb visible light, which significantly increases photon absorption. Fig. 2(c) shows how pure gambier dye creates a less uniform coating with some rough areas. The performance of DSSC may be limited by the fact that gambier dye is a natural dye that is both cost-effective and eco-friendly, but its stability and light-absorption efficiency are usually lower than those of synthetic dyes. A stronger and more uniform structure is generated in Fig. 2(d) by the combination of ruthenium and gambier dyes. The combination of the strong visible light absorption of ruthenium dye with the eco-friendly qualities of gambier dye could increase the range of light absorbed. Compatibility must be guaranteed, and dye collection must be prevented to prevent energy losses. The results that were obtained suggest the mixed dye form can be advantageous in DSSCs because it optimizes dye loading while maintaining an outstanding electron transport efficiency.

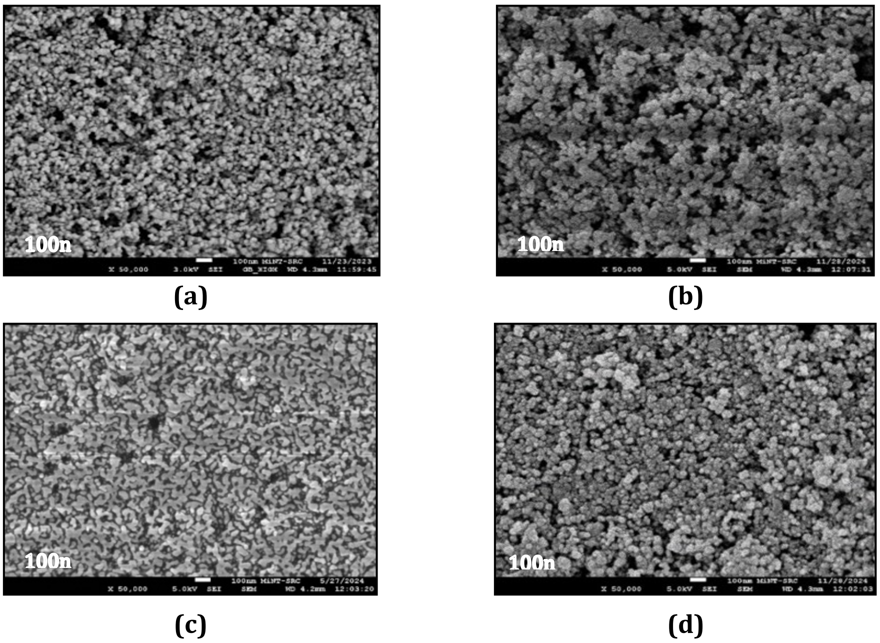

Fig. 5 (*a) Pure TiO_2 Film; (b) Pure ruthenium dye; (c) Pure gambier dye; (d) Combination of two dyes*

3.2 UV-VIS Spectroscopy

The wavelength and absorbance of each natural dye have been compared with those of synthetic and natural dyes. The light absorbance is likely caused by some of the pigments in the natural dye. More important than pigments' ability to reflect light is their ability to absorb light wavelengths [22]. The optical characteristics of DSSC depend on UV-Vis spectroscopy. Three dye samples are depicted in the graph: gamier dye (G), ruthenium dye (R), and a mixture of the two colors (Mix). The graph in Fig. 3 shows them.

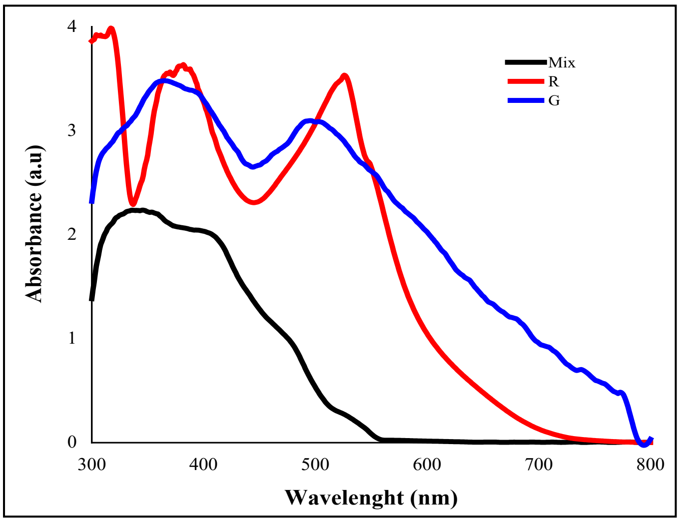

Fig. 6 *The UV-visible spectra of three sample of dyes*

The UV-Vis spectrum of the gambier dye, which displays the letter "G," indicates its potential as a photosensitizer for DSSC. The significant absorption peak observed in the 500–700 nm region demonstrates its capacity to efficiently absorb visible spectrum light, particularly in the red and near-red wavelengths. The color pigments in natural dyes have a direct impact on how well they absorb wavelengths. This means that blue pigments typically absorb red or orange light, but yellow pigments absorb blue light. While natural dyes are limited to the capability to absorb of their pigments, synthetic dyes are designed to capture photons across a broader spectrum, improving the effectiveness of light harvesting [10,22,26].

Particularly in the 350–550 nm range, the strong and separate absorption peaks represent the broad absorption profile and high molecular extinction value of the ruthenium dye ("R"), which has been designed for efficient light harvesting through the visible spectrum. Synthetic dyes, such ruthenium-based black dye, are well-known for their wide absorption spectrum and excellent performance in dye-sensitized solar cells (DSSCs). Unlike natural dyes, synthetic dyes can be molecularly modified to optimize photon capture at different wavelengths, such as the near-infrared spectrum, which is often unavailable to natural pigments [23].

Ruthenium dye has been combined with the better wavelength effects of the gambier dye and the enhanced photon absorption capabilities of the ruthenium dye. This results in a broader UV spectrum coverage and reduces the gaps that are visible when using either dye alone. This combination proves essential for improving DSSC performance since it makes better use of the available light energy. The combined effects of gambier dye's capacity to extend into longer wavelengths (300–550 nm) and ruthenium dye's significant absorption in the visible range make the "Mix" dye extremely helpful. Combining natural and synthetic dyes may improve light-harvesting performance, as shown by the "Mix" dye's extended absorption spectrum. Stability and high intensity of absorption are provided by the ruthenium dye, while the gambier dye provides cost-effectiveness and environmental sustainability. This combination provides the best possible balance between environmental and performance factors, which is consistent with the development goals of sustainable DSSC. Based on these results, the "Mix" dye is an attractive possibility to enhance the optical and electrical performance of DSSC since it offers a wider range of ultraviolet light.

3.3 I-V Measurement

A more sophisticated electrical gadget known as Dye-sensitized solar cell or DSSC uses dyes to capture the sunlight for electricity generation. The ability of a dye molecule to absorb light, excite electrons and facilitate the transfer of electrons to the semiconductor layer commonly transected as the light-harvesting layer (including TiO_2) is a significant determinant of the efficiency of DSSCs. According to Fig. 4 and Table 1, the study compares the photovoltaic result of DSSCs fabricated with gambier dye (G), ruthenium dye (R), and a blended dye (Mix). Based on a high Voc, Jsc, and FF, ruthenium dye has the highest efficiency at 1.25%. This is because of the better absorption wavelength range, effective charge pair formation, low recombination loss, and good photon absorption and charge transfer.

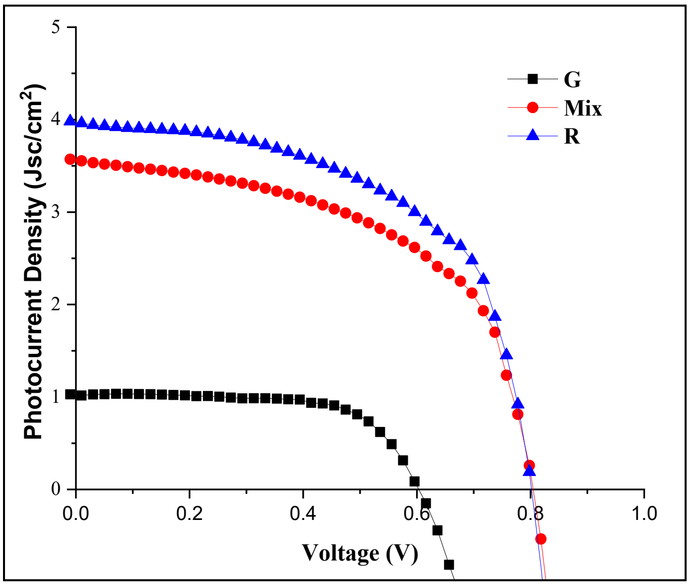

Fig. 7 *I-V curves of DSSCs obtained for pure gambier dye (G), pure ruthenium dye (R) and combination of dyes (Mix)*

Table 1 *The photoelectric performance parameters of pure gambier dye (G), pure ruthenium dye (R) and combination of two dyes (mix)*

Dye	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill Factor (*FF*)	Efficiency(η)
G	0.6011	1.0314	72.1098	0.43
R	0.8474	3.9799	45.9682	1.25
Mix	0.7449	3.5583	51.1273	1.09

In contrast, the gambier dye on the one hand provides stability, porosity, non-toxic character and can be used at lower cost, however, display a lower photoelectric conversion efficiency because of smaller light absorption, less electron injection and charge buildup, so it is not ideal for high performing photovoltaic applications [17]. The Mix dye, a product of a blend of gambier and ruthenium dyes, provide moderate performance due to the expansion of light absorption range and increased photocurrent generation all from the balance achieved between efficiency, sustainability and cost. This combination shows the possibilities to enhance DSSCs using the advantages we have identified in both dyes while avoiding the weaknesses, pointing out that dye compatibility and natural dye quality are significant aspects that must be addressed to achieve further improvements in sustainable and eco-friendly, low-cost DSSCs.

3.4 IPCE Measurement

The dye must be able to absorb light in the visible spectrum (400–700 nm) to have the best photon-to-electron conversion and improve a DSSC's efficiency. Consequently, dye selection and optimization are important to the general operation of the cell. The effectiveness of dyes in DSSCs cannot be determined simply by looking at the absorption spectra. The wavelengths of light that dye can absorb are shown by absorption spectra, however they do not describe how much of the absorbed light is transformed into electrical power. The idea known as the Incident Photon-to-Current Efficiency, or IPCE, is applied here. IPCE shows how to use the photogenerated charges to create current and inject it into the semiconductor, allowing for an immediate connection between the dye's electrical and optical characteristics. When the dye has a high IPCE, it can both properly absorb light and pass energy that creates current. The combination of DSSC's absorption spectra and IPCE analysis is, therefore, necessary for a complete understanding and enhancement of its performance.

The spectrums of absorption of three dyes are shown in Fig. 5 for ruthenium dye (R), gambier dye (G), and a mixture of the two (Mix). Gambier dye is environmentally friendly because it looks like natural dye made from plants. The dye showed important photon absorption in the blue area of visible light, as shown by the high absorption peak that was discovered at about 500 nm. It is unable to efficiently capture sunlight in the visible spectrum because of its decreased absorption in the green, yellow, and red regions. The synthetic black dye ruthenium shows absorption in most visible light wavelengths, with the highest absorption occurring at 550 nm. Because it perfectly fits the solar spectrum, this broad absorption is especially helpful for DSSC applications, allowing it to effectively capture an important amount of the total solar energy.

The considerable change in the absorption spectrum of the dye combination (Mix) can be explained by the complementary absorption characteristics of the ruthenium and gambier dyes, which result in a wider and more balanced light-harvesting wavelength than the individual dyes. Gambier dye is a natural dye that has a small absorption at longer wavelengths but a considerable absorption of blue spectrum light and shorter wavelengths, approximately 400–500 nm, because to its special pigments. In contrast, the synthetic dye ruthenium dye has good metal-ligand charge transfer transitions that allow it to absorb over the mid-visible to red area, which is approximately 500–600 nm.

Together, the two dyes produce a spectrum that includes the essential 400–700 nm range, which is where most solar energy is found. This wide and balanced spectrum enables the combination to absorb photons from both high-energy blue light and low-energy red light, improving the overall density of absorbed photons and the corresponding photocurrent. The main reason for the shift in wavelength coverage is the two dyes' crossing and simultaneous absorption capabilities, which fill in the spectrum gaps created by each dye when used alone. Similar procedures boost photon consumption and the likelihood that light will be converted to electric current, which in the end improves device performance and ensures non-selective solar light absorption—both of which are essential for effective DSSC. Hence, Fig. 3 shows the extended absorption range of the mixed dye; Fig. 4 demonstrates improved current-voltage characteristics; and Fig. 5 confirms that the hybrid dye system yields higher IPCE compared to the natural dye alone, indicating better solar energy harvesting.

It is expected that the ruthenium dye's enhanced and expanded absorption spectrum and extremely effective electron injection ability will lead to a greater IPCE in terms of IPCE implications. Due to its poor electron injection efficiency and limited capacity to absorb energy levels, gambier dye, which is inexpensive and environmentally begin, may have a lower IPCE value than other similar products. However, the blend offers a chance to compensate for its weaknesses and strengths. The effectiveness of combining ruthenium dye with gambier dye, a natural dye, suggests that a ratio between the two may be ideal for practical and affordable dye-sensitized solar cells.

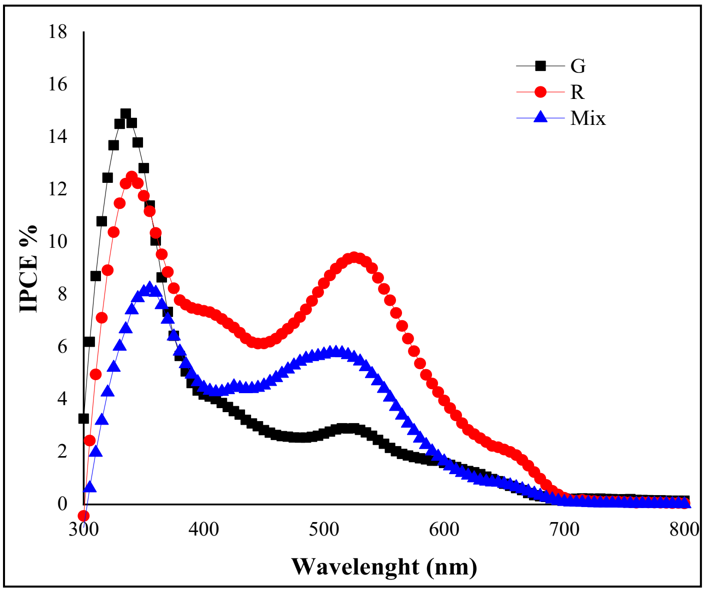

Fig. 8 *IPCE spectra of pure gambier dye (G), pure ruthenium dye (R) and combination of dyes (mix)*

Compared to previous studies such as Supriyanto et al. (2023) [7] and Nakhaei et al. (2022) [10], which reported efficiencies around 0.9%–1.4% for similar hybrid DSSC systems, the results in this work show comparable or superior performance, confirming the effectiveness of the combined gambier-ruthenium dye approach.

4. Conclusion

This paper elucidates how proper combination of dyes, and their choice can improve the efficiency of the DSSC. Through overall analysis of the FESEM image, UV-Vis absorption spectra, I-V performance curves, and IPCE, we can conclude that the combination of natural gambier dye with synthetic ruthenium dye to form a mixed dye system really has strong effect of promoting about the overall performance of dye-sensitized solar cells (DSSCs). The FESEM images demonstrated that the mixed dye-coated TiO_2 film possesses a more even and conductive network-like morphology as opposed to the uneven and weak coating of pure gambier which suggests the enhanced dye coverage and electron transport pathway in the former. UV-Vis spectroscopy revealed that the mixed dye offers more complete absorption range over the visible spectrum because mixing the strong light-absorbing ruthenium in 400-600 nm with the long-term absorption of gambier in 500-700 nm amplifies the capacity of the cell to harness sunlight. As shown in the I-V measurements, although ruthenium dye gave the highest efficiency (1.25%), mixed dye also gave good results (1.09%) indicating clearly the great improvement of gambier alone (0.43%) with the synergistic effect of both dyes with respect to greater photocurrent (Jsc) and better fill factor (FF). Moreover, the IPCE spectra also stated that the mixed dye possessed a broader and more even photon-current conversion profile through the solar spectrum, which enhanced the quantum efficiency over gambier by itself. In general, natural and synthetic dyes blend is a rather good approach to enhance the efficiency of DSSC, creating a cost-effective and environmentally sustainable solution to keep high levels of light-harvesting and conversion of electrons in DSSC.

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Conflict of Interest

The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its submission and declare no conflict of interest on the manuscript.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Nurathirah M. A;* ***data collection:*** *Nurathirah M. A;* ***analysis and interpretation of results:*** *Nurathirah M.A, D.G. Saputri, M.K. Ahmad;* ***draft manuscript preparation:*** *M.Y. Ahmad, K.N.Ramli. All authors reviewed the results and approved the final version of the manuscript.*

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