

INTERNATIONAL JOURNAL OF
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REVOLUTION (IJIREV)www.gaexcellence.com/ijirev**EFFECT OF MANGOSTEEN PERICARP DYE
SENSITIZATION PERIOD ON THE MORPHOLOGICAL
AND ELECTRICAL PROPERTIES OF TiO₂/P3HT HYBRID
THIN FILMS FOR SOLID-STATE DYE-SENSITIZED
SOLAR CELLS**

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Abstract:

The effect of the sensitization period of mangosteen pericarp (*Garcinia mangostana* L.) dye on the morphological and electrical properties of TiO₂/P3HT hybrid thin film for solid-state DSSC application is studied. The dye solution extracted is yellowish red in color, consisting of anthocyanin and α -mangostin as the photosensitizers, which can absorb visible light and be used as natural sensitizing compounds for DSSC

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applications. Electrodeposition of TiO_2 thin films was conducted on an indium tin oxide (ITO) glass substrate by an electrochemical method with 3 scans. Afterwards, they were dipped in the natural dye for periods of 5, 10, 15, and 20 min to ascertain the optimum immersion time. The SEM examination of the morphology of the TiO_2 thin films at a $5000\times$ magnification and 15 kV accelerating voltage showed clear differences revealing the changes in the structure and uniformity of the films at different immersion times. The obtained results highlighted that immersion time influenced the charge-transfer efficiency, with shorter times producing homogeneously dispersed nanoparticles, while longer times caused particle aggregation. Under light conditions, the highest electrical conductivity (0.044 S cm^{-1}) of mangosteen pericarp dye was obtained at a 10-min sensitization time. SEM analysis indicated that the 5-min and 10-min samples had relatively similar morphologies, which could be conducive to charge transport, while longer sensitization periods (15–20 min) led to increased porosity and particle aggregation. In general, the best immersion time for the surface morphology and electrical conductivity parameters relevant to DSSC properties is 10 min. In short, the morphology and electrical conductivity of the hybrid thin film were influenced by the immersion period.

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Keyword:

Dye Loading, Dye-Sensitized Solar Cell, Electrical Conductivity, *Garcinia Mangostana* L., Immersion Period, Morphology



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Introduction

Progress in low-cost photovoltaic technology, as an alternative sustainable energy source to traditional silicon-based solar cells, has accelerated as the demand for sustainable and renewable energy has grown globally (Mondal et al., 2026). In the context of low-cost photovoltaic technologies, dye-sensitized solar cells (DSSCs), which are also regarded as third-generation solar cells, have garnered considerable attention because of their simple fabrication, low production cost, and use of natural and abundant materials (Malhotra et al., 2024). A typical DSSC is composed of a nanocrystalline titanium dioxide (TiO_2) photoanode sensitized with dye molecules which harvest sunlight and produce photoexcited electrons. The addition of semiconducting polymers in photoelectrodes based on TiO_2 has proven to be a successful approach to promote charge transport, to prevent electron-hole recombination, and to boost photovoltaic performance. The p-type semiconducting polymer poly(3-hexylthiophene) (P3HT) is known for its excellent electrical conductivity, high hole mobility, chemical stability, and the ability to absorb a large amount of visible light (Liang et al., 2022).

The dye sensitizer is a vital component in the light collection and conversion of solar energy to electrical energy. Synthetic dyes, including ruthenium complexes, have been widely employed due to their high efficiency. They, however, are costly, challenging to manufacture, and pose environmental issues (Prajapat et al., 2024). Therefore, natural dyes have gradually become a subject of interest as environmentally friendly sensitizers because of their biodegradability, nontoxic nature, easy availability, and cost-effectiveness (Yadav et al., 2023). The mangosteen (*Garcinia mangostana* L.) pericarp is one of the most abundant agricultural wastes containing high concentrations of anthocyanins, xanthenes, flavonoids, and other phenolic compounds with good absorption of visible light, which is essential for photoconsuming dyes and functional groups that can be anchored onto the TiO₂ surface (Ijod et al., 2026). Utilization of mangosteen pericarp extract not only offers a sustainable alternative to synthetic dyes, which are more costly, but also contributes to the circular economy and green chemistry principles by utilizing agricultural by-products.

Despite the fact that many studies have been conducted on the hybrid thin films of TiO₂/P3HT and on natural dye sensitizers alone, few studies have been performed to determine the effect of the dye immersion duration on the morphological and electrical properties of a TiO₂/P3HT hybrid film with mangosteen pericarp extract. It is important to have a full understanding of this relation to optimize fabrication conditions and enhance the performance of environmentally friendly hybrid photoelectrodes. Hence, the effect of the immersion period on the morphological and electrical properties of a TiO₂/P3HT hybrid film sensitized with natural dyes extracted from the mangosteen pericarp is the focus of this study. The hybrid thin films were prepared by electrochemical deposition and then immersed in the natural dye solution for different durations and spin-coated with P3HT solution. The surface morphology of these hybrid thin films was studied by scanning electron microscopy (SEM), and the electrical conductivity of these hybrid thin films was determined by a four-point probe. The results offer insight into the optimization of dye-sensitization conditions to get desirable morphological and electrical features in a hybrid thin film of TiO₂/P3HT for photovoltaic applications.

Literature Review

This section summarizes the current knowledge on solid-state dye-sensitized solar cells (ss-DSSCs) based on TiO₂ semiconductors, P3HT conductive polymers, and natural dyes extracted from mangosteen pericarp and on the factors influencing the performance of DSSCs.

Dye-Sensitized Solar Cells

The world today is dependent on fossil fuels for energy. Human activities like the combustion of fossil fuels (coal and oil) have raised the concentration of carbon dioxide (CO₂) in the atmosphere, and these activities pose a lasting threat to the environment on a global scale and contribute to climate change (Shahul Hamid et al., 2026). Now, as the world reels from a growing demand for renewable and sustainable energy, the advancement of solar energy technologies as a practical alternative to fossil fuels has quickened. According to Al-Ezzi and Ansari (2022), a solar cell is a device which changes solar energy into electrical energy by the photovoltaic effect. It is a photoelectric device where electrical properties such as current, voltage, and resistance vary when exposed to light, allowing the generation of electrical power (Patel et al., 2024). Although conventional silicon-based solar cells have high power conversion efficiency, they are too costly to produce and require high-purity silicon to be utilized.

As such, 3rd-generation solar cell technologies specifically, DSSCs, have garnered significant research attention as an economically viable and sustainable alternative to traditional cells. A DSSC is a photovoltaic device that transforms solar energy into electrical energy by using a photosensitizing dye. DSSCs are different from traditional silicon-based solar cells because they use a dye-sensitized semiconductor, such as titanium dioxide (TiO_2), to absorb sunlight and transfer the electrons, along with an electrolyte that is known as a redox electrolyte (Aslam et al., 2020a). Nevertheless, in these DSSCs, the use of a liquid electrolyte results in the corrosion of the electrodes. In this case, a semiconducting polymer like P3HT is used as the hole-transport material, and this kind of solar cell is called a solid-state DSSC. A typical DSSC is made from a mesoporous photoanode layer of TiO_2 coated with a light-harvesting dye either made synthetically or with natural material. The synthetic dyes, including ruthenium complexes, porphyrin dyes, and cyanine dyes, have excellent light-harvesting capability and high-power conversion efficiency. Despite these, however, they have certain cons that restrict their practical use, such as high production cost, a difficult synthesis process, limited availability, toxicity, and environmental impact (Alim et al., 2022). On the other hand, natural dyes emerged as attractive dyes because they are abundant, biodegradable, nontoxic, environmentally friendly, and can be used as photosensitizers in sustainable DSSC applications.

Titanium Dioxide

TiO_2 has three naturally occurring crystalline phases, namely anatase, rutile, and brookite, as shown in Figure 1 (Chalastara et al., 2020). Nanocrystalline TiO_2 , especially in its anatase phase, has gained significant interest due to its high chemical stability, controllable morphology, low price, nontoxicity, and appropriate band gap energy (3.2 eV for anatase and 3.0 eV for rutile) (Ismail et al., 2024). However, TiO_2 has a relatively large band gap that results in a photoresponse wavelength less than ~ 380 nm, corresponding to the UV region of the sun's spectrum, which accounts for less than 5% of the incident light. Therefore, it is not able to use visible light to the full extent, which limits its overall photovoltaic performance. Even so, TiO_2 is the most popular semiconductor material used in DSSCs due to its favorable conduction band position, high electron mobility, large specific surface area, excellent chemical stability, and efficient photoelectric properties as a mesoporous photoanode material (Pirdaus et al., 2026). These exceptional properties have led to numerous applications of TiO_2 , such as solar energy conversion, photocatalysis, optoelectronics, catalysis, photochromic devices, and gas sensing.

Surface area, exposed crystal facets, particle size, and degree of crystallinity are important factors affecting the photovoltaic performance of the TiO_2 nanoparticles. These physicochemical properties are important for the adsorption of the dye, the efficiency of light harvesting, and the efficiency of electron transport in DSSCs (González-Verjan et al., 2020a). Hantusch et al. (2018) reported that, in the case of TiO_2 nanoparticles, they are prone to aggregation with each other by weak van der Waals interactions. Under moderate-temperature heat treatment, various processes take place which can have a profound impact on the surface area and shape of the nanoparticles. Firstly, the specific surface area increases as a result of the formation of pores from the evaporation or decomposition of the remaining organic compounds. Moreover, with the decrease in particle size, the surface area increases and thus supplies more sites for dye adsorption. Long heat treatment, however, encourages particle agglomeration and grain growth whereby more stable covalent bonds between particles begin to be formed in place of weaker van der Waals interaction bonds. This process results in rigid

grains of reduced porosity, which consequently reduces the specific surface area of the photovoltaic TiO_2 photoanode and may affect its photovoltaic performance (Hantusch et al., 2018).

The process of deposition, as well as calcination temperature, significantly affects the physical properties of TiO_2 materials (Arifin et al., 2024). Generally, the TiO_2 films change from amorphous to anatase and then to rutile with increasing calcination temperature (Lal et al., 2021). Thermal treatment at high temperatures is an important factor to improve the structural and electrical properties of TiO_2 films. On one hand, the calcination process improves the electrical contact between TiO_2 nanoparticles and the substrate, which helps in the transportation of electrons. On the other hand, it facilitates the creation of a porous nanocrystalline network of interconnected TiO_2 nanoparticles with a high surface area and pathways for efficient electron transport for the adsorption of the dye.

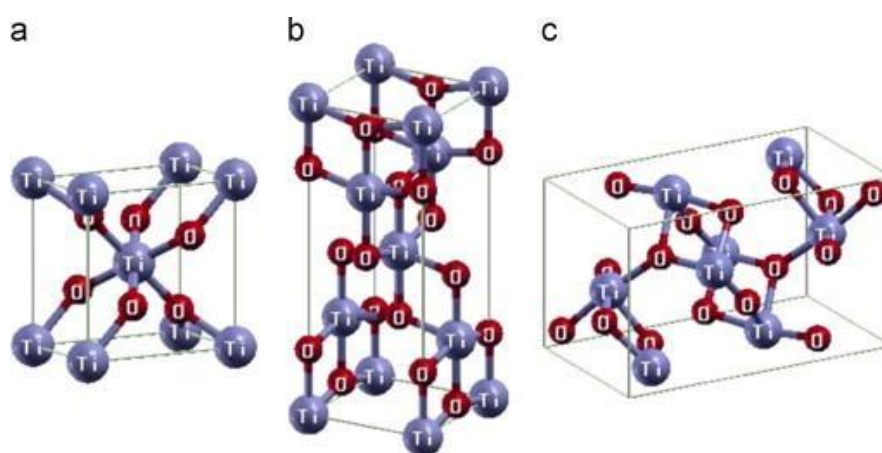


Figure 1: Structure of TiO_2 (a) Rutile, (b) Anatase, and (c) Brookite (Mohamad et al., 2015)

Poly (3-Hexylthiophene) (P3HT)

P3HT is a conjugated polymer which can absorb visible light and transport charge and has been widely used in optoelectronic devices. It has a conjugated backbone with alternating single and double bonds that enable π -electrons to travel up and down the polymer chain, as shown in Figure 2. The overlapping p -orbitals within this structure enable the electronic states to be delocalized along the polymer chain. Therefore, if enough energy is absorbed from the photons, the electrons can move from the highest occupied molecular orbital (HOMO) to the lowest unoccupied molecular orbital (LUMO) (Nguyen et al., 2021; Cohgi & Coluccini, 2024).

P3HT is known for its extensive optical absorption range (~ 400 – 650 nm), photostability, flexibility, and charge-transport properties (Hussein et al., 2025). P3HT is a semiconducting polymer with p -type behavior and can serve as a hole transport material in conjunction with an inorganic semiconductor like TiO_2 . The role of TiO_2 in the hybrid film is mainly that of electron transport, and P3HT functions as a hole transport component. The use of both materials together thus offers different charge-transport functions in the same film.

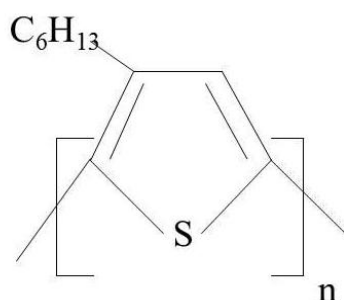


Figure 2: The Chemical Structure of P3HT (Hussein et al., 2025)

Natural Dyes

Due to their high light-harvesting property and favorable photovoltaic response, the ruthenium-based sensitizers like N3 and N719 are widely used in DSSCs. However, their more extensive utilization is hindered by the high cost, intricate preparation processes, and potential toxicity and environmental effects of the materials. Therefore, plant pigments are being explored as alternatives. Compared to many synthetic dyes, they are generally easier to obtain and cheaper, as well as being more biodegradable. Natural sensitizers are found in various biological materials such as fruit, flowers, leaves, peels, and bark, and are appealing for their abundance, biodegradability, and low cost.

Mangosteen (*Garcinia mangostana* L.) pericarp is of special interest, as it is usually considered a waste product in the agricultural industry but contains a high concentration of naturally colored compounds, as seen in Figure 3. During fruit processing, there is much waste in the form of the pericarp, which accounts for about 70% of the mass of the mangosteen fruit (Soontornwat et al., 2025). The production of this material as a photosensitizing extract therefore provides an opportunity to valorize the agricultural waste and to obtain a renewable dye source for photovoltaic generation.

The pericarp has a number of bioactive compounds such as anthocyanins, xanthenes, tannins, and flavonoids. In Figure 4(a), the chemical structure of anthocyanin is shown. The absorbance in the visible region is particularly important for DSSCs, and anthocyanins are a type of dye that can absorb in the visible region due to the conjugated structures. Moreover, mangosteen is rich in xanthone derivatives, especially α -mangostin, which has an extended aromatic conjugated system which can interact with UV-Vis's radiation, as shown in Figure 4(b). The interactions between dye molecules and the surface of the semiconductor may also be enhanced by hydroxyl and carbonyl groups within these compounds in order to develop effective sensitization of the semiconductor (Li et al., 2025).

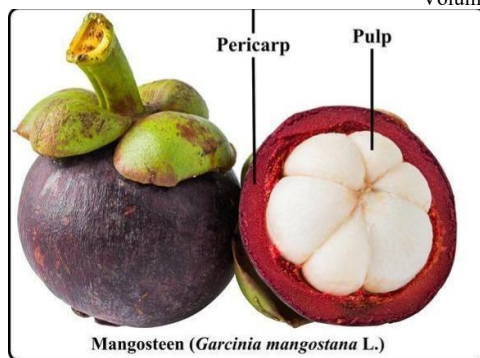


Figure 3: Mangosteen (*Garcinia mangostana* L.) Pericarp (Ijod et al., 2026)

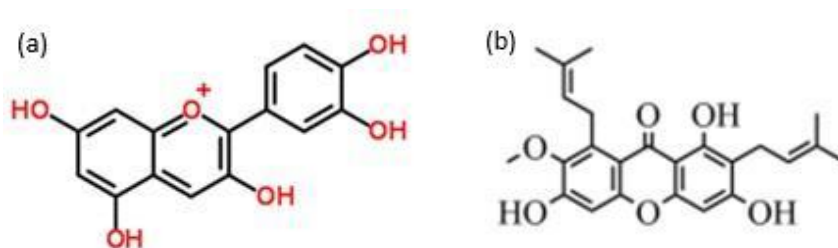


Figure 4: Chemical Structure of (a) Anthocyanin (Mattioli et al., 2020) and (b) Alpha-mangostin (Rizaldy et al., 2021)

Factors Affecting the Performance of DSSC

Several parameters such as dye composition, extraction solvent, and the sensitization period can affect the light harvesting and the transfer of the interfacial charge, which determine the performance of the DSSC.

Types of Solvent Used for Dye Extraction

Different solvents used for extraction correspond to different pigment molecules and bioactive materials obtained from plant material. Hence, the polarity of the solvents is crucial to consider while preparing the natural sensitizer. Ethanol is used for a large variety of solutes, including many phenolic and pigment-containing compounds, and is relatively easy to manage. Lohvina et al. (2021) found that the use of ethanol is a good choice for the recovery of polyphenolic compounds from plant materials. In the case of application in DSSCs, the extraction medium could also affect the interaction between the retrieved dye molecules and the TiO₂ surface. Hence, a proper solvent will improve the yield of pigments and make it easier to prepare the dye solution for the sensitization of semiconductors.

Pigment of Natural Dyes

The response to light by the natural sensitizer is highly sensitive to the pigment molecule content of the extract. A good DSSC sensitizer should absorb a part of the sunlight spectrum that is useful for the conversion process and should have chemical groups to interact with the semiconductor surface (Hug et al., 2014). In the case of plant-derived dyes, both carbonyl and hydroxyl functional groups may influence the interaction with TiO₂ and could potentially play a role in surface complexation (Moloto et al., 2026). The absorption characteristics of various

natural pigments are different due to the differences in the molecular structure of the pigment. The pigmented part of mangosteen fruit, namely mangosteen pericarp, has a significant visible-light absorbance capacity, and pigments containing anthocyanin are the main pigments responsible for the color of mangosteen extract (Jamalullail et al., 2017). These properties render the pericarp a possible natural sensitizer in TiO₂-based solar cells.

Dye Sensitization Period

The duration of dye sensitization is an important processing parameter as the process of dye adsorption onto TiO₂ is time-dependent (Shahrul et al., 2022). A brief sensitization period might not allow for adequate interaction between the sensitizer and semiconductor surface, while a long period of sensitization might lead to molecular aggregation or overcoverage of the surface. Both can affect the shape and electric properties of the resulting photoelectrode. The optimal sensitization time is dependent on the composition and concentration of the dye and the interaction between the dye and the TiO₂, as reported in previous studies. For instance, Hossain et al. (2017) have observed an optimum sensitization time of 2 hours for a turmeric dye, while Hardeli et al. (2019) have obtained better photovoltaic behavior with a much longer sensitization time. This shows that the same duration of sensitization could not be used for all natural dyes.

Krawczak & Zdyb (2020) also found that the uptake of the dye is influenced by the duration of the exposure and the dye concentration. Depending on the concentration, longer contact times may be necessary to ensure adequate surface exposure, while others can be sensitized in a shorter time using a higher-concentration solution. Hence, it is necessary to set up a suitable sensitization period to promote good dye–TiO₂ interactions without unnecessary processing and dye buildup. The effect of short sensitization times is less well known for mangosteen-pericarp-sensitized TiO₂/P3HT hybrid films. The present work thus deals with four different sensitization times of 5, 10, 15, and 20 min to see the variation of these parameters with the different sensitization times, namely, surface morphology and electrical conductivity.

Methodology

Materials

ITO-coated glass substrate having a nominal sheet resistance of 6–8 Ω sq⁻¹ was purchased from Sigma-Aldrich. The commercial TiO₂ powder (P25), Triton X-100, acetone, and acetic acid were also provided by Sigma-Aldrich. Ethanol (97%) and 2-propanol (99%) were both obtained from Fluka. During the preparation of the films, distilled water and P3HT were also used. All chemicals were used as received without any further treatments.

Extraction and Preparation of Natural Dye

The pigment source used was mangosteen fruits bought from the local market in Kuala Terengganu, Malaysia. The extraction process was modified from Salleh et al. (2025). The pericarps were cleaned, separated from the edible part, cut into smaller pieces, and dried at 60 °C to a constant weight. The dried material was then ground to a very fine powder. The mangosteen pericarp powder was extracted by mixing with 50 mL ethanol and kept under refrigerated conditions for 3 days. The resulting mixture was filtered to remove solids. The extract collected was wrapped in aluminum foil to avoid light exposure and kept in a

refrigerator until needed for further use. After the extraction process, the solution was found to be clear with a yellowish-red color, as demonstrated in Figure 5.

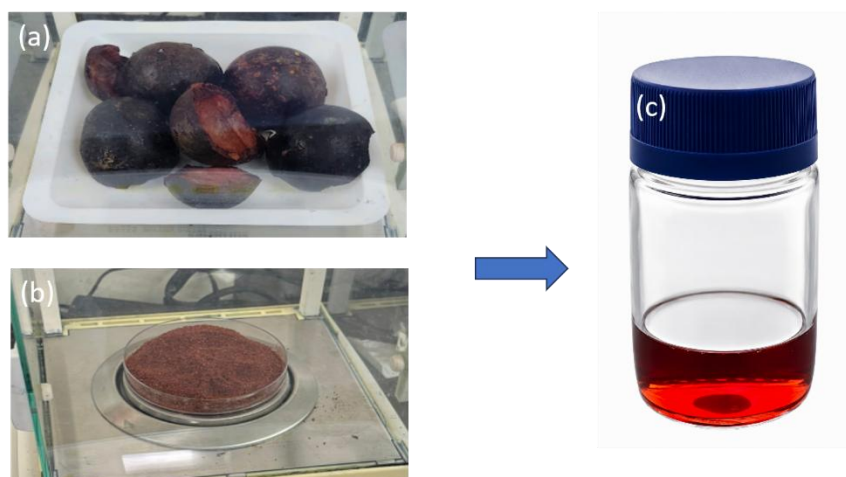


Figure 5: Preparation of Mangosteen Pericarp Dyes (a) Fresh Pericarp, (b) Finely Ground Pericarp Powder, and (c) Extracted Dye Solution.

Preparation of Titanium Dioxide (TiO₂) Colloidal

To prepare a TiO₂ paste, 0.2 g of the commercial TiO₂ powder was ground, and a few drops of 0.035 M acetic acid were added. Then, Triton X-100 was added in small amounts to help disperse the particles and prevent the particles from agglomerating. The prepared paste was added to 100 mL of deionized water and stirred magnetically for 1 h at 300 rpm to get a uniform dispersion of the TiO₂.

Preparation of Poly(3-hexylthiophene) (P3HT)

A homogeneous solution of P3HT was made by dissolving 0.15 g of P3HT in 10 mL of chlorobenzene. The mixture was kept at 60 °C under continuous magnetic stirring with high stirring speed (850 rpm) overnight for complete dissolution of the polymer.

Fabrication of Thin Film

ITO-coated glass was fabricated into 2 cm × 2 cm substrates and sonicated in distilled water, acetone, and 2-propanol for 10 min per solvent. The cleaned substrates were then left to dry at room temperature. The TiO₂ film was electrodeposited onto the ITO substrate within the potential range of −1.0 V to +1.0 V at a scan rate of 50 mV s^{−1} in three cycles. After deposition, the films were heat-treated at 450 °C for 2 h to enhance contact among the particles in the TiO₂ layer (Jiang et al., 2024). The cooled substrates at around 80 °C were sensitized with the mangosteen extract for 5, 10, 15, and 20 min at room temperature, in the dark, after which each film was gently washed with ethanol and dried at 60 °C for 10 min. The P3HT was then deposited on top of the TiO₂/dye by spin coating at a rate of 300 rpm, resulting in the ITO/TiO₂/dye/P3HT hybrid structure. A similar film without dye sensitization using mangosteen extract (ITO/TiO₂/P3HT) was used as the control.

Characterization of Natural Dye and Thin Film

The mangosteen extract was used to measure optical absorption with a UV–Vis spectrophotometer (Cary 50Conc) in the range of 200–700 nm. The chemical functional groups present in the extract were analyzed using a Nicolet iS20 FTIR spectrometer in the range of 4000–500 cm^{-1} . A magnified SEM image (JEOL) at 15 kV was taken to assess the surface features of the hybrid films at 5000 $\times$. A four-point probe (Jandel RM3) was used to make electrical measurements. Readings were taken at three different points on the film surface to estimate the spatial variation, and the mean reading was taken for the analysis. The sheet resistance (R_s), resistivity (ρ), and conductivity (σ) values were calculated using the following equations:

$$R_s = 4.532 \times \frac{V}{I} \quad (1)$$

$$\rho = R_s \times t \quad (2)$$

$$\sigma = \frac{1}{\rho} \quad (3)$$

where V is the measured potential difference, I represents the applied current of 1 mA, t is the film thickness, and 4.532 denotes the correction factor used in the sheet resistance calculation.

Results and Discussion

Absorption spectrum of Mangosteen Dye

The dye extracted appeared as a clear yellowish-red solution as shown in Figure 5, which is evidence for the presence of naturally occurring color in the mangosteen pericarp. The bioactive molecular components of the fruit responsible for its characteristic color include anthocyanins and α -mangostin, which have conjugated molecular structures that absorb light in the visible region (Maddah et al., 2025a). Figure 6 shows the UV–visible absorption spectrum of the ethanol extract of mangosteen pericarp. The spectrum was recorded over the visible wavelength range of 400–700 nm.

The mangosteen extract showed significant absorption in the visible region with peak absorptions at about 535 nm and 667 nm. The wide range of absorption shows that the extract has the capacity to absorb light in a large part of the visible region. This absorption behavior aligns with the presence of pigments in the extract, including anthocyanins, which give it a reddish hue (Bahreini et al., 2024). Thus, the yellowish-red color of the solution observed is consistent with its absorption characteristics in the visible spectrum. Sofyan et al. (2018) also reported similar absorption behavior for a natural dye made from mangosteen extract, which corroborates the presence of pigment compounds which are visible-light-absorbing in the extract. The absorption of photons by the mangosteen dye throughout this relatively wide range

of wavelengths therefore points to its potential applications as a natural light-harvesting sensitizer for photovoltaic applications.

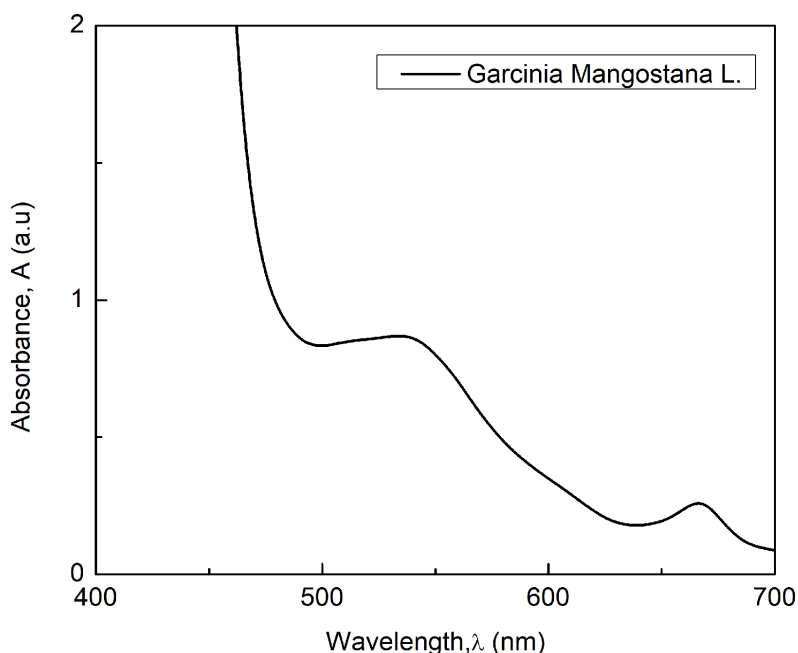


Figure 6: UV-Vis Absorption Spectrum of Mangosteen Pericarp Dyes Extracted Using Ethanol Solvent

Functional Group of Mangosteen Dye

The FTIR spectrum of the pericarp extract of mangosteen is shown in Figure 7, and the results of peak assignments are given in Table 1. A wide band in the region around $3600\text{--}3000\text{ cm}^{-1}$ is due to O–H vibration of hydrogen-bonded hydroxyl groups. The band between ~ 2973 and $\sim 2878\text{ cm}^{-1}$ is due to C–H stretching. The band near 1640 cm^{-1} is attributed to the carbonyl (C=O) stretching, in which the position of the band may be affected by the conjugation and intramolecular hydrogen-bond interactions in the xanthone-related molecules. The bands in the region $1045\text{--}1142\text{ cm}^{-1}$ are attributed to the C–O and C–O–C stretching modes, while the bands in the region $800\text{--}880\text{ cm}^{-1}$ are attributed to the out-of-plane aromatic C–H bending modes.

Similar spectral characteristics have been reported earlier on an ethanolic extract from mangosteen pericarp (MP). Arifin et al. (2021), for example, identified O–H, C–H, C=O, and C–O-related bands at approximately 3318 , 2981 , 2881 , 1640 , and 1076 cm^{-1} , respectively. The presence of hydroxyl-, carbonyl-, and ether-containing functionalities in the extract is supported by the agreement between these reported bands and the present spectrum. These groups are present in anthocyanins and xanthenes and could be responsible for the interactions between the sensitizer and the surface of TiO_2 (Sofyan et al., 2026).

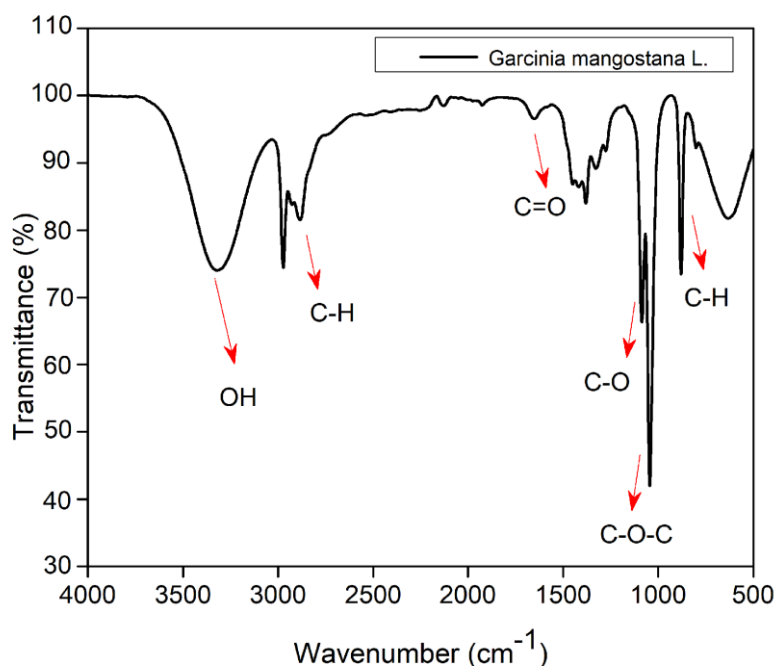


Figure 7: FTIR Spectrum of Mangosteen Pericarp Extracted Using Ethanol Solvent

Table 1: FTIR Absorption Bands and Corresponding Functional Groups of the Extract of Mangosteen Pericarp

No.	Wavenumber (cm ⁻¹)	Functional Group	Group
1.	876	C-H	Out-of-plane aromatic ring vibrations
2.	1032	C-O-C	Ether
3.	1076	C-O stretching	Phenolic
4.	1640	C=O stretching	Carbonyls
5.	2881	C-H	Alkyl
6.	2981	C-H	Alkyl
7.	3318	O-H	Hydrogen-bonded phenols/ alcohols

Surface Morphology of the Hybrid Thin Film

The SEM images of hybrid thin films for the different immersion periods at 5000× and 15 kV are shown in Figure 8(a-e). The surface of the control sample was relatively even and smooth. The hybrid film prepared with a 5-min immersion showed a relatively compact nature with a uniform surface, and the sample prepared with a 10-min immersion had a relatively uniform morphology with slight aggregation. This condition also coincided with the maximum electrical conductivity, indicating that the morphology is relatively consistent and may have more favorable channels for the passage of charges (Fu et al., 2019).

A longer immersion time led to a less homogeneous surface. Larger agglomerates and higher porosity were evident at 15 min, while the 20-min sample exhibited greater aggregation and surface roughness. The growing heterogeneity of the morphology with increasing sensitization period can be interpreted as a change in the surface of the hybrid film; further agglomeration

can lead to disruption of charge transport pathways, charge trapping, and recombination (Rathod et al., 2026). Overall, the 10-min immersion period resulted in the most favorable surface morphology as it offers a good balance of dye uptake and charge transport in the hybrid thin film.

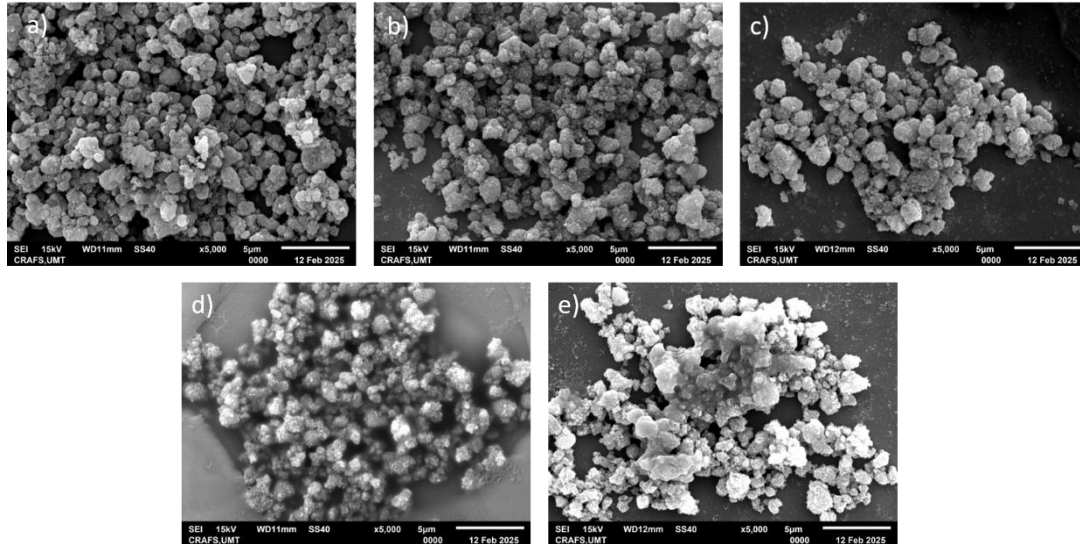


Figure 8: SEM Surface Morphologies Of ITO/TiO₂/Dye/P3HT Hybrid Thin Films Prepared At Different Dye-Sensitization Periods: (A) Control Without Dye Sensitization, (B) 5 Min, (C) 10 Min, (D) 15 Min, And (E) 20 Min.

Electrical Conductivities Of Hybrid Thin Films

The electrical conductivity of the hybrid thin films was significantly influenced by the dye immersion time and was well correlated with the SEM images. The maximum conductivity was achieved at 10 min: 0.038 S cm⁻¹ in the dark and 0.044 S cm⁻¹ in the light. The conductivity of the prepared samples under illumination did not show a significant change for the initial 5 min, whereas the conductivity of the samples prepared after 10 and 20 min showed an improvement, which indicates the greater photoresponse of the latter after dye sensitization (Kazmi et al., 2017). The hybrid film prepared under such conditions had a relatively uniform surface with a small aggregation phenomenon, which was conducive to charge transport.

The lower conductivity at shorter sensitization periods might correspond to less surface sensitization, whereas at longer immersion periods, larger agglomerates and a rougher surface are produced. Such morphological changes can lead to an increase in charge trapping and recombination, thus decreasing conductivity. The results demonstrated that the 10-min sensitization period was the most beneficial in both surface uniformity and electrical conductivity of all the treatment times.

Table 2: Electrical Conductivity Of ITO/TiO₂/Dye/P3HT Hybrid Thin Films Prepared At Different Dye-Sensitization Periods Under Dark And Illuminated Conditions.

Sensitization period	Conductivity (S cm ⁻¹)	
	Dark (0 W m ⁻²)	Light (100 W m ⁻²)
Control sample	0.031	0.030

5 min	0.024	0.023
10 min	0.038	0.044
15 min	0.028	0.033
20 min	0.026	0.037

Conclusion

The mangosteen pericarp extract had a wide visible-light absorption spectrum and possessed hydroxyl, carbonyl, and ether-like functional groups, which can be attributed to anthocyanin- and xanthone-containing compounds. All these qualities make the extract a possible natural sensitizer for hybrid films based on TiO_2 . Surface morphology and electrical conductivity of the ITO/ TiO_2 /dye/P3HT films also depended on the dye-sensitization time. As the sensitization period decreased, surfaces were more homogeneous; the longer the periods, the more heterogeneous the surfaces were, and the more the particles had aggregated.

The 10-min sensitization period exhibited the most satisfactory morphology and the highest electrical conductivity of 0.038 S cm^{-1} in the dark and 0.044 S cm^{-1} under illumination among the conditions investigated. This indicates that 10 min is a proper duration for the surface sensitization and charge-transport properties in the hybrid film. The results overall reveal that the sensitization period is a crucial parameter in processing the mangosteen-sensitized TiO_2 /P3HT hybrid thin films to achieve desired morphological and electrical properties. To verify the impact of the sensitization period on the real performance of solar cells, further photovoltaic characterizations with full device measurements are needed.

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